2013

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Recommended Citation

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A study of the Densities and Viscosities of Multi-Component Regular Liquid Systems at 293.15 K and 298.15 K

By

Niloufar Mohajerani

A Thesis
Submitted to the Faculty of Graduate Studies
Through Environmental Engineering
In Partial Fulfillment of the Requirements for
The Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada
2013

A study of the Densities and Viscosities of Multi-Component Regular Liquid Systems at 293.15 K and 298.15 K

by

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April 24, 2013

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ABSTRACT

The viscosities and densities of the quinary regular system: cyclohexane + *p*-xylene + chlorobenzene + 1-propanol + 1-octanol and its quaternary, ternary and binary subsystems were measured and reported at 293.15 K and 298.15 K.

The experimental data obtained during the course of the present study were employed to test the predictive capabilities of six selected viscosity models available in the literature; *viz.*, the generalized McAllister model, the *pseudo*-binary McAllister model, the group contribution GC-UNIMOD model, the generalized corresponding state principle model (GCSP), the Allan and Teja correlation, and the Grunberg and Nissan law of viscosity.

The results of testing indicated that the *pseudo*-binary McAllister model predicted the experimental data better than the other models. Such a result is not in agreement with previous studies due to the relatively high size ratio of molecules of the components constituting some systems as well as differing shapes of such molecules in the present study.

DEDICATION

This thesis is dedicated to my parents ‘Nasrin Saatchi’ and ‘Mansour Mohajerani’, for their endless love, support and encouragement.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my Professor Dr. Abdul-Fattah A. Asfour for giving me this opportunity and guiding me through all steps with his knowledge and kindness.

I would like also to thank my parents who supported me from overseas these years both financially and emotionally through all problems I faced in the new chapter of my life. I am also thankful to my brother, Masroor, who gave me confidence and the power to overcome my pains and keep following my dreams.

My thanks also go to professors in the Environmental Engineering program at the University of Windsor who mentored me with their knowledge and experience.

I would also express my deep appreciation to my special friends, Ali, Aida, Hanif and Bart for being examples of true friends and who helped me to deal with pains.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Viscosity is the transport property of a fluid which characterizes resistance to flow. Viscosity represents the concept of internal friction between the molecules of the fluid when any part of a fluid moves; adjacent layers tend to be carried along too. In engineering processes such as heat and mass transfer, the information about viscosity of liquid mixtures is important because viscosity data show the behavior of liquid mixtures. Viscosity is the quantity that determines the forces to be overcome when fluids are pumped through pipelines and in bearings, etc.

The shear stress F is defined as the shearing force, P, divided by the area A over which it acts. The velocity gradient D equals the velocity difference v divided by the distance between the surfaces h. In Newtonian liquids, the shear stress is directly proportional to the velocity gradient:

$$F = - \mu D \tag{1.1}$$

Equation (1.1) is known as *Newton's law of viscosity*. The constant μ is the absolute viscosity which has the units, g. $cm^{-1}.s^{-1}$, and is known as the 'poise' in honor of Poiseuille, one of the great pioneers of viscometry. In glass viscometers, the liquid flows through a capillary due to gravity that means the head of the liquid is the driving pressure. These types of viscometers measure the kinematic viscosity v of the fluid since the measurement is proportional to the density of the liquid.

$$\mu = v \rho \tag{1.2}$$

Viscosity is a function of temperature. In gases, the viscosity increases with increasing the temperature whereas in liquid systems, viscosity decreases with increasing temperature often by an appreciable amount. Therefore, temperature control is exercised during all viscosity measurements, and viscosity values should be tabulated with temperature. Also, in liquid mixtures viscosity depends on composition as well as temperature.

The mechanisms and molecular theory of gas viscosity have been reasonably well clarified by non-equilibrium statistical mechanics and the kinetic theory of gases (Millet, *et al.* 1996) but the theory of liquid viscosity is less well developed. This lack of knowledge is because of the uncertainty about the structure of liquids and the intermolecular forces among molecules in the liquid state. It is particularly desirable to determine liquid viscosities from experimental data when such data exist. In an attempt to solve this problem researchers are working to develop theories for calculating the viscosities of liquid mixtures.

The problem associated with the structure of liquids was recognized and indicated by Asfour (1980). He suggested classifying liquid solutions into three classes, *viz*., *n*-alkane mixtures, regular solutions, and associated systems. That classification led to the successful prediction of the dependence of mutual diffusivities on composition for different liquid systems (Asfour, 1985, Dullien and Asfour, 1985, and Asfour and Dullien, 1986). Asfour and co-workers successfully extended this classification to the prediction of the viscosities of multi-component liquid systems for *n*-alkane liquid systems and regular solutions.

The methods of calculating the viscosity of liquids in the literature is classified into two categories, namely, correlative and predictive equations. Whereas the former require experimental data, the latter require pure component and molecular parameters. Many of the existing methods are not predictive and require viscosity data to determine adjustable parameters or, for mixtures interaction parameters.

In the present study, the empirical and semi-theoretical models are presented and their predictive capabilities are tested. Semi-theoretical models refer to those models which have a theoretical basis but contain adjustable parameters which can be determined from experimental data. Such models include: The generalized McAllister three-body interaction model, the *pseudo*-binary McAllister interaction model, the GC-UNIMOD model, the generalized corresponding state principle (GCSP) model, the Allan and Teja model, and the Grunberg and Nissan model

1.2 Objectives

Experimental data on multi-component liquid systems are scarce in literature. Ternary and quaternary systems data are rare in the literature whereas for quinary liquid systems, Dr. Asfour's laboratory is the only laboratory in the world to report such data.

The main objectives of the present study are as follows:

- Measuring the kinematic viscosities and densities of the quinary regular system: cyclohexane + p-xylene + chlorobenzene + 1-propanol + 1-octanol and its binary, ternary and quaternary subsystems over the entire composition range at 293.15 K and 298.15 K.
- Testing the predictive capabilities of the selected viscosity models using the experimental data obtained in the present study.

The systems investigated in the present study are listed in Table 1.1.

Table 1.1: **<u>The Systems Investigated in the Present Study</u>**

1. The binary subsystems of the quinary system: cyclohexane + p-xylene + chlorobenzene + 1-propanol + 1-octanol

cyclohexane (1) + p-xylene (2)
cyclohexane (1) + chlorobenzene (2)
cyclohexane (1) + 1-propanol (2)
cyclohexane (1) + 1-octanol (2)
p-xylene (1) + chlorobenzene (2)
p-xylene (1) + 1-propanol (2)
p-xylene (1) + 1-octanol (2)
chlorobenzene (1) + 1-propanol (2)
chlorobenzene (1) + 1-octanol (2)
1-propanol (1) + 1-octanol (2)

---

2. The ternary subsystem of the quinary system : cyclohexane + p-xylene + chlorobenzene + 1-propanol + 1-octanol

cyclohexane (1) + p-xylene (2) + chlorobenzene (3)
cyclohexane (1) + p-xylene (2) + 1-propanol (3)
cyclohexane (1) + p-xylene (2) + 1-octanol (3)
cyclohexane (1) + chlorobenzene (2) + 1-propanol (3)
cyclohexane (1) + chlorobenzene (2) + 1-octanol (3)
cyclohexane (1) + 1-propanol (2) + 1-octanol (3)
p-xylene (1) + chlorobenzene (2) + 1-propanol (3)
p-xylene (1) + chlorobenzene (2) + 1-octanol (3)
p-xylene (1) + 1-propanol (2) + 1-octanol (3)
chlorobenzene (1) + 1-propanol (2) + 1-octanol (3)

Table 1.1 Cont'd.

3. The quaternary subsystem of the quinary system : cyclohexane + p-xylene + chlorobenzene + 1-propanol + 1-octanol

cyclohexane (1) + p-xylene (2) + chlorobenzene (3) + 1-propanol (4)
cyclohexane (1) + p-xylene (2) + chlorobenzene (3) + octanol (4)
cyclohexane (1) + p-xylene (2) + 1-propanol (3) + 1-octanol (4)
cyclohexane (1) + chlorobenzene (2) + 1-propanol (3) + 1-octanol (4)
p-xylene (1) + chlorobenzene (2) + 1-propanol (3) + 1-octanol (4)

4. The quinary system : cyclohexane (1) + p-xylene (2) + chlorobenzene (3) + 1-propanol (4) + 1-octanol (5)

1.3 Contributions and Significance

The density, kinematic viscosity and absolute viscosity values reported in the present study provide reliable and valuable additions to the literature for the quinary system: cyclohexane + p-xylene + chlorobenzene + 1-propanol + 1-octanol, and its binary, ternary and quaternary sub-systems over the entire composition range at 293.15 K and 298.15 K.

The data reported herein can be used in critically testing viscosity prediction models.

CHAPTER 2

PERTINENT LITERATURE REVIEW

2.1 General

In engineering problems, calculation of viscosity of liquid mixtures plays an important role. Knowledge of viscosity dependence on composition in different aspects of engineering is important in the areas of heat, mass transfer, and fluid mechanics. Accordingly, authentic methods for calculating the viscosity of liquid mixtures are required in industry.

In the literature, methods are available for viscosity prediction which are presented in this chapter. These methods can be categorized into two types of models, *viz*., semi-theoretical and empirical. The semi-theoretical models depend on theory and experimental data whereas the empirical models are dependent on the acquisition of costly and time consuming experimental data.

In recent years, there have been efforts to develop and report predictive models rather than correlative ones in order to avoid experiments as much as possible. One example of this endeavor has been done by Asfour *et al*. (1991). They succeeded in converting the purely correlative McAllister model (1960) into a predictive method. They reported a technique that allowed them to calculate the values of the adjustable parameters contained in the model by using pure component properties and molecular parameters.

The literature contains a number of models that aim at predicting the values of the kinematic or absolute viscosities of liquid mixtures. Among these models, six of the most reliable ones are selected in the present study to be tested using the experimental data collected. The tested models include : 1) the generalized McAllister three-body interaction model, 2) the *pseudo*-binary McAllister model, 3) the GC-UNIMOD model, 4) the generalized corresponding-states principle (GCSP), 5) the Allan and Teja correlation, and 6) the Gruenberg and Nissan model. The first four methods are predictive, or have been modified to behave as predictive, and the last two are correlative and depend on experimental data. Discussion of these models is in order.

2.2 The Semi-Theoretical Models for Predicting the Viscosity of Liquid Mixtures

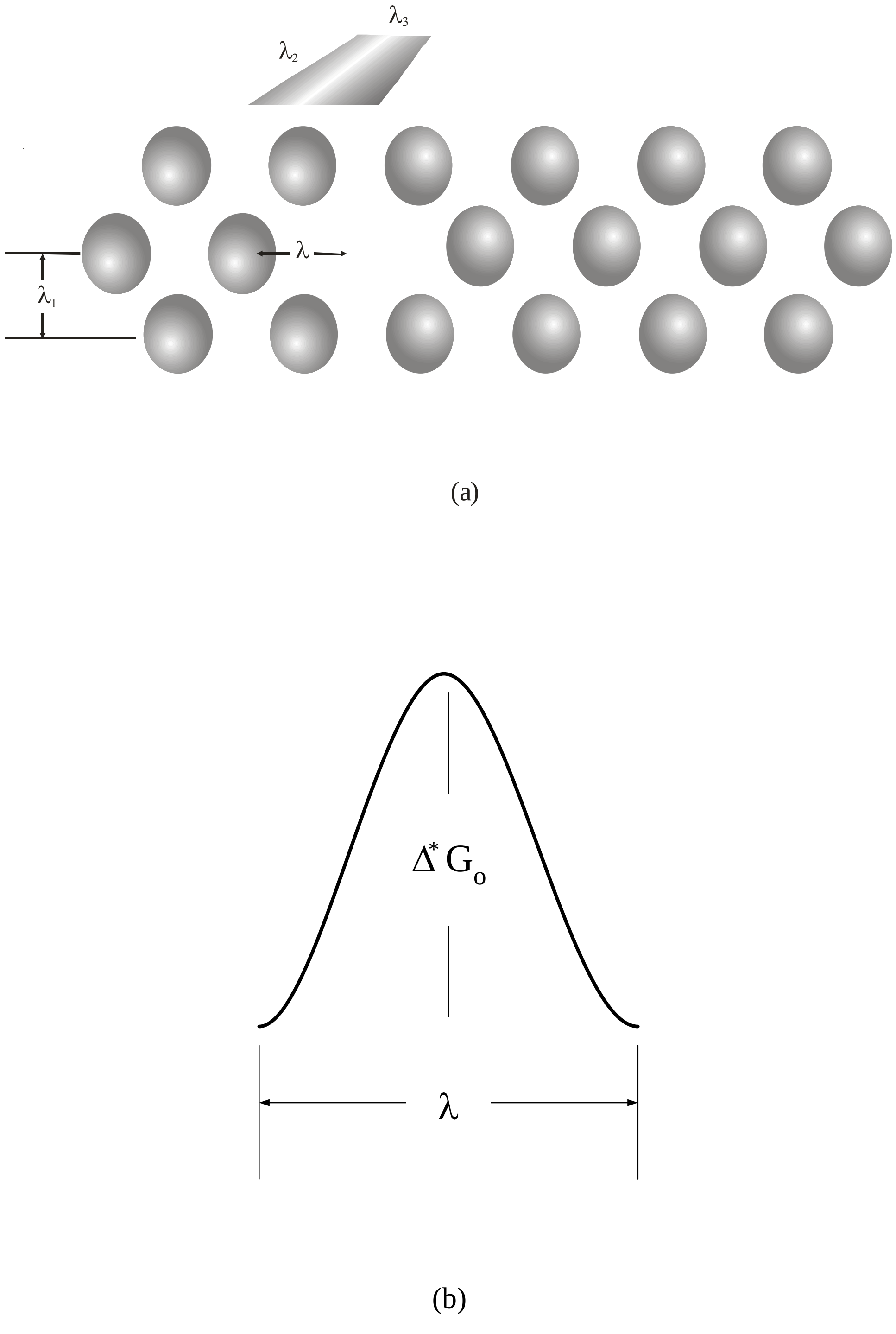
2.2.1 The McAllister three-body interaction model

McAllister (1960) based his work on Eyring's theory of absolute reaction rates. This theory was established on the assumption that there are layers of molecules in the liquid and if the shear stress is applied to a layer with the distance of λ_1 from the next layer then there would be a "hole" or a vacant site in the second layer to receive the molecule as shown in Figure 2.1(a). The availability of this positions requires the movement of molecules from their stable positions and overcome the potential energy barrier, ΔG^*, depicted in Figure 2.1 (b). In this jump, the molecule posses a movement frequency in the forward and backward directions calculated by the equation,

$$r_0 = \frac{KT}{h} e^{\frac{-\Delta G_0^*}{kT}} \tag{2.1}$$

where T is the absolute temperature, K is the Boltzmann constant, and h is Planck's constant.

In equation (2.1), if there is no force employed on the fluid then the forward and backward jumping rates are equal and the liquid is not able to flow; but if a shear force exerted to the



(a)

(b)

Figure 2.1: Eyring’s model of Liquid Viscosity

molecules in the liquid, then the molecules move in the forward and backward directions differently. Hence, the work enforced the molecules is given,

$$\varepsilon_a = f\lambda_2\lambda_3(\frac{\lambda}{2}) \tag{2.2}$$

where f is the shear force per unit area, $\lambda_2\lambda_3$ is the average area occupied by each molecule and λ is defined as the available space between the molecules.

If the molecule moves in the forward direction of the shear force and attain the work, ε_a , then the frequency in this direction will be

$$r_f = \frac{KT}{h}\exp(-\frac{\Delta G_0^* - \varepsilon_a}{kT}) \tag{2.3}$$

and correspondingly in the backward direction is as follows:

$$r_b = \frac{KT}{h}\exp(-\frac{\Delta G_0^* + \varepsilon_a}{kT}) \tag{2.4}$$

and the net frequency is given by

$$r_n = \left[\frac{KT}{h}\exp\left(-\frac{\Delta G_0^*}{kT}\right)\right]\left[\exp(\varepsilon_a) - \exp(-\varepsilon_a)\right] \tag{2.5}$$

equation (2.5) can be rearranged to equation (2.6)

$$r_n = \frac{f\lambda_2\lambda_3\lambda}{h}\exp\left(-\frac{\Delta G_0^*}{kT}\right) \tag{2.6}$$

The velocity gradient between two layers of the molecules by the distance of λ_1 is defined as

$$\frac{dv}{dx} = \frac{\lambda r}{\lambda_1} \tag{2.7}$$

where λ is the distance per jump and r is the number of jumps per second. Since the Newton’s law becomes as

$$f = -\mu \frac{dv}{dx} \tag{2.8}$$

Then by substitution of equation (2.7) into equation (2.8) yields

$$\mu = \frac{\lambda_1 h}{\lambda_1 \lambda_2 \lambda} e^{\frac{\Delta G^*}{RT}} \tag{2.9}$$

where ΔG^* is the potential energy barrier in the form of free Gibbs energy and R is the universal gas constant.

assuming that $\lambda=\lambda_1$ and also $\lambda_1\lambda_2\lambda_3$ identified as the effective volume of the molecule then equation (2.9) converts to

$$\mu = \frac{hN}{V_m} e^{\frac{\Delta G^*}{RT}} \tag{2.10}$$

where N is Avogadro’s number and V_m is the molar volume of the liquid. In the case of kinematic viscosity equation (2.10) rewritten as

$$\nu = \frac{\mu}{\rho} = \frac{hN}{M} e^{\frac{\Delta G^0}{RT}} \tag{2.11}$$

where M is the molecular weight and ΔG^0 is the molar activation energy of viscous flow.

2.2.1.1 Three-body interaction model for a binary mixture liquid system

McAllister (1960) proposed his viscosity model for binary liquid mixtures on the basis of Eyring's theory by equation (2.11). He assumed that if the size ratio of molecules of type 1 and 2 is less than 1.5, then the interactions are three bodied and are all in one plane. Also, if the size ratio is larger than 1.5, the type of interaction considered is three-dimensional four-body interaction which means that other molecular collisions are possible. In such a case, when a molecule of type 1 with a size ratio of 1.5 or more passes the molecular energy barrier to the available vacant area, it may interact with molecule of type 1, type 2 or paired interaction in the presence of both situations. Figures 2.2 and 2.3 show types of viscosity interactions in three-body and four-body interaction cases in a binary mixture, respectively.

In Figure 2.2, six types of possible unlike interactions in the three-body model are shown with the classification of 1-1-1, 2-2-2, 1-2-1, 2-1-2, 1-1-2, 1-2-2. McAllister assumed that the likelihood of each interaction is dependent on the mole fraction of each component in the mixture. Also, he assumed that the free energy of activation is additive. On the basis of those assumptions, occurrence of different types of interactions is given as

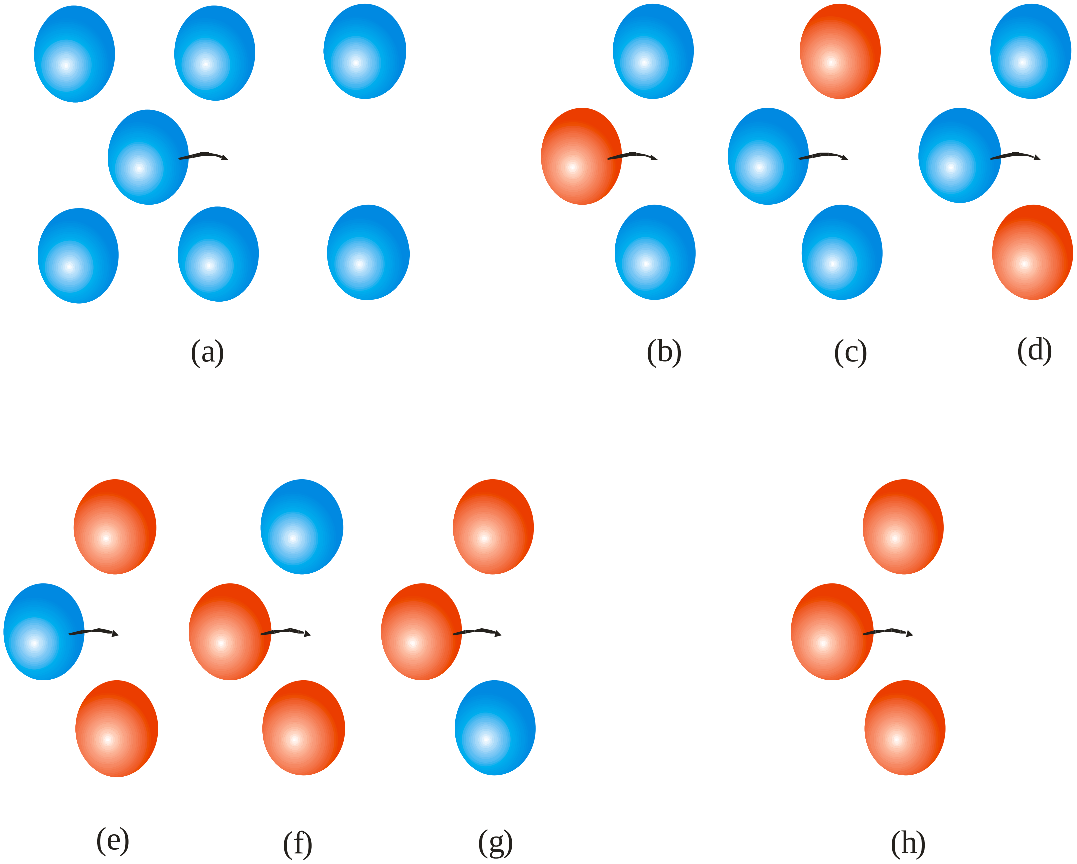


Figure 2.2: Types of interactions in a Binary System, Three –Body Interaction Model

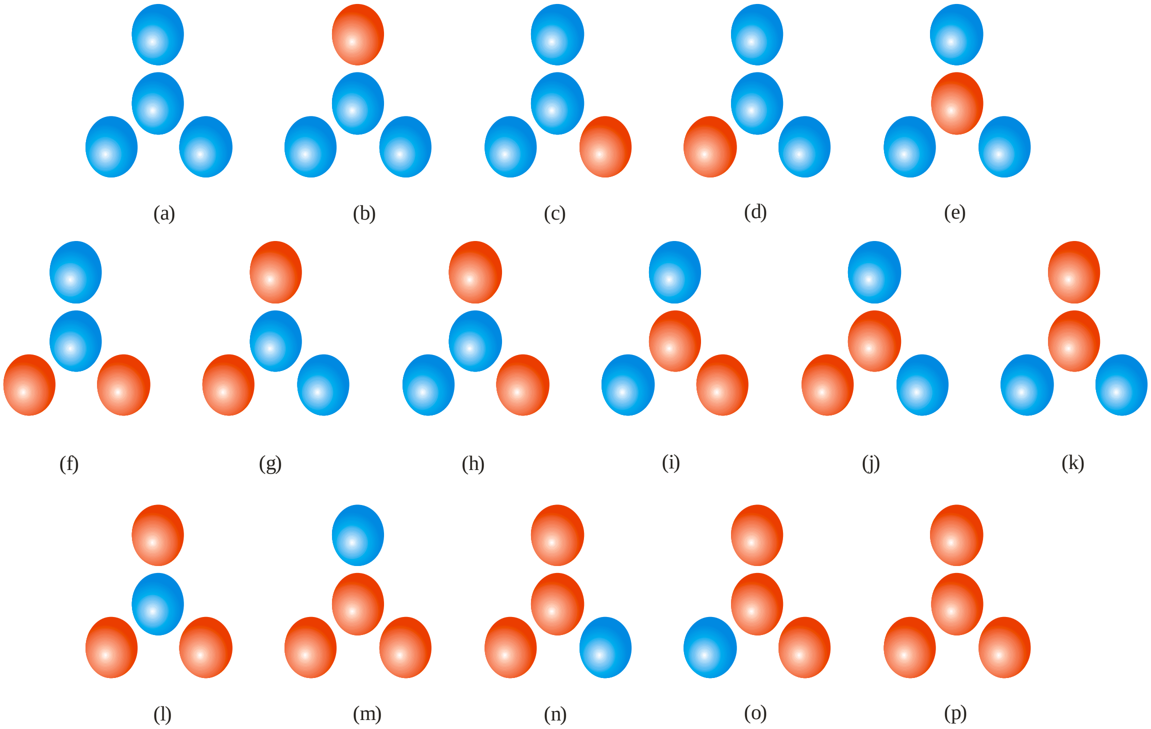


Figure 2.3: Types of Interactions in a Binary Mixture, Four –Body Interaction Model

Types of interaction	*1-1-1*	*1-2-1*	*2-1-1, 1-1-2*	*2-1-2*	*2-2-1, 1-2-2*	*2-2-2*
Fraction of total occurrence	x_1^3	$x_1^2 x_2$	$2x_1^2 x_2$	$x_1 x_2^2$	$2x_1 x_2^2$	x_2^3

Consequently, for the mixture, the free energy of activation, ΔG^* ,yields

$$\Delta G^* = x_1^3 \Delta G_1^* + x_1^2 x_2 \Delta G_{121}^* + 2x_1^2 x_2 \Delta G_{112}^* + x_1 x_2^2 \Delta G_{212}^* + 2x_1 x_2^2 \Delta G_{122}^* + x_2^3 \Delta G_2^* \tag{2.12}$$

Two additional assumptions made for simplicity are as follows:

$$\Delta G_{121}^* = \Delta G_{112}^* = \Delta G_{12}^* \tag{2.13}$$

$$\Delta G_{212}^* = \Delta G_{122}^* = \Delta G_{21}^* \tag{2.14}$$

Substitution of equation (2.13) and (2.14) into equation (2.15), results in

$$\Delta G^* = x_1^3 \Delta G_1^* + 3x_1^2 x_2 \Delta G_{12}^* + 3x_1 x_2^2 \Delta G_{21}^* + x_2^3 \Delta G_2^* \tag{2.15}$$

Although ΔG_{121} and ΔG_{112} are physically different, the substitutions were essential in order to decrease the number of constants to two.

The other format of equation (2.12) can be re-written as

$$\Delta G^* = x_1^3 \Delta G_1^* + x_1^2 x_2 \left(\Delta G_{121}^* + 2\Delta G_{112}^* \right) + x_1 x_2^2 \left(\Delta G_{212}^* + 2\Delta G_{122}^* \right) + x_2^3 \Delta G_2^* \tag{2.16}$$

where

$$\Delta G_{12}^* = \frac{\left(\Delta G_{121}^* + 2\Delta G_{112}^* \right)}{3} \tag{2.17}$$

$$\Delta G_{21}^* = \frac{\left(\Delta G_{212}^* + 2\Delta G_{122}^* \right)}{3} \tag{2.18}$$

Equation (2.15) specifies that for each type of energy of activation considered in this study, a corresponding kinematic viscosity dedicated and given by

$$\nu = \left(\frac{hN}{M_{avg}} \right) e^{\frac{\Delta G^*}{RT}} \tag{2.19}$$

M_{avg} is the average molecular weight of the mixture and is expressed by

$$M_{avg} = \sum_i x_i M_i \tag{2.20}$$

for pure component i

$$\nu_i = \left(\frac{hN}{M_i} \right) e^{\frac{\Delta G_{ij}^*}{RT}} \tag{2.21}$$

and for interactions

$$\nu_{ij} = \left(\frac{hN}{M_{ij}} \right) e^{\frac{\Delta G_{ij}^*}{RT}} \tag{2.22}$$

where

$$M_{ij} = \frac{\left(2M_{ij} + M_j \right)}{3} \tag{2.23}$$

Substitution of equation (2.12) into equation (2.19) yields equation (2.24) for the kinematic viscosity of the mixture,

$$\nu = \frac{hN}{M_{avg}} e^{\left[x_1^3 \Delta G_1^* + 3x_1^2 x_2 \Delta G_{12}^* + 3x_1 x_2^2 \Delta G_{21}^* + x_2^3 \Delta G_2^*\right] / RT} \tag{2.24}$$

Taking the logarithm of equation (2.24) and omitting the free energies of activation by applying equations (2.21) and (2.22) gives

$$\begin{aligned} \ell n \nu = {} & x_1^3 \ell n \nu_1 + 3x_1^2 x_2 \ell n \nu_{12} + 3x_1 x_2^2 \ell n \nu_{21} + x_2^3 \ell n \nu_2 - \ell n\left[x_1 + x_2 M_2 / M_1\right] \\ & + 3x_1^2 x_2 \ell n\left[\left(2 + M_2 / M_1\right)/3\right] + 3x_1 x_2^2 \ell n\left[\left(1 + 2M_2 / M_1\right)/3\right] + x_2^3 \ell n\left[M_2 / M_1\right] \end{aligned} \tag{2.25}$$

The only undetermined values in equation (2.25) are the binary interaction parameters ν_{12} and ν_{21} at each temperature which can be determined by fitting the experimental data to equation (2.25) using least-squares. The McAllister model fits a variety of experimental data and is known as the best correlative model for the viscosities of liquid mixtures.

2.2.1.2 Extension of the McAllister three-body model to ternary liquid systems

Chandramouli and Laddha (1964) expanded McAllister's the three-body interaction model for viscosity of binary liquid mixtures to ternary mixtures. They assume three types of molecules with the size ratio of less than 1.5 and three-body interactions in a plane. The proposed expression of the kinematic viscosity of the mixture after substitutions and rearrangement is as follows:

$$\begin{aligned} \ell n \nu = {} & x_1^3 \ell n \nu_1 + x_2^3 \ell n \nu_2 + x_3^3 \ell n \nu_3 + 3x_1^2 x_2 \ell n \nu_{12} + 3x_1^2 x_3 \ell n \nu_{13} + 3x_2^2 x_1 \ell n \nu_{21} \\ & + 3x_3^2 x_1 \ell n \nu_{31} + 3x_3^2 x_2 \ell n \nu_{32} + 6x_1 x_2 x_3 \ell n \nu_{123} - \ell n\left(x_1 M_1 + x_2 M_2 + x_3 M_3\right) \\ & + 3x_1^3 \ell n M_1 + x_2^3 \ell n M_2 + x_3^3 \ell n M_3 + 3x_1^2 x_2 \ell n\left(2M_1 + M_2\right)/3 \\ & + 3x_1^2 x_3 \ell n\left(2M_1 + M_3\right)/3 + 3x_2^2 x_1 \ell n(2M_2 + M_1)/3 + 3x_2^2 x_3 \ell n(2M_2 + M_3)/3 \\ & + 3x_3^2 x_1 \ell n(2M_3 + M_1)/3 + 3x_3^2 x_2 \ell n(2M_3 + M_2)/3 \\ & + 6x_1 x_2 x_3 \ell n(M_1 + M_2 + M_3)/3 \end{aligned} \tag{2.26}$$

where M_1, M_2 and M_3 are the molecular weights of components1, 2, and 3. Moreover, there are seven constants; six binary constants and one ternary constant. The three binary systems of components of types 1 and 2, types 2 and 3, and 1 and 3 yield the constants ν_{12} and ν_{21}, ν_{23} and ν_{32}, and ν_{31} and ν_{13}, respectively and a ternary constant ν_{123}. The values of the binary constants are determined by fitting experimental data of the viscosity of the pure components. The value of the ternary interaction parameter is determined by fitting the experimental data using the method of the least-squares.

2.2.1.3 Conversion of the McAllister model from a correlative to a predictive model

Despite the fact that McAllister three-body interaction viscosity model gives promising results for calculating the viscosity of liquid mixture, it is still a correlative model and requires costly and time consuming experimental data to obtain the values of the interaction parameters.

Asfour *et al*. (1991) reported a method to calculate the values of the binary interaction parameters of binary *n*-alkane solutions with the use of pure component properties and molecular parameters. Later on, Nhaesi and Asfour (1998) developed a new model for predicting the McAllister model parameters from pure components properties of regular binary liquid mixtures. Subsequently, Nhaesi and Asfour (2000a, 2000b) introduced a method for predicting the viscosity of multi-component mixtures.

Asfour *et al.* (1991) presented a novel technique for predicting the values of binary interaction parameters or *n*-alkane binary solutions. The experimental data were fitted to equation (2.25) and the values of the parameters were plotted versus the corresponding temperature levels. Asfour *et al*. (1991) assumed that,

$$\nu_{12} \propto \left(\nu_1 \nu_1 \nu_2\right)^{1/3} \quad (2\text{-}27)$$

Plotting the value of the lumped parameter, $\nu_{12} \propto \left(\nu_1{}^2 \nu_2\right)^{1/3}$, against the inverse of the absolute temperature 1/T, shown in Figure 2.4, gives a horizontal line which indicates that the lumped parameter is independent of temperature. Because of that, Asfour (1991) plotted the lumped parameter versus $\left[(N_2 - N_1)^2 / \left(N_1^2 N_2\right)^{1/3}\right]$ as shown in Figure 2.5, where N_A and N_B are the number of carbon atoms per molecule of component i and j. The equation of the plotted straight line is written as:

$$\nu_{12} / \left(\nu_1^2 \nu_2\right)^{1/3} = 1 + k_1 (N_2 - N_1)^2 / \left(N_1^2 N_2\right)^{1/3} \quad (2.28)$$

where k_1 is the slope of the straight line and the value of that is equal to 0.044 for the systems where $\left|N_1 - N_2\right| \le 3$. Equation (2.28) gives the value of interaction parameter, ν_{12}, from pure components properties. The value of ν_{21} can be computed by

$$\nu_{21} = \nu_{12} \left(\nu_2 / \nu_1\right)^{1/3} \quad (2.29)$$

Substituting the values of interaction parameters calculated from pure components kinematic viscosities and substituting equations (2.28) and (2.29), into equation (2.25) determines the kinematic viscosities of the binary systems at different compositions. Consequently, this method converts the McAllister three-body model for binary mixtures into a predictive model.

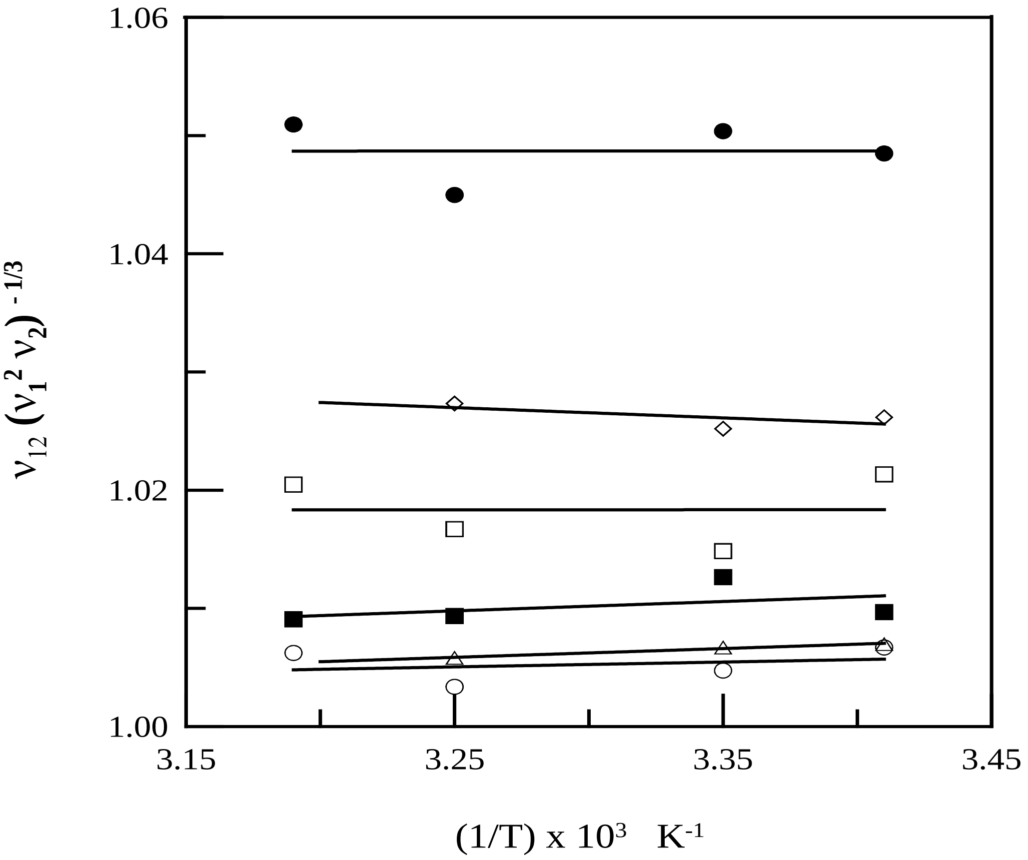


Figure 2.4: Variation of the Lumped Parameter $\nu_{12}/(\nu_1\nu_1\nu_2)^{1/3}$ with 1/T Systems for which $|N_2-N_1|\leq3$

Legend

- △ Hexane (A) - Heptane (B)
- ◇ Hexane (A) - Octane (B)
- ○ Heptane (A) - Octane (B)
- ● Heptane (A) - Decane (B)
- ■ Tetradecane (A) - Hexadecane (B)
- □ Octane (A) - Decane (B)

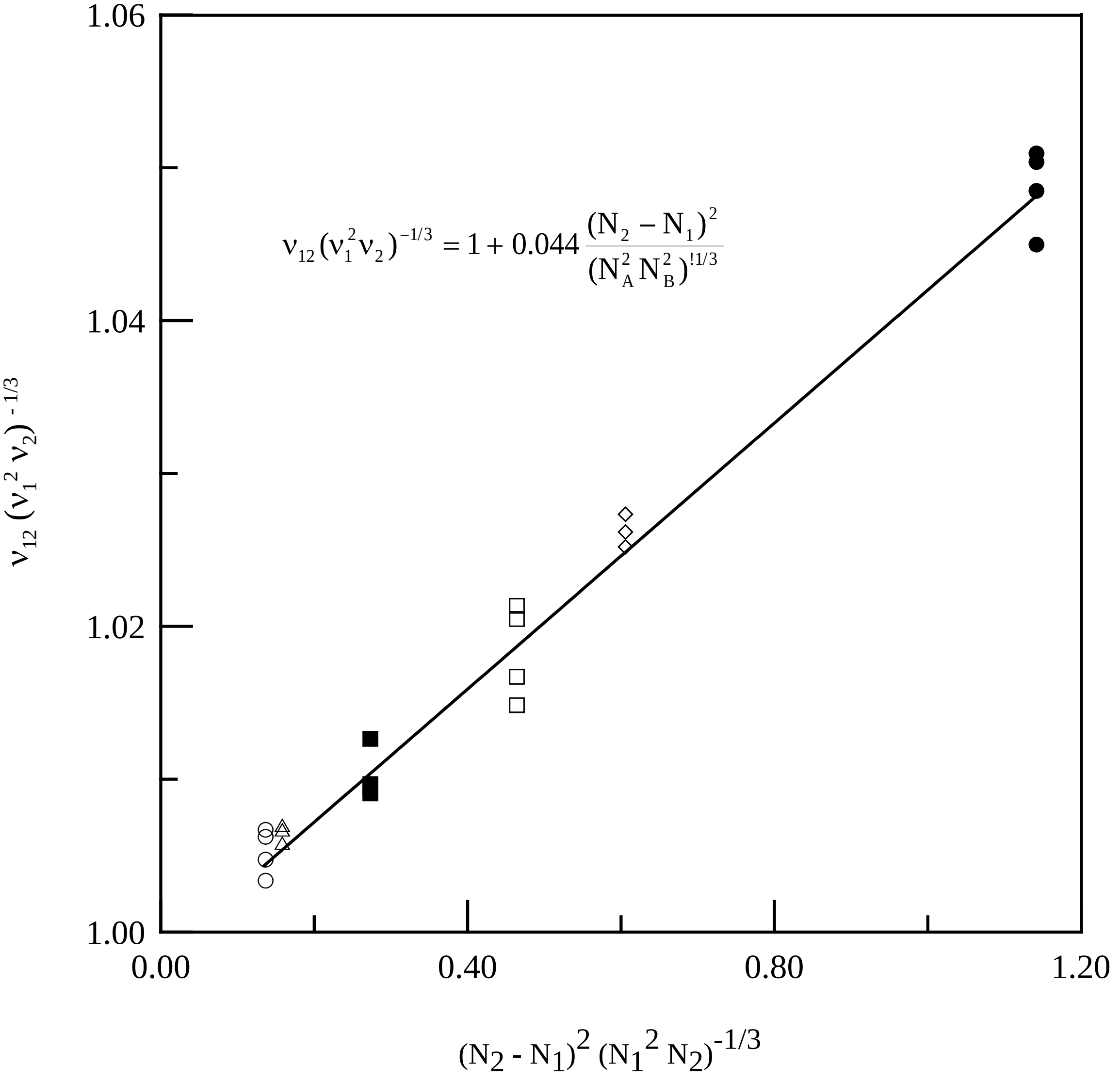


Figure 2.4: Variation of the Lumped Parameter $v_{12}/(v_1{}^2\ v_1)^{1/3}$ versus $[(N_2\text{-}N_1)^2/(N_1{}^2N_2)^{1/3}]$

Asfour *et al*. (1991) showed that in the case of liquid mixtures with $\left|N_1 - N_2\right| \geq 4$, McAllister four-body interaction model with three interaction parameters is applicable and they proposed equation (2.30) for the calculating the value of the four-body interaction parameter, ν_{iijj}, exercising the same strategy as for the three bodied model, which yields:

$$\nu_{1122} / \left(\nu_1^2 \nu_2^2\right)^{1/4} = 1 + k_2 \frac{\left(N_2 - N_1\right)^2}{\left(N_1^2 N_2^2\right)^{1/4}} \qquad (2.30)$$

The value of k_2, is also the slope of the straight line and the value is determined by the method of least-squares and was found to be equal to 0.03.

The other three interaction parameters are assumed to be as follows:

$$\nu_{1112} \propto \left(\nu_1^3 \nu_2\right)^{1/4} \qquad (2.31)$$

$$\nu_{1122} \propto \left(\nu_1^2 \nu_2^2\right)^{1/4} \qquad (2.32)$$

$$\nu_{2221} \propto \left(\nu_1 \nu_2^3\right)^{1/4} \qquad (2.33)$$

Dividing equation (2.31) by equation (2.32) and equation (2.33) by equation (2.32) results in the following equations:

$$\nu_{1112} = \nu_{1122} \left(\nu_1 / \nu_2\right)^{1/4} \qquad (2.34)$$

$$\nu_{2221} = \nu_{1122} \left(\nu_2 / \nu_1\right)^{1/4} \qquad (2.35)$$

Nhaesi and Asfour (1998) attempted to present the predictive form of the three-body interaction McAllister model for regular solutions utilizing the effective carbon number (ECN) concept that they developed. They plotted the kinematic viscosity data of *n*-alkanes (C_5-C_{20}) at 308.15K versus the corresponding carbon number of those alkanes, as depicted in Figure 2.6. The equation of the straight line depicted in Figure 2.6 is given by,

$$\ell n\left(\nu_{at308.15K}\right)=A+BN \tag{2.36}$$

where ν is the kinematic viscosity in cSt and N is the carbon number. The values of A and B are -1.943 and 0.193, respectively. Later on, Al Gherwi and Asfour (2005), El-Hadad (2004) and Cai (2004), and El-Sayed (2009) indicated that equation (2.36) tends to overpredict the values of the effective carbon number for compounds such as cyclohexane and cyclooctane. They noted that lower errors resulted when the ECN values obtained from equation (2.36) were multiplied by 0.75.

Nhaesi and Asfour (1998) plotted $\nu_{12} \propto \left(\nu_1^2\nu_2\right)^{1/3}$ against $[(N_2-N_1)^2/(N_1^2N_2)^{1/3}]$ where N_i and N_j are the effective carbon numbers of components and j, respectively and obtained a straight line as shown in Figure (2.7). The equation of the straight line was obtained, by the least-square technique, to be as follows:

$$\frac{\nu_{12}}{\left(\nu_1^2\nu_2\right)^{1/3}}=0.8735+0.0715\frac{\left(N_2-N_1\right)^2}{\left(N_1^2N_2\right)^{1/3}} \tag{2.37}$$

The value of the binary interaction,ν_{21}, is calculated by equation (2.29).

2.2.1.4 The generalized McAllister three-body model

Nhaesi and Asfour (2000a) developed a predictive form of the generalized McAllister three-body interation model for multicomponent mixtures. They determined the values of the interaction

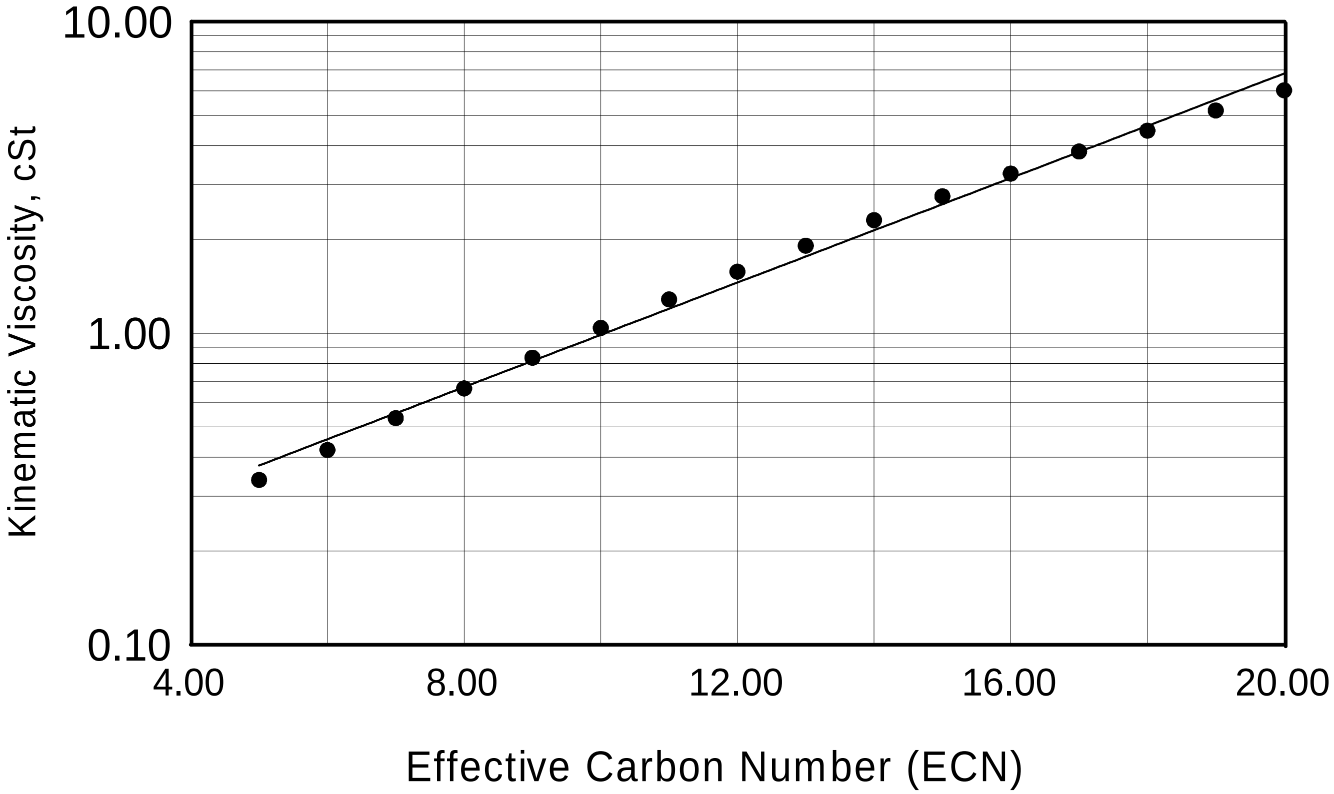


Figure 2.5: Kinematic Viscosity for *n*-alkanes versus the Effective Carbon Number (ECN)

parameters from the values of the viscosities of the pure components. This model includes the binary and ternary interaction parameters similar to the three-body interaction model of ternary systems suggested by Chandramouli and Laddha (1963).

Nhaesi and Asfour (2000a) made some assumptions to define their equation. First, they assumed that the interactions are three-bodied and second, that the free energies of activation are additive on a molar basis.

The activation energy of an *n*-component liquid mixture is given by,

$$\Delta G_m = \sum_{i=1}^{n} x_i^3 \Delta G_i + 3\sum_{i=1}^{n}\sum_{j=1}^{n} x_i^2 x_j \Delta G_{ij} + 6\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n} x_i x_j x_k \Delta G_{ijk} \tag{2.38}$$

The components of the mixture are i, j and k where i has the highest number of carbons and k has the lowest.

In equation (2.38) two additional assumptions are made as follows:

$$\Delta G_{iji} = \Delta G_{iij} = \Delta G_{ij} \tag{2.39}$$

$$\Delta G_{jij} = \Delta G_{ijj} = \Delta G_{ji} \tag{2.40}$$

Equation (2.41) correlates the kinematic viscosity of the mixture and ΔG is adopted from an Arrhenius-type equation.

$$\nu_m = \frac{hN_\circ}{M_{avg}} e^{\left(\Delta G_m / RT\right)} \tag{2.41}$$

where

$$M_{avg} = \sum_{i=1}^{n} x_i M_i \tag{2.42}$$

for pure components i,

$$\nu_i = \frac{hN_\circ}{M_i} e^{(\Delta G_i / RT)} \tag{2.43}$$

for the binary interaction of type ij,

$$\nu_{ij} = \frac{hN_\circ}{M_{ij}} e^{(\Delta G_{ij} / RT)} \tag{2.44}$$

where

$$M_{ij} = (2M_i + M_j)/3 \tag{2.45}$$

for ternary interactions

$$\nu_{ijk} = \frac{hN_\circ}{M_{ijk}} e^{(\Delta G_{ijk} / RT)} \tag{2.46}$$

where

$$M_{ijk} = (M_i + M_j + M_k)/3 \tag{2.47}$$

Taking the logarithm of equations (2.41), (2.43), (2.44) and (2.46) and substituting them into equation (2.37) eliminates the free energies of activation. The following equation is the generalized McAllister three-body model for multi-component liquid mixture:

$$\begin{aligned}\ell n \nu_m = \sum_{i=1}^{n} x_i^3 \ell n(\nu_i M_i) + 3 \sum_{\substack{i=1 \\ i \neq j}}^{n} \sum_{j=1}^{n} x_i^2 x_j \ell n(\nu_{ij} M_{ij}) \\ + 6 \sum_{\substack{i=1 \\ i<j<k}}^{n} \sum_{j=1}^{n} \sum_{k=1}^{n} x_i^2 x_j x_k \ell n(\nu_{ijk} M_{ijk}) - \ell n(M_{avg})\end{aligned} \tag{2.48}$$

The kinematic viscosity of the *n*-component liquid mixture can be obtained from equation (2.48) if the properties of pure components are available. The number of binary and ternary interaction parameters depends on the components in the system. Nhaesi and Asfour (2000a) suggested the use of equations (2.49) and (2.50) for the determination of the number of binary interactions, N_2 as well as the number of ternary interactions parameters, N_3

$$N_2 = \frac{n!}{2!(n-2)!} \tag{2.49}$$

$$N_3 = \frac{n!}{3!(n-3)!} \tag{2.50}$$

The effective carbon number and the value of the binary interaction parameters can be calculated by following the procedure suggested by Nhaesi and Asfour (1998).

Nhaesi and Asfour (2000a) introduced a method for determining the value of ternary parameter from pure component properties and the number of carbon atoms per molecule or the effective carbon number of each component in the mixture in the cases of *n*-alkane and regular liquid mixtures, respectively; *viz*.,

$$\frac{\nu_{ijk}}{\left(\nu_i \nu_j \nu_k\right)^{1/3}} = 0.9637 + 0.0313 \frac{\left(N_k - N_i\right)^2}{N_j} \tag{2.51}$$

where i,j, and k are the components of the mixture in ascending number of carbons and N_i, N_j and N_k are their number of carbons, respectively.

2.2.2 The *pseudo*-binary McAllister model

Nhaesi and Asfour (2000b) suggested the incorporation of the pseudo-binary model developed earlier by Wu and Asfour (1992) into the generalized McAllister model for multi-component liquid mixtures. In this way, Nhaesi and Asfour (2000b) argued that this reduces the complexity and time taken for calculations since the *pseudo*-binary model reduces the number of components; no matter how large it is, to only two. Consequently, in the *pseudo*-binary McAllister model, the pure components are separated into pure component 1 and *pseudo*-component 2', where component 2' includes components 2, 3,..,n. Nhaesi and Asfour (2000b) further indicated that ternary interaction parameters are eliminated since multicomponent liquid systems are treated as *pseudo*-binary mixtures.

Nhaesi and Asfour (2000b) proposed the following series of mixing rules in order to determine the properties of component 2':

$$\left(ECN\right)_{2'} = \sum_{i=2}^{n} X_i \left(ECN\right)_i \tag{2.52}$$

where

$$X_i = \frac{x_i}{\sum_{i=2}^{n} x_i} \tag{2.53}$$

The molecular weight and the kinematic viscosity of the component 2' are respectively as follows:

$$\ell n M_{2'} = \sum_{i=2}^{n} X_i \ell n M_i \tag{2.54}$$

$$\ell n \nu_{2'} = \sum_{i=2}^{n} X_i \ell n \nu_i \tag{2.55}$$

2.2.3 The group contribution (GC-UNIMOD) model

Cao *et al*. (1992) presented a viscosity model for correlating the kinematic viscosity of pure liquids, binary systems and afterwards predict the viscosity of multicomponent systems. Their technique is based on statistical thermodynamics, Eyring's absolute rate theory, and the UNIFAC model. The kinematic viscosity equation for multicomponents is given as,

$$\ell n(\nu M) = \sum_{i=1}^{n} x_i \ell n(\nu_i M_i) - \sum_{i=1}^{n} q_i n_i x_i \sum_{j=1}^{n} \theta_{ji} \ell n \tau_{ji} \tag{2.56}$$

where M is the molecular weight of the liquid mixture, x_i and M_i is the mole fraction and molecular weight of segment i in the liquid mixture, respectively. Also, q_i is the area parameter of molecule i and n_i is the proportionality constant of segment i calculated by equation (2.57),

$$\ell n\ n_i = \sum_{j=0} A_j T^j \tag{2.57}$$

Where the values of A_j are correlated using the experimental data and T is the temperature of the system.

Also, θ_{ji} is the local composition parameter given by

$$\theta_{ji} = \frac{\theta_i \tau_{ji}}{\sum_{i=1}^{n} \theta_{ji} \tau_{ji}} \tag{2.58}$$

where τ_{ji} is the interaction parameter and θ_i is the average area fraction of component i in the liquid mixture calculated by

$$\tau_{ji} = \exp\left(-\frac{z}{2} \frac{U_{ji} - U_{ii}}{RT} \right) \tag{2.59}$$

$$\theta_i = \frac{x_i q_i}{\sum_{j=1}^{n} x_j q_j} \tag{2.60}$$

where z is the coordination number of the lattice and is determined from the following equation suggested by Skjold-Jorgensen (1980),

$$z = 35.2 - 0.1272T + 0.00014T^2 \tag{2.61}$$

U_{ji} and U_{ii} are the corresponding potential energies between two sites and they are temperature dependent.

$$U_{ii} = \sum_{j=0}^{n} B_j T_j \tag{2.62}$$

In the case of binary systems, this model can correlate the viscosity data even if the data are at different temperatures and can be predictive for multicomponent systems.

Later, Cao *et al*. (1993a) established a new viscosity model for the viscosity correlation and prediction of pure and multicomponent liquids. Also, it includes a model for activity coefficients of liquid mixtures where both the viscosity and the activity coefficients are expressed by the same parameters. This model is called the "viscosity-thermodynamics" model (UNIMOD). The parameters can be determined from viscosity and thermodynamic properties which are more readily available. This method is either predictive or correlative due to derivation from thermodynamic or viscosity data. Equation (2.63) defines the UNIMOD kinematic viscosity as follows:

$$\ell n(\nu M)=\sum_{i=1}^{n}\varphi_i \ell n\left(\nu_i M_i\right)+2\sum_{i=1}^{n}\varphi_i \ell n\left(\frac{x_i}{\varphi_i}\right)-\sum_{i=1}^{n}\frac{q_i n_i \varphi_i}{r_i}\sum_{j=1}^{n}\theta_{ji}\ell n\left(\tau_{ji}\right) \qquad (2.63)$$

where φ_i is the average segment fraction of component i given as

$$\varphi_i=\frac{x_i r_i}{\sum_{j=1}^{n}x_j r_j} \qquad (2.64)$$

where x_i is the mole fraction of the component type i given by

$$x_i=\frac{N_i}{\sum_{j=1}^{n}N_j} \qquad (2.65)$$

r_i is the number of segments in a molecule i which is calculated together with q_i by the UNIFAC group volume and surface area proposed by Hansen *et al*. (1991). Furthermore, M_i, is the molecular weight of component i which is acquired from the DIPPR data bank developed by Daubert and Danner (1989).

Cao *et al.* (1993b) combined the group-contribution approach with the UNIMOD model and suggested a new model called GC-UNIMOD. In this model the viscosity equation is divided into two parts; *viz.*, a combinatorial part and a residual part. The equation is given by,

$$\ell n(\nu)=\sum_{j=1}^{n}\left[\zeta_i^C+\zeta_i^R\right] \tag{2.66}$$

Where ζ_i^C and ζ_i^R are the combinatorial and the residual parts, respectively given by

$$\zeta_i^C=\phi_i \ell n\left(\nu_i \frac{M_i}{M}\right)+2\phi_i \ell n\left(\frac{x_i}{\phi_i}\right) \tag{2.67}$$

$$\zeta_i^R=-\frac{q_i n_i \phi_i}{r_i}\sum_{j=1}^{n}\phi_i \ell n\left(\tau_{ji}\right) \tag{2.68}$$

The residual part can also be given, using group contribution, as follows:

$$\zeta_i^R=\sum_{(all\ group\ k)}\nu_k^{(i)}\left[\Xi_{ki}-\Xi_{ki}^{(i)}\right] \tag{2.69}$$

Where $\nu_k^{(i)}$ is the number of groups k per molecule of component i, Ξ_{ki} is the group residual viscosity of group k for component i in the mixture and $\Xi_{ki}^{(i)}$ is the group residual viscosity of group k for component i in the solution of groups of pure liquid i.

Substituting equations (2.66) and (2.68) in equation (2.65) yields

$$\ell n(\nu) = \sum_{i=1}^{n}\left[\phi_i \ell n\left(\nu_i \frac{M_i}{M}\right) + 2\phi_i \ell n\left(\frac{x_i}{\phi_i}\right) + \sum_{all\ group\ k} \nu_k^{(i)}\left[\Xi_{ki} - \Xi_{ki}^{(i)}\right]\right] \tag{2.70}$$

where

$$\Xi_{mi} = -\frac{Q_k}{R_k} N_{ki}^{vis} \phi_i \sum_{all\ group\ k} \theta_{km} \ell n(\Psi_{km}) \tag{2.71}$$

where Q_k is the surface area parameter of group k, R_k is the volume parameter of group k, Ψ_{km} is the group interaction parameter between group k and m, and N_{ki}^{vis} is the viscosity parameter of group in component i which are calculated from equations (2.72) through (2.75)

$$Q_k = \frac{A_{wk}}{2.5\,x10^9} \tag{2.72}$$

$$R_k = \frac{V_{wk}}{15.17} \tag{2.73}$$

$$N_{ki}^{vis} = Q_k\left(\frac{q_i - r_i}{2} - \frac{1 - r_i}{z}\right) \tag{2.74}$$

$$\Psi_{km} = \exp\left(-\frac{a_{km}}{T}\right) \tag{2.75}$$

where a_{km} is the interaction energy parameter for group k and m.

Also,

$$q_i = \sum_{(all\ group\ k)} \nu_k^{(i)} Q_k \tag{2.76}$$

$$r_i = \sum_{(all\ group\ k)} \nu_k^{(i)} R_k \tag{2.77}$$

2.2.4 The generalized corresponding-states principle (GCSP) model

Teja and Rice (1981) introduced their generalized corresponding-states principle model (GCSP) using the properties of two pure components employed in the liquid mixture as the reference and the corresponding-state principle. The GCSP viscosity equation given as

$$\ell n(\eta\varepsilon) = \ell n(\eta\varepsilon)^{r1} + \frac{\omega - \omega_{r1}}{\omega_{r2} - \omega_{r1}}\left[\ell n(\eta\varepsilon)^{r2} - \ell n(\eta\varepsilon)^{r1}\right] \tag{2.78}$$

where

$$\varepsilon = M^{-1/2} T_c^{2/3} P_c^{1/6} \tag{2.79}$$

where $\eta\varepsilon$ is the reduced viscosity, ω is the acentric factor of the non-spherical fluid and $r_1$and r_2 represent the reference fluids. In addition, P_c and T_c are the critical pressure and temperature of the pure components, respectively.

In case of liquid mixtures, the van der Waals one-fluid model is used to replace pure component properties, ω, M ,T_c and P_c by pseudo-critical properties, ω_m ,M_m ,T_{cm} and P_{cm} of the mixture suggested by Wong *et al*. (1983) as follows

$$\left(T_{cm}^2 / P_{cm}\right) = \sum_i \sum_j x_i x_j \left(T_{cij}^2 / P_{cij}\right) \tag{2.80}$$

$$\left(T_{cm} / P_{cm}\right) = \sum_i \sum_j x_i x_j \left(T_{cij} / P_{cij}\right) \tag{2.81}$$

$$\omega_m\left(T_{cm}/P_{cm}\right)=\sum_i\sum_j x_i x_j\left(T_{cij}/P_{cij}\right)^{2/3}\omega_{ij} \tag{2.82}$$

where

$$T_{cij}=\xi_{ij}\left(T_{cii}T_{cjj}\right)^{1/2} \tag{2.83}$$

where ξ is the binary interaction parameter; and set one if the GCSP method is predictive.

$$\left(T_{cij}/P_{cij}\right)^{1/3}=\frac{1}{2}\left[\left(T_{cii}/P_{cii}\right)^{1/3}+\left(T_{cjj}/P_{cjj}\right)^{1/3}\right] \tag{2.84}$$

$$\omega_{ij}=\frac{1}{2}\left(\omega_{ii}+\omega_{jj}\right) \tag{2.85}$$

When the values of *pseudo*-critical properties are substituted in equations (2.78) and (2.79), one obtains the kinematic viscosities of the multicomponent liquid mixture.

2.3 The Empirical Models for Predicting the Viscosities of Liquid Mixtures

2.3.1 The Allan and Teja correlation

Allan and Teja (1991) presented a method for the prediction of the viscosity of hydrocarbons based on data for the normal alkanes. They suggested the use of an Antoine-type equation which correlates the viscosity and the temperature of liquids, as follows:

$$\ell n\mu=A\left[-1/B+1/\left(T+C\right)\right] \tag{2.86}$$

where μ and T are the absolute viscosity and the temperature of the system, respectively.

A, B, and C are constants calculated using the liquid viscosity data between ambient pressures and saturation pressures. The correlation of the number of carbon atoms of *n*-alkanes by fitting liquid viscosity data together gives the following equations:

$$A=145.73+ 99.01n+ 0.83n^2- 0.125n^3 \tag{2.87}$$

$$B= 30.48+34.01n-1.23n^2+0.017n^3 \tag{2.88}$$

$$C= -3.07- 1.99n \tag{2.89}$$

where n is the carbon number of the mixture which is calculated with the help of the following mixing rule:

$$N_m = \sum_{i=1}^{n} x_i N_i \tag{2.90}$$

In order to determine the viscosity of hydrocarbon mixture, the composition and the carbon number of pure components should be known. The mixture data are not required in this model which makes it predictive and easier to use.

The main deficiency of the Allan and Teja correlation according to Gregory (1992), is that the results for the carbon numbers greater than 22 contain errors.

2.3.2 The Grunberg and Nissan mixture law for viscosity

The methods to estimate or correlate the viscosity of liquid mixture assume that the viscosity of the pure components of the mixture is known. In 1887, Arrhenius proposed his method for predicting the viscosity of the binary mixture solutions as follows:

$$\log \eta = x_1 \log \eta_1 + x_2 \log \eta_2 \tag{2.91}$$

Where η is the viscosity of the binary solution and x_1 and x_2 are the mole fractions and η_1 and η_2 are viscosities of components 1 and 2, respectively.

Grunberg and Nissan (1949) believed there are positive and negative deviations occurring during working with Arrhenius equation. For that reason they proposed an applicable equation which is more accurate except in case of aqueous solutions. They suggested an Arrhenius-type and low temperature viscosity equation with the application of vapor pressures and viscosities of solutions for correlating the viscosity data of binary solutions given as

$$\log \eta_m = x_1 \log \eta_1 + x_2 \log \eta_2 + x_1 x_2 G_{12} \tag{2.92}$$

where G_{12} is an interaction parameter which is a function of the components 1 and 2 as well as the temperature. The value of G_{12} is calculated by plotting the viscosity of the system η_m versus the liquid mole fraction 1, (x_1). The value G reported by Grunberg and Nissan (1949) for the trans-decalin and cis-decalin is - 0.0224 and it gave promising results when used with the data collected by Bird and Daly (1939). Grunberg and Nissan (1949) showed that the interaction parameter can assume negative and positive values in the case of positive and negative deviations from Rault's. Margules (1895) proposed equation (2.93) to calculate G_{12} by using the constant value b, given by

$$G_{12}=C.b \tag{2.93}$$

where

$$\log \gamma_1 = bN_2^2 \qquad (2.94)$$

Whereas γ_1 is the activity coefficient of component 1 and C is the ratio of viscosity to the logarithm of vapor pressure which always takes a negative value.

Later, Irving (1977) presented an equation for multi-component mixtures based on Grunberg and Nissan (1949) equation as follows:

$$\ell n \eta_m = \sum_{i=1}^{n} x_i \ell n \eta_i + \sum_{i=1}^{n} \sum_{j=1}^{n} x_i x_j G_{ij} \qquad (2.95)$$

CHAPTER 3

EXPERIMENTAL PROCEDURES AND EQUIPMENT

3.1 General

This chapter presents the procedure of solution preparation, the determination of density and viscosity of the multicomponent liquid mixtures including binary, ternary, quaternary and quinary systems. Also, it contains the results of the verification of the purity of the chemicals used in composing the solutions and those used for the calibration of the density meter.

3.2 Materials

The chemicals used in this study are divided into two groups. The first group contains the chemicals that were used in calibrating the density meter and the viscometer. The second group contains the chemicals that were used in composing the systems of interest in the present study. The calibration fluids used in calibrating the viscometers were purchased from Cannon Instruments Company. The calibration fluids employed in calibrating the density meter were: ethylbenzene, nitrobenzene, 1-butanol, 1-nonanol and deacane. The chemicals employed in preparing the liquid mixtures include: cyclohexane, *p*-xylene, chlorobenzene, 1-propanol and 1-octanol.

The manufacturer's stated purity of the chemicals employed in composing the liquid systems were +99%. The stated purities were verified by means of gas chromatographic analysis. Table 3.1 lists the stated purity of chemicals as well as the purities as determined by gas chromatographic analysis.

Table 3.1: Gas Chromatography Analysis Results of the Pure Components

Compound	Manufacturer	Stated Purity mol %	GC Analysis mass %
p-Xylene	Sigma - Aldrich	99+	99.98
Chlorobenzene	Sigma - Aldrich	99.8	99.99
Nitrobenzene	Sigma - Aldrich	99+	99.85
Cyclohexane	Aldrich	99+	99.69
Ethylbenzene	Sigma - Aldrich	99.8+	99.98
1-Propanol	Sigma - Aldrich	99.5+	99.88
1-Butanol	Sigma - Aldrich	99.8+	99.89
1-Octanol	Sigma - Aldrich	99+	99.98
1-Nonanol	Sigma - Aldrich	98+	99.69

3.3 Preparation of Solutions

In order to prepare the samples, the volume of each component estimated by a computer program and injected into clean and dried 30 mL glass vials. First, each glass vial was sealed by Tuf-bond (Silicon-Teflon) discs where the Teflon side faces the solution in order to prevent the chemical reactions and the silicon side minimizes the evaporation of the volatile contents after puncturing the disc by a syringe. An aluminum cap is placed on the disc so that the disc is retained.

A Mettler HK 160 electronic balance with a precision of ± 1 x 10^{-7} kg was used for weighing the vials when they are empty and after injection of each component. After composing the solutions the vials were kept in the refrigerator until the time of measurements.

3.4 Density Measurements

The densities of the calibration chemicals, pure components, and samples were measured at 293.15 K and at 298.15 K by an Anton-Paar DMA 60/602 density meter unit that contains a U-tube shaped hollow oscillator. The density meter is placed in a temperature controlled wooden chamber that was designed by Asfour (1980). The wooden chamber and the density meter with the temperature control system are shown in Figure 3.1. The frequency variation in the DMA 602 oscillator is monitored by the DMA 60 processing unit and displayed on the digital screen as six digits values in seconds. The frequency alters due to changes in the sample mass and the temperature during the process. Equation (3.1), provided by the manufacturer, was used to calculate the density from the density meter readings:

$$\rho = \frac{AT^2}{1 - BT^2} - C \tag{3.1}$$

where ρ is the density and T is the period of oscillation, in seconds, shown by the density meter. A,B, and C are adjustable parameters that were determined by fitting the well-known density values of the calibration fluids with their corresponding density meter readings using least-squares.

The density meter is placed in a wooden chamber accessed through a plastic removable cover. The chamber heats up with the electrical bulbs placed inside the chamber to reach the desired temperature. An Omega precision thermometer equipped with a calibrated ITS-90 platinum probe, with the precision of ±0.005 K, monitored the temperature inside the density meter. The density meter's measuring cell was flushed with ethanol and dried by blowing dry air into the cell. After each injection, the sample was kept to between 15 to 20 minutes to reach thermal equilibrium before taking readings.

Figure 3.1: The Anton-Paar Density Meter Unit and The temperature Control Chamber

3.5 Viscosity Measurements

The kinematic viscosities of calibration chemicals, pure components and samples were determined by Cannon-Ubbelohde glass capillary viscometers with a stated precision of ± 0.1%. The different size viscometers were calibrated with the viscosity standards depending on the range of their viscosities.

The temperature was maintained using CT-1000 temperature controlled bath manufactured by Canon Instruments Company with the accuracy of ± 0.01K. The system was adjusted within ± 0.01 K of the target temperature. Similarly, the density meter's temperature was monitored by an Omega Precision thermometer equipped with a calibrated ITS-90 platinum temperature probe with an accuracy of better than ± 0.01 K.

The travel time of the liquid samples through the viscometer were recorded as efflux time in seconds and are given in equation (3.2) for kinematic viscosity calculation.

$$\nu = Et - \frac{F}{t^2} \tag{3.2}$$

In the above equation, E and F are the constants determined from calibration. Also, t is the efflux time in seconds.

Cleanliness of viscometers is essential for accurate measurements and reliable results. Therefore, the viscometers were filled with a special detergent and rinsed several times with deionized water. Then, the viscometers were rinsed with acetone a couple of times and dried up in a drying electrical oven at 120° C for approximately 10 minutes. Leaving the viscometers more than 10 minutes may change their calibration. After the viscometers are completely dry, they were left in a tray outside the oven to cool down to the room temperature.

The liquid of interest is poured into bulb “A” as shown in Figure 3.2, where the liquid surface stays between two etched marks. The viscometer is kept in at the temperature of interest by placing it in the CT-1000 constant temperature bath shown in Figure 3.3. The viscometers stand in a vertical position using plastic holders supplied by Cannon Instruments Company. The viscometer is left in the constant temperature bath for about 20 to 25 minutes to reach thermal equilibrium. The constant temperature bath is shown in Figure 3.3.

Tube 2 is covered with a finger and suction is applied to tube 3 by means of a pipette suction bulb. This results in bringing liquid into bulbs “C” and “D” without air bubbles into the solution. When the liquid surface reaches bulb “D”, the finger and suction are removed. The liquid starts to flow down the bulb and as it reaches the first etched mark an electronic stop watch is clicked. Once the liquid reaches the second etched mark the stop watch is clicked again. The time indicated on stop watch is known as the efflux time. The measurement is repeated three times and the average time is recorded. If the difference of the measured value from the average is less than 0.2% it is reported, otherwise it is repeated.

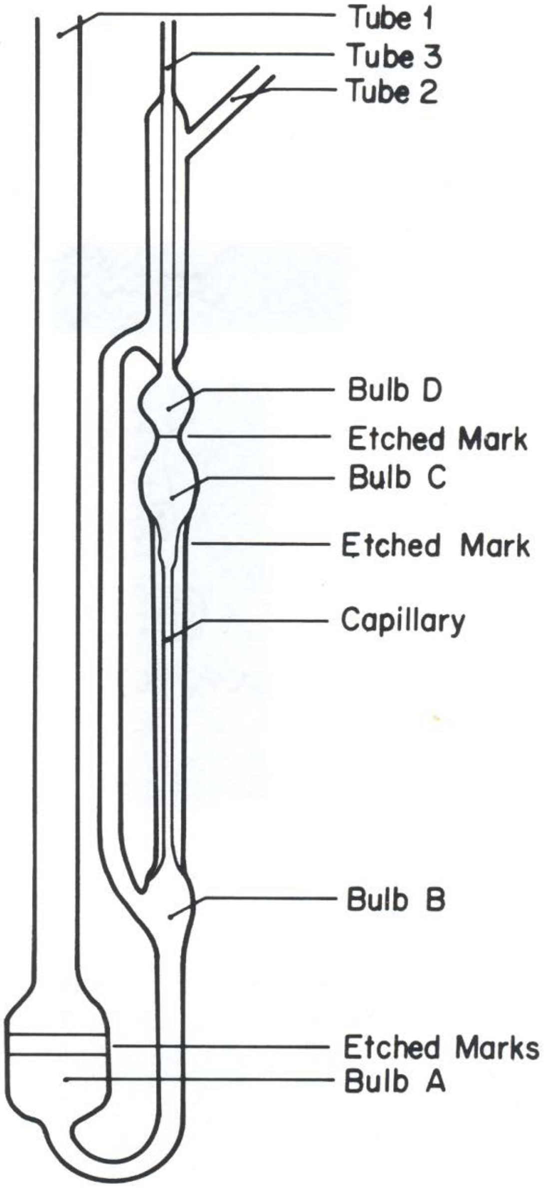


Figure 3.2: The Cannon – Ubbelohde Glass Capillary Viscometer

Figure 3.3: The CT–1000 Viscosity Bath and the Omega Precision Thermometer

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSION

4.1 General

The present chapter presents the experimental of the viscosities and densities of the pure components of the quinary regular solution: cyclohexane + *p*-xylene + chlorobenzene + 1-propanol + 1-octanol and all its binary, ternary and quaternary subsystems at 293.15 K and 298.15K.

Furthermore, the results of calibrating the density meter and the viscometers are given and discussed. In addition, in the last part of the present chapter, the results of testing the predictive capabilities of the selected viscosity models given in Chapter 2 are reported.

4.2 Calibration of the Density Meter

The density meter was calibrated by using pure compounds with accurately known densities at 293.15K and 298.15K. In order to obtain the constants in equation (3.1), the measured densities were substitute into this equation and the values of the constants A, B and C were calculated using the least-squares technique at each temperature.

The pure solutions which were employed for the calibration of density meter consist of ethylbenzene, nitrobenzene, 1-butanol, 1-nonanol, and decane.

The calibration data for the density meter and the calibration constants are reported in Tables 4.1 and 4.2.

4.3 Calibration of Viscometers

In the present study, four different sizes of Cannon-Ubbelohde viscometers were employed. Three viscometers of size 25 numbered as 25B349, 25B350 and 25B366 which cover a viscosity range of 0.5 through 2mm^2/s were calibrated using viscosity standards N0.8 and N1.0. For viscometers of sizes 50 numbered as 50B158, 50B159 and 50B831 within the viscosity range of 0.8 through 4 mm^2/s, the viscosity standards N0.8, N1.0, and N2.0 were employed. Viscosity standards N2.0, N4.0 and S3.0 were used to calibrate viscometers of size 75 and viscosity standards N2.0, N4.0, S3.0, and S6.0 were used for viscometers size 100. The range of the viscosities which viscometers of sizes 75 and 100 cover viscosity ranges 1.6 – 8 mm^2/s and 3 -15 mm^2/s, respectively. The viscometers size 75 are numbered 75K95 and K96 whereas the size 100 viscometers are numbered 100C334, 100C335, and 100C336.

The efflux time obtained in the calibration process and the corresponding kinematic viscosity values of the viscosity standards labeled on the bottle at each temperature were substituted in equation (3.2) and the constants E and F were determined using least-squares.

The calibration data for the viscometers and the values of the constants are summarized in Tables 4.3 and 4.4. The values of the standard deviation are also specified at each temperature.

Table 4.1: Calibration Data for the Density Meter at 293.15 K.

Component	Temperature = 293.15 K		References
	Density Meter Readings (s)	Density (kg/L)	
Ethylbenzene	0.733396	0.8670	TRC Tables (1986)
Nitrobenzene	0.792378	1.2032	TRC Tables (1988)
1-Butanol	0.722880	0.8097	TRC Tables (1991)
1-Nonanol	0.726260	0.8281	TRC Tables (1991)
Decane	0.707925	0.73012	Tranzado *et al.* (2002)

Calculated Values of the Density Meter Adjustable Parameters at 293.15 K

A=3.65583 B=0.0186351 C=1.119336 STD= 6.334 x 10^{-5} kg/L

Table 4.2: Calibration Data for the Density Meter at 298.15 K.

Component	Temperature=298.15		Reference
	Density Meter Readings (s)	Density (kg/L)	
Ethylbenzene	0.72351	0.8625	TRC Tables (1986)
Nitrobenzene	0.791280	1.19861	TRC Tables (1988)
1-Butanol	0.721934	0.8056	Rauf *et al.* (1983)
1-Nonanol	0.725384	0.8247	TRC Tables (1991)
Decane	0.706975	0.72635	Tranzado *et al.* (2002)

Calculated Values of the Density Meter Adjustable Parameters at 298.15 K

A=3.59836 B=0.0338662 C=1.10321 STD=1.64 x 10^{-4} kg/L

Table 4.3: Calibration Data for the Viscometers at 293.15 K

Viscometer	Viscosity Standard	Efflux Time (s)	Viscosity of Standard Fluid x 10^6 (m^2/s)	Parameters		Standard Deviation (m^2/s)
				E x 10^9 (m/s^2)	F x 10^6 ($m^2.s$)	
25B349	N0.8	427.08	0.7535	1.77	434.70	———
	N1.0	707.88	1.2520			
25B350	N0.8	430.40	0.7535	1.75	226.08	———
	N1.0	714.24	1.2520			
25B366	N0.8	398.25	0.7535	1.90	734.83	———
	N1.0	658.57	1.2520			
50B158	N0.8	174.67	0.7535	4.35	243.31	2.5 x 10^{-9}
	N1.0	289.24	1.2520			
	N2.0	656.30	2.8570			
50B159	N0.8	192.99	0.7535	3.94	246.81	3.1x 10^{-11}
	N1.0	318.51	1.2520			
	N2.0	725.50	2.8570			
50B831	N0.8	184.12	0.7535	4.09	1.27	2.3 x 10^{-10}
	N1.0	305.78	1.2520			
	N2.0	698.00	2.8570			
75K95	N2.0	309.22	2.8570	9.27	1219.29	10.8 x 10^{-9}
	N4.0	721.06	6.6890			
	S3.0	505.50	4.6640			
75K96	N2.0	319.98	2.8570	9.0	2573.55	2.2 x 10^{-9}
	N4.0	743.16	6.6890			
	S3.0	519.38	4.6640			
100C334	N2.0	172.04	2.8570	16.75	781.65	20.3 x 10^{-9}
	N4.0	401.62	6.6890			
	S3.0	278.30	4.6640			
	S6.0	646.10	10.840			
100C335	N2.0	176.07	2.8570	14.71	665.42	685.4x 10^{-9}
	N4.0	411.55	6.6890			
	S3.0	285.53	4.6640			
	S6.0	663.59	10.840			
100C336	N2.0	166.24	2.8570	17.28	614.23	21.4 x 10^{-9}
	N4.0	389.32	6.6890			
	S3.0	270.42	4.6640			
	S6.0	625.96	10.840			

Table 4.4: Calibration Data for the Viscometers at 298.15 K

Viscometer	Viscosity Standard	Efflux Time (s)	Viscosity of Standard Fluid x 10^6 (m^2/s)	Parameters		Standard Deviation x 10^9 (m^2/s)
				E x 10^9 (m/s^2)	F x 10^9 ($m^2.s$)	
25B349	N0.8	403.87	0.7118	1.77	820.03	———
	N1.0	659.13	1.1680			
25B350	N0.8	408.29	0.7118	1.76	1117.93	———
	N1.0	665.15	1.1680			
25B366	N0.8	379.94	0.7118	1.92	2494.48	———
	N1.0	612.14	1.1680			
50B158	N0.8	165.19	0.7118	3.99	-2037.07	41x 10^{-9}
	N1.0	269.51	1.1680			
	N2.0	651.72	2.5870			
50B159	N0.8	182.40	0.7118	3.97	503.53	6.3 x 10^{-9}
	N1.0	298.31	1.1680			
	N2.0	651.55	2.5870			
50B831	N0.8	174.12	0.7118	4.00	1.28	34.7 x 10^{-9}
	N1.0	285.75	1.1680			
	N2.0	632.82	2.5870			
75K95	N2.0	279.77	2.5870	9.21	-391.07	10.5 x 10^{-9}
	N4.0	629.38	5.8130			
	S3.0	445.46	4.091			
75K96	N2.0	289.28	2.5870	8.98	1029.42	4 x 10^{-9}
	N4.0	647.25	5.8130			
	S3.0	456.78	4.0910			
100C334	N2.0	155.78	2.5870	16.77	643.47	1.8 x 10^{-9}
	N4.0	347.00	5.8130			
	S3.0	244.78	4.0910			
	S6.0	539.97	9.0540			
100C335	N2.0	159.52	2.5870	16.28	150.95	11.9 x 10^{-9}
	N4.0	358.26	5.8130			
	S3.0	250.54	4.0910			
	S6.0	556.02	9.0540			
100C336	N2.0	150.41	2.5870	17.30	493.65	11.1 x 10^{-9}
	N4.0	336.87	5.8130			
	S3.0	237.88	4.0910			
	S6.0	522.88	9.0540			

4.4 Composing the Liquid Solutions

The quinary liquid regular solution and its binary, ternary and quaternary subsystems investigated in the present study are composed of pure chemicals: cyclohexane, *p*-xylene, chlorobenzene, 1-propanol, and 1-octanol.

The viscosities and densities of the pure components collected through experimental work were compared to their corresponding values reported in the literature. Table 4.5 shows both the experimental data collected in the present work and the literature data of the viscosities and densities.

It can be seen from the data listed in Tables 4.5 and 4.6 that the experimental viscosity and density values of pure compounds obtained in the present study are in good agreement with their corresponding literature values.

Tables 4.7 through 4.10 present the calculated densities and viscosities of the binary, ternary, quaternary and quinary systems at 293.15 K and 298.15 K over the entire composition range.

Table 4.5: Densities and Viscosities of the Pure Components and their Corresponding Literature Values at 293.15 K.

Compound	Temperature 293.15 K					
	Density (kg/L)		Kinematic Viscosity x 10^6 (m^2/s)		Absolute Viscosity (mPa.s)	
	Literature Value	Experimental Value	Literature Value	Experimental Value	Literature Value	Experimental value
Cyclohexane	0.7785[1]	0.7784	1.2540[5]	1.244	0.9800[11]	0.968
***p*-Xylene**	0.8609[2]	0.8608	0.7460[5]	0.750	0.6560[10]	0.646
Chlorobenzene	1.1064[3]	1.1064	0.7304[6]	0.726	0.8084[9]	0.830
1-Propanol	0.8037[4]	0.8040	2.1960[7]	2.764	2.2380[9]	2.222
1-Octanol	0.8261[4]	0.8255	11.1020[8]	10.918	9.200[1]	9.013

[1] TRC Tables (1991)

[2] TRC Tables (1996)

[3] TRC Tables (1990)

[4] TRC Tables (1966)

[5] TRC Tables (1955)

[6] Singh, R. P (1985)

[7] TRC Tables (1988)

[8] Tranzado *et al.* (2001)

[9] Yang *et al.* (2004)

[10] Al-Kandary (2006)

[11] Geist *et al.* (1946)

Table 4.6: Densities and Viscosities of the Pure Components and their Corresponding Literature Values at 298.15 K.

Compound	Temperature 293.15 K					
	Density (kg/L)		Kinematic Viscosity x 10^6 (m^2/s)		Absolute Viscosity (mPa.s)	
	Literature Value	Experimental Value	Literature Value	Experimental Value	Literature Value	Experimental value
Cyclohexane	0.7739[1]	0.7735	1.1570[5]	1.155	0.8958[14]	0.894
***p*-Xylene**	0.8566[2]	0.8564	0.7040[5]	0.713	0.61390[10]	0.611
Chlorobenzene	1.1011[3]	1.1011	0.6884[6]	0.685	0.7580[9]	0.755
1-Propanol	0.7997[4]	0.7999	1.9430[7]	2.467	1.943[12]	1.974
1-Octanol	0.8222[4]	0.8219	9.356[8]	9.236	7.363[13]	7.591

[12] TRC (1995)

[13] Rauf *et al.*(1983)

[14] Gomez-Diaz *et al.* (2001)

Table 4.7:Densities and Viscosities of the Binary System: Cyclohexane (1)+ *p* -Xylene (2) at 293.15 K.

X_1	X_2	Kinematic Viscosity x $10^6 (m^2/s)$	Density (kg/m^3)	Absolute Viscosity (mPa.s)
0.0000	1.0000	0.7471	0.8608	0.6431
0.1002	0.8998	0.7528	0.8523	0.6416
0.2320	0.7680	0.7633	0.8415	0.6423
0.3118	0.6882	0.7768	0.8342	0.6480
0.3853	0.6147	0.7882	0.8279	0.6525
0.4964	0.5036	0.8246	0.8183	0.6748
0.5880	0.4120	0.8582	0.8107	0.6957
0.7001	0.2999	0.9284	0.8013	0.7439
0.8493	0.1507	1.0637	0.7896	0.8399
0.8932	0.1068	1.1033	0.7862	0.8674
1.0000	1.0000	1.2537	0.7783	0.9757

Table 4.7 (Cont'd): Densities and Viscosities of the Binary System: Cyclohexane (1) + *p*-Xylene (2) at 298.15 K.

X_1	X_2	Kinematic Viscosity x $10^6 (m^2/s)$	Density (kg/m^3)	Absolute Viscosity (mPa.s)
0.0000	1.0000	0.7046	0.8563	0.6033
0.1002	0.8998	0.7107	0.8478	0.6025
0.2320	0.7680	0.7291	0.8371	0.6103
0.3118	0.6882	0.7386	0.8297	0.6128
0.3853	0.6147	0.7548	0.8233	0.6214
0.4964	0.5036	0.7758	0.8138	0.6313
0.5880	0.4120	0.8102	0.8061	0.6531
0.7001	0.2999	0.8597	0.7967	0.6849
0.8493	0.1507	0.9758	0.7849	0.7659
0.8932	0.1068	1.019	0.7815	0.7963
1.0000	1.0000	1.1638	0.7735	0.9002

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: Cyclohexane (1) + Chlorobenzene (2) at 293.15 K.

X_1	X_2	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/m^3)	Absolute Viscosity (mPa.s)
0.0000	1.0000	0.7258	1.1064	0.8030
0.0949	0.9051	0.7289	1.0726	0.7818
0.2088	0.7912	0.7531	1.0326	0.7776
0.3096	0.6904	0.7683	0.9980	0.7668
0.4169	0.5831	0.7959	0.9637	0.7670
0.5047	0.4953	0.8348	0.9328	0.7787
0.6137	0.3863	0.8899	0.9022	0.8029
0.6722	0.3278	0.9172	0.8782	0.8055
0.7966	0.2034	1.0166	0.8438	0.8578
0.8606	0.1394	1.0900	0.8186	0.8923
1.0000	0.0000	1.2537	0.7784	0.9759

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: Cyclohexane (1) +Chlorobenzene (2) at 298.15 K.

X_1	X_2	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	0.6821	1.1011	0.7511
0.0949	0.9051	0.6834	1.0675	0.7295
0.2088	0.7912	0.7017	1.0277	0.7211
0.3096	0.6904	0.7187	0.9929	0.7136
0.4169	0.5831	0.7528	0.9584	0.7215
0.5047	0.4953	0.7869	0.9279	0.7302
0.6137	0.3863	0.8333	0.8915	0.7429
0.6722	0.3278	0.8592	0.8736	0.7506
0.7966	0.2034	0.9485	0.8374	0.7943
0.8606	0.1394	0.9900	0.8136	0.8055
1.0000	0.0000	1.1638	0.7735	0.9002

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: Cyclohexane (1) + 1-Propanol (2) at 293.15 K.

X_1	X_2	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	2.7603	0.8040	2.2193
0.1115	0.8885	2.4091	0.7986	1.9239
0.2058	0.7942	2.1526	0.7947	1.7107
0.2922	0.7078	1.9545	0.7916	1.5472
0.3907	0.6093	1.7690	0.7886	1.3950
0.4946	0.5054	1.5856	0.7855	1.2455
0.5870	0.413	1.4543	0.7835	1.1394
0.7048	0.2952	1.3414	0.7813	1.0480
0.7992	0.2008	1.2786	0.7798	0.9970
0.8926	0.1074	1.2547	0.7788	0.9772
1.0000	0.0000	1.2537	0.7784	0.9759

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: Cyclohexane (1) + 1-Propanol (2) at 298.15 K.

X_1	X_2	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	2.3717	0.7999	1.8971
0.1115	0.8885	2.0939	0.7943	1.6632
0.2058	0.7942	1.8817	0.7904	1.4873
0.2922	0.7078	1.7158	0.7874	1.3452
0.3907	0.6093	1.5631	0.7840	1.2255
0.4946	0.5054	1.4245	0.7812	1.1128
0.5870	0.4130	1.3355	0.7788	1.0401
0.7048	0.2952	1.2645	0.7765	0.9819
0.7992	0.2008	1.2031	0.7750	0.9324
0.8926	0.1074	1.1833	0.7739	0.9158
1.0000	0.0000	1.1638	0.7735	0.9002

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: Cyclohexane (1) + 1-Octanol (2) at 293.15 K.

X_1	X_2	Kinematic Viscosity x $10^6 (m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	10.9179	0.8255	9.0127
0.10481	0.89519	8.8964	0.8208	7.3022
0.19147	0.80853	7.4432	0.8168	6.0796
0.27024	0.72976	6.4110	0.8135	5.2153
0.37951	0.62049	5.1952	0.8087	4.2014
0.50451	0.49549	3.8828	0.8034	3.1194
0.61242	0.38758	3.0195	0.7976	2.4083
0.67355	0.32645	2.6050	0.7946	2.0699
0.79622	0.20378	1.9220	0.7887	1.5159
0.88223	0.11777	1.5779	0.7843	1.2375
1.0000	0.0000	1.2537	0.7784	0.9759

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: Cyclohexane (1) + 1-Octanol (2) at 298.15 K.

X_1	X_2	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	9.2169	0.8219	7.5753
0.10481	0.89519	7.8521	0.8172	6.4167
0.19147	0.80853	6.6339	0.8131	5.3940
0.27024	0.72976	5.8455	0.8098	4.7337
0.37951	0.62049	4.6713	0.8048	3.7595
0.50451	0.49549	3.5099	0.7994	2.8058
0.61242	0.38758	2.6890	0.7934	2.1334
0.67355	0.32645	2.3567	0.7904	1.8627
0.79622	0.20378	1.7060	0.7843	1.3380
0.88223	0.11777	1.3421	0.7797	1.0464
1.0000	0.0000	1.1638	0.7735	0.9002

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: *p*-Xylene (1) + Chlorobenzene (2) at 293.15 K.

X_1	X_2	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	0.7269	1.1064	0.8042
0.09092	0.90908	0.7277	1.0796	0.7857
0.21962	0.78038	0.7304	1.0462	0.7641
0.30605	0.69395	0.7332	1.0222	0.7494
0.40782	0.59218	0.7361	0.9936	0.7314
0.49709	0.50291	0.7387	0.9735	0.7191
0.60816	0.39184	0.7415	0.9474	0.7025
0.71168	0.28832	0.7431	0.9248	0.6872
0.8026	0.1974	0.7445	0.9037	0.6728
0.90473	0.09527	0.7462	0.8835	0.6593
1.0000	0.0000	0.7471	0.8608	0.6431

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: *p*-Xylene (1) + Chlorobenzene (2) at 298.15 K.

X_1	X_2	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	0.6821	1.1012	0.7511
0.0909	0.9091	0.6841	1.0744	0.7350
0.2196	0.7804	0.6873	1.0411	0.7155
0.3061	0.6939	0.6895	1.0172	0.7013
0.4078	0.5922	0.6926	0.9886	0.6847
0.4971	0.5029	0.6949	0.9686	0.6731
0.6082	0.3918	0.6982	0.9426	0.6581
0.7117	0.2883	0.7008	0.9201	0.6448
0.8026	0.1974	0.7025	0.8990	0.6316
0.9047	0.0953	0.7043	0.8790	0.6191
1.0000	0.0000	0.7046	0.8563	0.6034

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: *p*-Xylene (1) + 1-Propanol (2) at 293.15 K.

X_1	X_2	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	2.7603	0.8040	2.2192
0.11353	0.88647	2.1017	0.8140	1.7109
0.20337	0.79663	1.7595	0.8215	1.4454
0.30569	0.69431	1.4465	0.8285	1.1984
0.41496	0.58504	1.1957	0.8350	0.9984
0.50786	0.49214	1.0586	0.8399	0.8891
0.60842	0.39158	0.9415	0.8446	0.7952
0.68858	0.31142	0.8655	0.8483	0.7342
0.79879	0.20121	0.8040	0.8529	0.6857
0.89615	0.10385	0.7615	0.8566	0.6523
1.0000	0.0000	0.7471	0.8608	0.6431

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: *p*-Xylene (1) + 1-Propanol (2) at 298.15 K.

X_1	X_2	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	2.3717	0.7999	1.8971
0.11353	0.88647	1.8399	0.8098	1.4899
0.20337	0.79663	1.4893	0.8171	1.2170
0.30569	0.69431	1.2377	0.8241	1.0199
0.41496	0.58504	1.0709	0.8305	0.8894
0.50786	0.49214	0.9378	0.8353	0.7834
0.60842	0.39158	0.8732	0.8400	0.7335
0.68858	0.31142	0.8019	0.8437	0.6766
0.79879	0.20121	0.7633	0.8483	0.6476
0.89615	0.10385	0.7142	0.8521	0.6085
1.0000	0.0000	0.7046	0.8564	0.6034

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: *p*-Xylene (1) + 1-Octanol (2) at 293.15 K.

X_1	X_2	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	10.9179	0.8255	9.0126
0.10443	0.8956	9.7514	0.8264	8.0585
0.1971	0.8029	8.4337	0.8286	6.9885
0.2815	0.71846	7.3012	0.8317	6.0721
0.4064	0.5936	5.2515	0.8364	4.3924
0.49180	0.5082	4.1516	0.8402	3.4884
0.5920	0.4080	3.0621	0.8440	2.5845
0.6916	0.3084	2.3307	0.8477	1.9757
0.7931	0.2069	1.6788	0.8514	1.4293
0.8712	0.1287	1.3049	0.8549	1.1155
1.0000	0.0000	0.7471	0.8608	0.6431

Table 4.7 (Cont’d): Densities and Viscosities of the binary system: *p*-Xylene (1) + 1-Octanol (2) at 298.15 K.

X_1	X_2	Kinematic Viscosity x $10^6 (m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	9.2169	0.8058	7.4270
0.1044	0.8956	8.3018	0.8077	6.7056
0.1971	0.8029	7.2172	0.8099	5.8453
0.2815	0.7185	6.3365	0.8126	5.1493
0.4064	0.5936	4.9141	0.8169	4.0146
0.4918	0.5082	3.9081	0.8201	3.2050
0.5920	0.4080	3.0763	0.8238	2.5342
0.6916	0.3084	2.1065	0.8274	1.7428
0.7931	0.2069	1.4106	0.8310	1.1722
0.8712	0.1288	1.1010	0.8344	0.9187
1.0000	0.0000	0.7246	0.8402	0.6088

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: Chlorobenzene (1) + 1-Propanol (2) at 293.15 K.

X_1	X_2	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	2.7603	0.8040	2.2192
0.1028	0.8972	2.3890	0.8431	2.0142
0.1574	0.8426	2.1910	0.8663	1.8981
0.3057	0.6943	1.8000	0.9184	1.6530
0.4011	0.5989	1.5487	0.9499	1.4711
0.4906	0.5094	1.4013	0.9773	1.3694
0.6072	0.3929	1.1709	1.0092	1.1817
0.7094	0.2906	1.0331	1.0371	1.0715
0.8163	0.1836	0.9492	1.0665	1.0123
0.8922	0.1078	0.8371	1.0819	0.9057
1.0000	0.0000	0.7269	1.1064	0.8042

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: Chlorobenzene (1) + 1-Propanol (2) at 298.15 K.

X_1	X_2	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	2.3717	0.7999	1.8970
0.1028	0.8972	2.1438	0.8371	1.7946
0.1574	0.8426	2.0280	0.8618	1.7476
0.3057	0.6943	1.6436	0.9135	1.5014
0.4011	0.5989	1.4531	0.9449	1.3730
0.4906	0.5094	1.2566	0.9721	1.2216
0.6072	0.3928	1.0825	1.0040	1.0868
0.7094	0.2906	1.0130	1.0318	1.0452
0.8164	0.1836	0.9366	1.0641	0.9967
0.8922	0.1078	0.8300	1.0766	0.8936
1.0000	0.0000	0.6821	1.1012	0.7511

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: Chlorobenzene (1) + 1-Octanol (2) at 293.15 K.

X_1	X_2	Kinematic Viscosity x $10^6 (m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	10.9179	0.8255	9.0128
0.1063	0.8937	9.6744	0.8394	8.1212
0.2008	0.7992	8.4662	0.8592	7.2743
0.2934	0.7066	7.3387	0.8787	6.4486
0.3913	0.6087	5.8996	0.9006	5.3133
0.5031	0.4969	4.3330	0.9302	4.0305
0.5960	0.4040	3.3849	0.9641	3.2634
0.6818	0.3182	2.3638	0.9887	2.3370
0.7835	0.2165	1.6569	1.0213	1.6922
0.9003	0.0997	1.1363	1.0662	1.2115
1.0000	0.0000	0.7269	1.1064	0.8042

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: Chlorobenzene (1) + 1-Octanol (2) at 298.15 K.

X_1	X_2	Kinematic Viscosity x $10^6 (m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	9.2169	0.8219	7.5756
0.1063	0.8937	8.3921	0.8353	7.0097
0.2008	0.7992	7.2868	0.8549	6.2297
0.2934	0.7066	6.3670	0.8747	5.5689
0.3913	0.6087	5.1769	0.8965	4.6411
0.5031	0.4969	4.0300	0.9258	3.7311
0.5960	0.4040	3.1325	0.9545	2.9901
0.6818	0.3182	2.3778	0.9839	2.3396
0.7835	0.2165	1.6866	1.0164	1.7143
0.9003	0.0997	1.0384	1.0592	1.0999
1.0000	0.0000	0.6821	1.1011	0.7511

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: 1-Propanol (1) + 1-Octanol (2) at 293.15 K.

X_1	X_2	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	10.9179	0.8255	9.0127
0.1051	0.8949	10.0170	0.8241	8.2549
0.2048	0.7952	8.9510	0.8228	7.3649
0.3059	0.6941	8.0826	0.8215	6.6398
0.3992	0.6008	7.1185	0.8198	5.8359
0.4865	0.5135	6.5311	0.8183	5.3443
0.6002	0.3998	5.5390	0.8160	4.5198
0.6861	0.3139	4.9031	0.8140	3.9911
0.7835	0.2165	4.1980	0.8108	3.4039
0.8999	0.1000	3.3441	0.8078	2.7013
1.0000	0.0000	2.7603	0.8040	2.2192

Table 4.7 (Cont'd): Densities and Viscosities of the binary system: 1-Propanol (1) + 1-Octanol (2) at 298.15 K.

X_1	X_2	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	1.0000	9.2169	0.8219	7.5863
0.1051	0.8949	8.6063	0.8205	7.0613
0.2048	0.7952	7.7707	0.8192	6.3655
0.3059	0.6941	6.8979	0.8178	5.6413
0.3992	0.6008	6.1992	0.8161	5.0592
0.4865	0.5135	5.5986	0.8146	4.5604
0.6002	0.3998	4.7997	0.8122	3.8984
0.6861	0.3139	4.2629	0.8101	3.4536
0.7835	0.2165	3.6807	0.8069	2.9700
0.8999	0.1000	2.8976	0.8038	2.3290
1.0000	0.0000	2.3717	0.7999	1.8971

Table 4.8 : Densities and Viscosities of the ternary system: Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) at 293.15 K.

X_1	X_2	X_3	Kinematic Viscosity x $10^6 (m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	0.000	1.0000	0.7258	1.1064	0.8030
0.0000	1.000	0.0000	0.7471	0.8608	0.6431
1.0000	0.0000	0.0000	1.2537	0.7783	0.9757
0.0709	0.1054	0.8237	0.7400	1.0513	0.7780
0.1755	0.5908	0.2337	0.7628	0.8957	0.6833
0.2668	0.2943	0.4389	0.7714	0.9367	0.7226
0.3423	0.1679	0.4897	0.7835	0.9447	0.7402
0.4774	0.3513	0.1713	0.8206	0.8573	0.7035
0.5271	0.2291	0.2437	0.8396	0.8696	0.7301
0.6601	0.0884	0.2515	0.9062	0.8610	0.7803

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) at 298.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	0.000	1.0000	0.6821	1.1011	0.7511
0.0000	1.000	0.0000	0.7046	0.8563	0.6033
1.0000	0.0000	0.0000	1.1638	0.7735	0.9002
0.0709	0.1054	0.8237	0.6978	1.0461	0.7300
0.1755	0.5908	0.2337	0.7233	0.8910	0.6445
0.2668	0.2943	0.4389	0.7214	0.9317	0.6722
0.3423	0.1679	0.4898	0.7391	0.9397	0.6945
0.4774	0.3513	0.1713	0.7765	0.8525	0.6620
0.5271	0.2291	0.2437	0.7858	0.8647	0.6795
0.6601	0.0884	0.2515	0.8536	0.8560	0.7308

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) at 293.15 K.

X_1	X_2	X_3	Kinematic Viscosity x $10^6 (m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	0.000	1.0000	2.7603	0.8040	2.2193
0.0000	1.000	0.0000	0.7471	0.8608	0.6431
1.0000	0.0000	0.0000	1.2537	0.7783	0.9757
0.1271	0.1508	0.7220	1.6695	0.7230	1.3533
0.2218	0.6292	0.1490	0.8035	0.7274	0.6705
0.3322	0.3328	0.3351	0.9919	0.7236	0.8071
0.3904	0.2092	0.4005	1.1730	0.7217	0.9427
0.4984	0.3917	0.1099	0.8639	0.7232	0.7011
0.5837	0.2592	0.1571	0.9440	0.7212	0.7562
0.6588	0.1270	0.2142	1.0844	0.7193	0.8574

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) at 298.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
0.0000	0.000	1.0000	2.3717	0.7999	1.8971
0.0000	1.000	0.0000	0.7046	0.8564	0.6034
1.0000	0.0000	0.0000	1.1638	0.7735	0.9002
0.1271	0.1508	0.7220	1.4735	0.8062	1.1879
0.2218	0.6292	0.1490	0.7531	0.8299	0.6250
0.3322	0.3328	0.3351	0.9214	0.8090	0.7455
0.3904	0.2092	0.4005	1.0258	0.7990	0.8196
0.4984	0.3917	0.1098	0.8099	0.8068	0.6534
0.5837	0.2592	0.1571	0.8804	0.7963	0.7010
0.6588	0.1270	0.2142	1.0049	0.7859	0.7897

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3) at 293.15 K.

X_1	X_2	X_3	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	1.2537	0.7784	0.9759
0.0000	1.0000	0.0000	0.7471	0.8608	0.6431
0.0000	0.0000	1.0000	10.9179	0.8255	9.0127
0.0807	0.1797	0.7396	5.2975	0.8271	4.3815
0.1450	0.7033	0.1517	1.0250	0.8417	0.8627
0.2513	0.3516	0.3970	2.0975	0.8246	1.7296
0.3157	0.2435	0.4409	2.5336	0.8184	2.0736
0.3787	0.4818	0.1395	1.0858	0.8229	0.8935
0.4904	0.327	0.1826	1.3003	0.8123	1.0563
0.6105	0.1584	0.2311	1.680	0.8016	1.3471

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3) at 298.15 K.

X_1	X_2	X_3	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	1.1638	0.7735	0.9002
0.0000	1.0000	0.0000	0.7046	0.8564	0.6598
0.0000	0.0000	1.0000	9.2169	0.8219	7.5754
0.0807	0.1797	0.7396	4.5757	0.8236	3.7684
0.1450	0.7033	0.1517	0.9220	0.8375	0.7722
0.2513	0.3516	0.3970	1.9178	0.8208	1.5741
0.3157	0.2435	0.4409	2.2791	0.8146	1.8566
0.3787	0.4818	0.1395	1.0122	0.8187	0.8288
0.4904	0.327	0.1826	1.1748	0.8082	0.9495
0.6105	0.1584	0.2311	1.5076	0.7975	1.2024

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) at 293.15 K.

X_1	X_2	X_3	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	1.2537	0.7784	0.9759
0.0000	1.0000	0.0000	0.7269	1.1064	0.8042
0.0000	0.0000	1.0000	2.7603	0.8040	2.2193
0.0912	0.2046	0.7042	1.6508	0.8767	1.4473
0.1520	0.7221	0.1259	0.7773	1.0213	0.7939
0.2315	0.4377	0.3308	0.9670	0.9366	0.9057
0.2900	0.2968	0.4132	1.1220	0.8915	1.000
0.3500	0.5331	0.1169	0.8222	0.9543	0.7846
0.4659	0.3817	0.1524	0.8956	0.9040	0.8097
0.5535	0.2045	0.2419	1.0507	0.8490	0.8920

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) at 298.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	1.1638	0.7735	0.9002
0.0000	1.0000	0.0000	0.6821	1.1011	0.7511
0.0000	0.0000	1.0000	2.3717	0.7999	1.8974
0.0912	0.2046	0.7042	1.3814	0.8723	1.2050
0.1520	0.7221	0.1259	0.7288	1.0163	0.7406
0.2315	0.4377	0.3308	0.8956	0.9317	0.8344
0.2900	0.2968	0.4132	1.0388	0.8868	0.9212
0.3500	0.5331	0.1169	0.7702	0.9494	0.7312
0.4659	0.3817	0.1524	0.8364	0.8992	0.7521
0.5535	0.2045	0.2419	0.9745	0.8442	0.8227

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3) at 293.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	1.2537	0.7784	0.9759
0.0000	1.0000	0.0000	0.7269	1.1064	0.8042
0.0000	0.0000	1.0000	10.9179	0.8255	9.0127
0.1398	0.1346	0.7256	6.3810	0.8304	5.2989
0.2019	0.6303	0.1678	1.1484	0.9693	1.1132
0.3384	0.3081	0.3535	2.0871	0.8795	1.8356
0.4073	0.2045	0.3882	2.4854	0.852	2.1176
0.4842	0.3963	0.1296	1.1315	0.8993	1.0177
0.5914	0.2364	0.1722	1.4305	0.8542	1.2219
0.6526	0.1235	0.2239	1.7707	0.8237	1.4585

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3) at 298.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	1.1638	0.7735	0.9002
0.0000	1.0000	0.0000	0.6821	1.1011	0.7511
0.0000	0.0000	1.0000	9.2169	0.8219	7.5754
0.1398	0.1346	0.7258	5.4662	0.8270	4.5209
0.2019	0.6303	0.1678	1.0122	0.9647	0.9766
0.3384	0.3081	0.3535	1.898	0.8754	1.6619
0.4073	0.2046	0.3882	2.2398	0.8479	1.8993
0.4842	0.3963	0.1196	1.0009	0.8947	0.8956
0.5914	0.2364	0.1722	1.3206	0.8498	1.1222
0.6526	0.1235	0.2239	1.5776	0.8194	1.2928

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3) at 293.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	1.2537	0.7784	0.9759
0.0000	1.0000	0.0000	2.7603	0.8040	2.2193
0.0000	0.0000	1.0000	10.9179	0.8255	9.0127
0.1207	0.1786	0.7007	6.550	0.8158	5.3432
0.2058	0.6406	0.1536	3.0195	0.7987	2.4117
0.3280	0.3402	0.3318	3.7542	0.8021	3.0112
0.3772	0.2298	0.3930	3.8769	0.8030	3.1131
0.4839	0.3972	0.1189	2.0597	0.7889	1.6250
0.5706	0.2685	0.1708	2.0296	0.7921	1.6076
0.6517	0.1551	0.1932	2.055	0.7904	1.6247

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3) at 298.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	1.1638	0.7735	0.9002
0.0000	1.0000	0.0000	2.3717	0.7999	1.8971
0.0000	0.0000	1.0000	9.2264	0.8219	7.5832
0.1207	0.1786	0.7007	6.1840	0.8123	5.0233
0.2058	0.6406	0.1536	2.6765	0.7948	2.1273
0.328	0.3402	0.3318	3.2894	0.7983	2.6259
0.3772	0.2298	0.3930	3.3799	0.7992	2.7012
0.4839	0.3972	0.1189	1.8070	0.7847	1.4177
0.5707	0.2685	0.1708	1.8371	0.7880	1.4476
0.6517	0.1551	0.1932	1.8749	0.7867	1.4742

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: *p*-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) at 293.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.7471	0.8608	0.6431
0.0000	1.0000	0.0000	0.7269	1.1064	0.8042
0.0000	0.0000	1.0000	2.7603	0.8039	2.2190
0.1206	0.1507	0.7287	1.5833	0.8699	1.3773
0.2170	0.61172	0.1712	0.7858	1.0028	0.7880
0.3344	0.3060	0.3595	0.9227	0.9224	0.8512
0.4041	0.1949	0.4010	0.9641	0.8927	0.8606
0.488	0.3967	0.1153	0.7683	0.9453	0.7263
0.5817	0.2408	0.1775	0.7922	0.9084	0.7197
0.6684	0.0946	0.2370	0.7817	0.8740	0.6833

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: *p*-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) at 298.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.7046	0.8563	0.6033
0.0000	1.0000	0.0000	0.6890	1.1011	0.7586
0.0000	0.0000	1.0000	2.3717	0.7999	1.8971
0.1206	0.1507	0.7287	1.3327	0.8655	1.1535
0.2170	0.61172	0.1712	0.7350	0.9980	0.7336
0.3344	0.3060	0.3595	0.8539	0.9179	0.7838
0.4041	0.1949	0.4010	0.8929	0.8883	0.7932
0.4880	0.3967	0.1153	0.7197	0.9407	0.6770
0.5817	0.2408	0.1775	0.7375	0.9040	0.6667
0.6684	0.0946	0.2370	0.7637	0.8697	0.6642

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: *p*-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3) at 293.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.7471	0.8608	0.6431
0.0000	1.0000	0.0000	0.7269	1.1064	0.8042
0.0000	0.0000	1.0000	10.9179	0.8255	9.0127
0.1363	0.1504	0.7134	5.6284	0.8539	4.8060
0.1946	0.6336	0.1718	1.1101	0.9854	1.0939
0.3259	0.3324	0.3417	1.9898	0.9062	1.8032
0.3898	0.1964	0.4138	2.5754	0.8822	2.2721
0.4857	0.3856	0.1287	1.0894	0.9296	1.0128
0.5699	0.2668	0.1633	1.1525	0.9070	1.0454
0.6684	0.1071	0.2245	1.3046	0.8715	1.1370

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: *p*-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3) at 298.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.7046	0.8563	0.6033
0.0000	1.0000	0.0000	0.6890	1.1011	0.7587
0.0000	0.0000	1.0000	9.2264	0.8219	7.5832
0.1363	0.1504	0.7134	4.7923	0.8503	4.0749
0.1946	0.6336	0.1718	1.0421	0.9809	1.0223
0.3259	0.3324	0.3417	1.7732	0.9022	1.5998
0.3898	0.1964	0.4138	2.3405	0.8782	2.0555
0.4857	0.3856	0.1287	0.9417	0.9253	0.8714
0.5699	0.2668	0.1633	1.0828	0.9028	0.9775
0.6684	0.1071	0.2245	1.1896	0.8674	1.0319

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: *p*-Xylene (1) + 1-Propanol (2) + 1-Octanol (3) at 293.15 K.

X_1	X_2	X_3	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.7471	0.8608	0.6431
0.0000	1.0000	0.0000	2.7603	0.8039	2.2190
0.0000	0.0000	1.0000	10.9179	0.8255	9.0127
0.0867	0.1798	0.7334	7.4473	0.8254	6.1468
0.1975	0.6546	0.1479	2.4808	0.8234	2.0427
0.3011	0.3620	0.3369	3.358	0.8314	2.7919
0.3701	0.2349	0.3949	3.4813	0.8350	2.9068
0.4567	0.4249	0.1184	1.6588	0.8374	1.3891
0.5535	0.2717	0.1748	1.7274	0.8419	1.4543
0.6226	0.1627	0.2147	1.7751	0.8448	1.4996

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: *p*-Xylene (1) + 1-Propanol (2) + 1-Octanol (3) at 298.15 K.

X_1	X_2	X_3	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.7046	0.8563	0.6033
0.0000	1.0000	0.0000	2.3717	0.7999	1.8971
0.0000	0.0000	1.0000	9.2264	0.8219	7.5832
0.0867	0.1798	0.7334	6.3817	0.8220	5.2456
0.1975	0.6546	0.1479	2.0864	0.8195	1.7099
0.3011	0.3620	0.3369	2.9538	0.8276	2.4446
0.3701	0.2349	0.3949	3.0985	0.8312	2.5755
0.4567	0.4249	0.1184	1.4601	0.8333	1.2168
0.5535	0.2717	0.1748	1.4964	0.8379	1.2538
0.6226	0.1627	0.2147	1.6617	0.8408	1.3972

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3) at 293.15 K.

X_1	X_2	X_3	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.72690	1.1064	0.8042
0.0000	1.0000	0.0000	2.7603	0.8039	2.2190
0.0000	0.0000	1.0000	10.9179	0.8255	9.0127
0.1178	0.1662	0.716	7.5585	0.8282	6.2602
0.1954	0.6522	0.1523	2.7562	0.8688	2.3945
0.3062	0.3580	0.3358	3.2976	0.8907	2.9371
0.4071	0.2277	0.3652	3.1075	0.9078	2.8108
0.4725	0.4157	0.1118	1.5389	0.9486	1.4598
0.5606	0.2743	0.1651	1.7025	0.9660	1.6446
0.6408	0.1437	0.2155	1.9059	0.9753	1.8590

Table 4.8 (Cont'd): Densities and Viscosities of the ternary system: Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3) at 298.15 K.

X_1	X_2	X_3	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.6890	1.1011	0.7586
0.0000	1.0000	0.0000	2.3717	0.7999	1.8971
0.0000	0.0000	1.0000	9.2264	0.8219	7.5832
0.1178	0.1662	0.716	6.4594	0.8249	5.3287
0.1954	0.6522	0.1523	2.4752	0.8648	2.1404
0.3062	0.3580	0.3358	2.9380	0.8867	2.6051
0.4071	0.2277	0.3652	2.8078	0.9037	2.5376
0.4725	0.4157	0.1118	1.4092	0.9441	1.3304
0.5606	0.2743	0.1651	1.4234	0.9616	1.3687
0.6408	0.1437	0.2155	1.8056	0.9710	1.7532

Table 4.9: Densities and Viscosities of the quaternary system: Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4) at 293.15 K.

X_1	X_2	X_3	X_4	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	1.2536	0.7784	0.9758
0.0000	1.0000	0.0000	0.0000	0.7471	0.8608	0.6431
0.0000	0.0000	1.0000	0.0000	0.7269	1.1064	0.8042
0.0000	0.0000	0.0000	1.0000	2.7603	0.7218	1.9924
0.1302	0.08631	0.1037	0.6798	1.5702	0.8430	1.3237
0.2581	0.2077	0.2407	0.2936	0.9327	0.8827	0.8233
0.2887	0.1772	0.0571	0.4770	1.2108	0.8240	0.9977
0.1678	0.2601	0.3975	0.1746	0.8125	0.9308	0.7562
0.2592	0.2703	0.0924	0.3855	1.0286	0.8418	0.8659
0.4892	0.1409	0.2662	0.1037	0.8689	0.8744	0.7598

Table 4.9 (Cont'd): Densities and Viscosities of the quaternary system: Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4) at 298.15 K.

X_1	X_2	X_3	X_4	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	1.1638	0.7735	0.9002
0.0000	1.0000	0.0000	0.0000	0.7046	0.8564	0.6034
0.0000	0.0000	1.0000	0.0000	0.6821	1.1011	0.7511
0.0000	0.0000	0.0000	1.0000	2.3717	0.7999	1.8971
0.0650	0.0525	0.0508	0.8317	1.3398	0.8384	1.1234
0.1885	0.1770	0.1650	0.4694	0.8676	0.8778	0.7615
0.1872	0.1248	0.0396	0.6484	1.1129	0.8194	0.9119
0.1358	0.2609	0.3590	0.2443	0.7569	0.9257	0.7007
0.1797	0.1295	0.0747	0.6160	0.9305	0.8371	0.7789
0.4435	0.1354	0.2543	0.1668	0.8121	0.8694	0.7061

Table 4.9 (Cont'd): Densities and Viscosities of the quaternary system: Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4) at 293.15 K.

X_1	X_2	X_3	X_4	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	1.2536	0.7784	0.9758
0.0000	1.0000	0.0000	0.0000	0.7471	0.8608	0.6431
0.0000	0.0000	1.0000	0.0000	0.7269	1.1064	0.8042
0.0000	0.0000	0.0000	1.0000	10.9179	0.8255	9.0127
0.1230	0.1026	0.0920	0.6824	5.2007	0.8384	4.3602
0.2265	0.2358	0.2554	0.2822	1.5431	0.8735	1.3479
0.2830	0.2048	0.0677	0.4444	2.5448	0.8334	2.1209
0.1415	0.2843	0.4313	0.1428	1.0388	0.9251	0.9610
0.2403	0.2827	0.1050	0.3719	1.9313	0.8462	1.6343
0.45	0.1524	0.2838	0.1138	1.0808	0.8787	0.9498

Table 4.9 (Cont'd): Densities and Viscosities of the quaternary system: Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4) at 298.15 K.

X_1	X_2	X_3	X_4	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	1.1638	0.7735	0.8973
0.0000	1.0000	0.0000	0.0000	0.7046	0.8564	0.6034
0.0000	0.0000	1.0000	0.0000	0.6821	1.1011	0.7511
0.0000	0.0000	0.0000	1.0000	9.2264	0.8219	7.5832
0.1230	0.1026	0.0920	0.6824	4.5174	0.8345	3.7700
0.2265	0.2358	0.2554	0.2822	1.3204	0.8691	1.1476
0.2830	0.2048	0.0677	0.4444	2.2958	0.8293	1.9039
0.1415	0.2843	0.4313	0.1428	0.9658	0.9205	0.8890
0.2403	0.2827	0.1050	0.3719	1.7648	0.8419	1.4859
0.45	0.1524	0.2838	0.1138	0.9811	0.8739	0.8575

Table 4.9 (Cont'd): Densities and Viscosities of the quaternary system: Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4) at 293.15 K.

X_1	X_2	X_3	X_4	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	1.2536	0.7784	0.9758
0.0000	1.0000	0.0000	0.0000	0.7471	0.8608	0.6431
0.0000	0.0000	1.0000	0.0000	2.7603	0.7218	1.9924
0.0000	0.0000	0.0000	1.0000	10.9179	0.8255	9.0127
0.1208	0.0694	0.1543	0.6555	6.0549	0.82023	4.9667
0.2241	0.2198	0.2755	0.2805	2.2609	0.8177	1.8488
0.3113	0.1708	0.0852	0.4326	2.7873	0.8157	2.2736
0.1670	0.2680	0.4360	0.1290	1.6665	0.8197	1.3660
0.2868	0.2539	0.1170	0.3424	2.1659	0.8184	1.7725
0.4655	0.1412	0.2944	0.0990	1.4829	0.8004	1.1869

Table 4.9 (Cont'd): Densities and Viscosities of the quaternary system: Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4) at 298.15 K.

X_1	X_2	X_3	X_4	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	1.1638	0.7735	0.9002
0.0000	1.0000	0.0000	0.0000	0.7046	0.8564	0.6034
0.0000	0.0000	1.0000	0.0000	2.3717	0.7999	1.8971
0.0000	0.0000	0.0000	1.0000	9.2264	0.8219	7.5832
0.1208	0.0694	0.1543	0.6555	5.2047	0.8165	4.2496
0.2241	0.2198	0.2755	0.2805	1.8702	0.8135	1.5215
0.3113	0.1708	0.0852	0.4326	2.4878	0.81160	2.0191
0.1670	0.2680	0.4360	0.1290	1.5168	0.8153	1.2367
0.2868	0.2539	0.1170	0.3424	1.9612	0.8142	1.5968
0.4655	0.1412	0.2944	0.0990	1.3227	0.7958	1.0526

Table 4.9 (Cont'd): Densities and Viscosities of the quaternary system: Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4) at 293.15 K.

X_1	X_2	X_3	X_4	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	1.2536	0.7784	0.9758
0.0000	1.0000	0.0000	0.0000	0.7269	1.1064	0.8042
0.0000	0.0000	1.0000	0.0000	2.7603	0.7218	1.9924
0.0000	0.0000	0.0000	1.0000	10.9179	0.8255	9.0127
0.1538	0.0998	0.1370	0.6094	5.5278	0.8379	4.6320
0.2551	0.2369	0.2801	0.2278	2.1044	0.8673	1.8251
0.3156	0.1777	0.0936	0.4130	3.0496	0.8506	2.5938
0.1678	0.2626	0.4623	0.1072	1.6959	0.8847	1.5005
0.2658	0.2767	0.1329	0.3245	2.2365	0.8747	1.9564
0.4698	0.1504	0.3049	0.0749	1.4366	0.8362	1.2014

Table 4.9 (Cont'd): Densities and Viscosities of the quaternary system: Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4) at 298.15 K.

X_1	X_2	X_3	X_4	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	1.1638	0.7735	0.9002
0.0000	1.0000	0.0000	0.0000	0.6821	1.1011	0.7511
0.0000	0.0000	1.0000	0.0000	2.3717	0.7999	1.8971
0.0000	0.0000	0.0000	1.0000	9.2264	0.8219	7.5832
0.1538	0.0998	0.1370	0.6094	4.7708	0.8340	3.9789
0.2551	0.2369	0.2801	0.2278	1.7439	0.8628	1.5046
0.3156	0.1777	0.0936	0.4130	2.6969	0.8463	2.2823
0.1678	0.2626	0.4623	0.1072	1.4988	0.8801	1.3191
0.2658	0.2767	0.1329	0.3245	2.0174	0.8703	1.7557
0.4698	0.1504	0.3049	0.0749	1.3178	0.8315	1.0958

Table 4.9 (Cont'd): Densities and Viscosities of the quaternary system: *p*-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4) at 293.15 K.

X_1	X_2	X_3	X_4	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	0.7471	0.8608	0.6431
0.0000	1.0000	0.0000	0.0000	0.7269	1.1064	0.8042
0.0000	0.0000	1.0000	0.0000	2.7603	0.7218	1.9924
0.0000	0.0000	0.0000	1.0000	10.9179	0.8255	9.0127
0.1233	0.1293	0.14278	0.6046	4.8737	0.8447	4.1170
0.2438	0.2312	0.2862	0.2389	1.7908	0.8875	1.5893
0.2844	0.2128	0.08616	0.4167	2.5083	0.8873	2.2257
0.1465	0.2702	0.4670	0.1164	1.5856	0.9011	1.4287
0.2525	0.2673	0.1170	0.3632	2.0571	0.8871	1.8249
0.4497	0.1346	0.3249	0.0908	1.1513	0.8746	1.0070

Table 4.9 (Cont'd): Densities and Viscosities of the quaternary system: *p*-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4) at 298.15 K.

X_1	X_2	X_3	X_4	Kinematic Viscosity x 10^6(m^2/s)	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	0.7076	0.8563	0.6059
0.0000	1.0000	0.0000	0.0000	0.6821	1.1011	0.7511
0.0000	0.0000	1.0000	0.0000	2.3717	0.7999	1.8971
0.0000	0.0000	0.0000	1.0000	9.2264	0.8219	7.5832
0.1233	0.1293	0.14278	0.6046	4.2309	0.8409	3.5577
0.2438	0.2312	0.2862	0.2389	1.4997	0.8831	1.3243
0.2844	0.2128	0.08616	0.4167	2.2463	0.8829	1.9833
0.1465	0.2702	0.4670	0.1164	1.4425	0.8964	1.2931
0.2525	0.2673	0.1170	0.3632	1.8627	0.8828	1.6445
0.4497	0.1346	0.3249	0.0908	1.0371	0.8701	0.9023

Table 4.10 (Cont'd): Densities and Viscosities of the quinary system: Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4) + 1-Octanol (5) at 293.15 K.

X_1	X_2	X_3	X_4	X_5	Kinematic Viscosity x $10^6 (m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	0.0000	1.2536	0.7784	0.9758
0.0000	1.0000	0.0000	0.0000	0.0000	0.7471	0.8608	0.6431
0.0000	0.0000	1.0000	0.0000	0.0000	0.7269	1.1064	0.8042
0.0000	0.0000	0.0000	1.0000	0.0000	2.7603	0.7218	1.9924
0.0000	0.0000	0.0000	0.0000	1.0000	10.9179	0.8255	9.0127
0.1438	0.2599	0.2557	0.1932	0.1474	1.2066	0.8902	1.0741
0.1373	0.1271	0.2624	0.1152	0.3578	2.2293	0.8810	1.9640
0.2205	0.1614	0.2664	0.0761	0.2756	1.6407	0.8827	1.4482
0.2767	0.2521	0.1620	0.1865	0.1226	1.2174	0.8587	1.0454
0.1534	0.3018	0.2093	0.3102	0.02513	0.9845	0.8825	0.8688

Table 4.10 (Cont'd): Densities and Viscosities of the quinary system: Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4) + 1-Octanol (5) at 298.15 K.

X_1	X_2	X_3	X_4	X_5	Kinematic Viscosity x $10^6(m^2/s)$	Density (kg/L)	Absolute Viscosity (mPa.s)
1.0000	0.0000	0.0000	0.0000	0.0000	1.1638	0.7735	0.9002
0.0000	1.0000	0.0000	0.0000	0.0000	0.7076	0.8563	0.6059
0.0000	0.0000	1.0000	0.0000	0.0000	0.6821	1.1011	0.7511
0.0000	0.0000	0.0000	1.0000	0.0000	2.3717	0.7999	1.8971
0.0000	0.0000	0.0000	0.0000	1.0000	9.2264	0.8219	7.5832
0.1438	0.2599	0.2557	0.1932	0.1474	1.1901	0.8855	1.0539
0.1373	0.1271	0.2624	0.1152	0.3578	1.8469	0.8766	1.6191
0.2205	0.1614	0.2664	0.0761	0.2756	1.5193	0.8782	1.3343
0.2767	0.2521	0.1620	0.1865	0.1226	1.0643	0.8541	0.9090
0.1534	0.3018	0.2093	0.3102	0.02513	0.9153	0.8777	0.8033

4.5 Testing the Predictive Capability of the Viscosity Models

In this part the predictive capabilities of six selected viscosity models will be tested. The selected models are: the generalized McAllister three-body interaction model, the pseudo-binary McAllister model, the GC-UNIMOD model, the Allan and Teja correlation, the generalized corresponding states principle (GCSP) model and the Grunberg and Nissan model. The models were tested by applying the experimental data presented in part 4.4. The calculations were carried out by using a computer program acquired by Walid A. Al-Gherwi (2004).

There are two values, the absolute average deviation (%AAD) and maximum percentage deviation (%MAX), which are utilized in order to compare the predictive capabilities of the viscosity models. The (%AAD) is given as

$$\%AAD = \frac{1}{n}\left\{\sum_{i=1}^{n}\frac{\left|v_i^{\exp} - v_i^{cal}\right|}{v_i^{\exp}}\times 100\right\} \tag{4-1}$$

where n is the number of experimental data points. The (%MAX) is given by

$$\%MAX = \max\left\{\frac{v_i^{\exp} - v_i^{cal}}{v_i^{\exp}}\right\}\times 100 \tag{4-2}$$

The determined values of %AAD and % MAX for each model are presented in Tables 4.11 through 4.34.

4.5.1 Testing the generalized McAllister three-body interaction model

As discussed earlier in Chapter 2, Nhaesi and Asfour (2000a) extended the *predictive* version of the McAllister model for binary n-alkane liquid systems that was reported by Asfour *et al.* (1991) to the generalized McAllister three-body interaction model. The generalized model that was developed and reported by Nhaesi and asfour (2000a) was employed to predict the viscosity of multi-components liquid mixtures. Equation (4.3) represents the general form of the generalized McAllister model stated by Nhaesi and Asfour (2000a).

$$\ell n\,\nu_m = \sum_{i=1}^{n} x_i^3 \ell n(\nu_i M_i) + 3 \sum_{\substack{i=1 \\ i\neq j}}^{n} \sum_{j=1}^{n} x_i^2\, x_j \ell n(\nu_{ij} M_{ij}) + 6 \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i<j<k}}^{n} \sum_{k=1}^{n} x_i^2 x_j x_k \ell n(\nu_{ijk} M_{ijk}) - \ell n(M_{avg}) \tag{4.3}$$

In order to determine the values of the binary interaction parameters for regular liquid mixtures, equations (4.4) and (4.5) were suggested by Nhaesi and Asfour (1998):

$$\frac{v_{12}}{(v_1^2 v_2)^{1/3}} = 0.8735 + 0.0715 \frac{(ECN_2 - ECN_1)^2}{(ECN_1^2 ECN_2)^{1/3}} \tag{4.4}$$

$$v_{21} = v_{12} \left(\frac{v_2}{v_1} \right)^{1/3} \tag{4.5}$$

In case of ternary systems the ternary interaction parameter is determined by using equation (4.6) developed by Nhaesi and Asfour (2000a) as follows:

$$\frac{v_{ijk}}{(v_i v_j v_k)^{1/3}} = 0.9941 + 0.03167 \frac{(N_k - N_i)^2}{N_j} \tag{4.6}$$

The viscosities of multi-component systems are calculated by employing equations (4.3) through (4.6). The viscosity models selected in this study were tested by using the collected data for ten binary, ten ternary, five quaternary and one quinary system at 293.15 K and 298.15 K.

In order to calculate the effective carbon number (ECN) for the pure components that were used to constitute the liquid systems equation (4.9) which was suggested by Nhaesi and Asfour (1998) was employed,

$$\ell n(v_{@308.15K}) = A + B(ECN) \tag{4.7}$$

In the above equation v is the kinematic viscosity of the pure components at 308.15 K and the values of constants A and B are -1.943 and 0.193, respectively. The values of the effective carbon numbers are reported in Table 4.13.

The results of testing the predictive capability of the generalized McAllister three-body interaction model are given in Tables (4.12) through (4.15) for the binary, ternary, quaternary, and quinary systems.

Table 4.11: The Effective Carbon Numbers of the Pure Compounds used in the Present Study.

Pure compound	Effective carbon number (ECN)
Cyclohexane	10.04
p-Xylene	7.73
Chlorobenzene	7.58
1-Propanol	13.53
1-Octanol	19.92

Table 4.12: Test Results for the Generalized Mc Allister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 293.15 K Temperature.

Binary Systems	**McAllister 3-Body Model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2)	3.06	7.84
Cyclohexane (1) + Chlorobenzene (2)	4.61	7.84
Cyclohexane (1) + 1-Propanol (2)	8.03	14.72
Cyclohexane (1) + 1-Octanol (2)	14.3	22.73
p-Xylene (1) + Chlorobenzene (2)	5.92	9.87
p-Xylene (1) + 1-Propanol (2)	26.85	45.42
p-Xylene (1) + 1-Octanol (2)	6.08	17.79
Chlorobenzene (1) + 1-Propanol (2)	7.12	14.21
Chlorobenzene (1) + 1-Octanol (2)	13.16	21.04
1-Propanol (1) + 1-Octanol (2)	7.43	12.43

%AAD = 8.7

Table 4.12(Cont'd):Test Results for the Generalized Mc Allister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 298.15 K Temperature.

Binary Systems	**McAllister 3-Body Model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2)	5.14	9.9
Cyclohexane (1) + Chlorobenzene (2)	4.6	7.3
Cyclohexane (1) + 1-Propanol (2)	6.99	12.33
Cyclohexane (1) + 1-Octanol (2)	13.65	23.31
p-Xylene (1) + Chlorobenzene (2)	5.99	9.87
p-Xylene (1) + 1-Propanol (2)	27.02	47.86
p-Xylene (1) + 1-Octanol (2)	6.48	18.39
Chlorobenzene (1) + 1-Propanol (2)	4.36	11.98
Chlorobenzene (1) + 1-Octanol (2)	0.84	2.46
1-Propanol (1) + 1-Octanol (2)	8.6	13.62

Average %AAD = 8.4

Table 4.13 : Test Results for the Generalized McAllister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 293.15 K Temperature.

Ternary Systems	McAllister 3-Body Model	
	%AAD	%MAX
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	3.63	8.88
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	18.99	37.4
Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3)	30.72	60.77
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	18.3	34.52
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	21.01	43.8
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	6.35	17.4
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	17.87	37.5
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	19.13	39.16
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	10.71	25.17
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	9.05	30.32

Average %AAD = 15.6

Table 4.13 (Cont'd) :Test Results for the Generalized Mc Allister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 298.15 K Temperature.

Ternary Systems	McAllister 3-Body Model	
	%AAD	%MAX
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	3.59	8.64
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	7.26	25.75
Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3)	41.78	75.84
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	17.69	32.36
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	22.24	42.41
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	5.47	15.89
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	17.21	35.37
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	19.23	36.23
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	11.37	27.24
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	8.73	29.65

Average %AAD = 15.5

Table 4.14 :Test Results for the Generalized Mc Allister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Quaternary Systems.

T = 293.15 K		
Quaternary Systems	**McAllister 3-Body Model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	17.17	36.36
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	24.31	59.54
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	28.64	143.53
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	14.08	35.11
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	24.13	54.09

Average %AAD = 21.7

T = 298.15 K		
Quaternary Systems	**McAllister 3-Body Model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	12.27	26.08
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	14.53	32.08
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	28.96	137.07
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	15.1	34.11
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	24.77	52.51

Average %AAD = 19.1

Table 4.15 : Test Results for the Generalized Mc Allister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Quinary Systems.

T=293.15 K		
Quinary System	**McAllister 3-Body Model**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	20.84	47.25

T=298.15 K		
Quinary System	**McAllister 3-Body Model**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	20.82	54.21

4.5.2 Testing the predictive capability of the pseudo-binary McAllister model

The model was suggested by Nhaesi and Asfour (2000b) which combines the *pseudo*-binary model developed by Wu and Asfour (1992) with the generalized McAllister model reported by Asfour and Nhaesi (2000a). This model treats the multi-component mixture as a binary system where the components 2,3,…,n are considered as one component.

The *pseudo*-binary McAllister model was used for predicting the kinematic viscosities of the quinary system investigated into the present study as well as its binary, ternary and quaternary subsystems at 293.15 K and 298.15 K. The results are listed in Tables (4.16) through (4.19).

Table 4.16 : Test Results for the *pseudo*-binary Mc Allister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 293.15 K.

Binary Systems	**Pseudo-Binary McAllister Model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2)	3.06	7.84
Cyclohexane (1) + Chlorobenzene (2)	4.61	7.84
Cyclohexane (1) + 1-Propanol (2)	8.03	14.72
Cyclohexane (1) + 1-Octanol (2)	14.30	22.73
p-Xylene (1) + Chlorobenzene (2)	5.92	9.87
p-Xylene (1) + 1-Propanol (2)	26.85	45.42
p-Xylene (1) + 1-Octanol (2)	6.09	17.79
Chlorobenzene (1) + 1-Propanol (2)	7.12	14.21
Chlorobenzene (1) + 1-Octanol (2)	3.16	11.04
1-Propanol (1) + 1-Octanol (2)	7.43	12.43

Average %AAD = 8.7

Table 4.16 (Cont'd): Test Results for the *pseudo*-binary Mc Allister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 298.15 K.

Binary Systems	**Pseudo-Binary McAllister Model**	
	%AAD	**%MAX**
Cyclohexane (1) + p-Xylene (2)	5.14	9.9
Cyclohexane (1) + Chlorobenzene (2)	4.6	7.3
Cyclohexane (1) + 1-Propanol (2)	6.99	12.33
Cyclohexane (1) + 1-Octanol (2)	13.65	23.31
p-Xylene (1) + Chlorobenzene (2)	5.99	9.87
p-Xylene (1) + 1-Propanol (2)	27.02	47.86
p-Xylene (1) + 1-Octanol (2)	6.48	18.39
Chlorobenzene (1) + 1-Propanol (2)	4.36	11.98
Chlorobenzene (1) + 1-Octanol (2)	0.84	2.46
1-Propanol (1) + 1-Octanol (2)	8.6	13.62

Average %AAD =8.4

Table 4.17 : Test Results for the *pseudo*-binary Mc Allister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 293.15 K.

Binary Systems	**Pseudo-Binary McAllister Model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	3.84	8.56
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	14.03	26.9
Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3)	9.34	17.28
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	12.82	23.37
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	4.58	11.09
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	5.96	16.45
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	12.91	30.03
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	5.63	27.98
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	11.87	27.04
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	10.35	32.36

Average %AAD =9.1

Table 4.17 (Cont'd) : Test Results for the *pseudo*-binary Mc Allister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 298.15 K.

Binary Systems	Pseudo-Binary McAllister Model	
	%AAD	%MAX
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	3.56	8.4
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	5.56	29.01
Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3)	18.05	30.38
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	12.26	25.51
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	5.34	13.46
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	5.29	14.95
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	12.29	29.11
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	4.2	19.19
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	12.55	29.53
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	10.03	32.2

Average %AAD = 8.9

Table 4.18: Test Results for the *pseudo*-binary McAllister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Quaternary Systems.

T = 293.15 K		
Quaternary Systems	**Pseudo-Binary McAllister Model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	12.57	25.84
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	5.13	15.39
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	16.7	88.14
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	4.14	12.72
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	12.82	34.86

Average %AAD = 10.3

T = 298.15 K		
Quaternary Systems	**Pseudo-Binary McAllister Model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	12.27	26.08
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	10.45	22.15
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	16.95	83.15
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	4.85	12.72
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	13.38	35.79

Average %AAD = 11.6

Table 4.19: Test Results for the *pseudo*-binary Mc Allister Three-Body Interaction Model Employing the Experimental Kinematic Viscosity and Density Data of the Quinary Systems.

T=293.15 K		
Quinary System	**Pseudo-Binary McAllister Model**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	7.94	24.4

T=298.15 K		
Quinary System	**Pseudo-Binary McAllister Model**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	7.83	21.99

4.5.3 Testing the predictive capability of the GC-UNIMOD model

This model was developed by Cao *et al*. (1993a) as a predictive viscosity model. They incorporated the group contribution (GC) method into the “viscosity-thermodynamics” model (UNIMOD) reported by Cao *et al*. (1993b). This model includes two parts; *viz*., a combinatorial part and residual part. The predictive capability of this model is strongly affected by the residual part (R) as reported by Nhaesi (1998).

Tables (4.20) through (4.23) report the results of testing the predictive capability of the GC-UNIMOD model for the quinary system: cyclohexane , *p*-xylene, chlorobenzene, 1-propanol, 1-octanol at 293.15 K and 298.15 K and its binary, ternary and quaternary sub-systems.

Table 4.20: Test Results for the GC-UNIMOD Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 293.15 K.

Binary Systems	GC-UNIMOD Model	
	%AAD	%MAX
Cyclohexane (1) + *p*-Xylene (2)	7.27	5.47
Cyclohexane (1) + Chlorobenzene (2)	10.46	6.2
Cyclohexane (1) + 1-Propanol (2)	10.68	7.55
Cyclohexane (1) + 1-Octanol (2)	10	1.79
p-Xylene (1) + Chlorobenzene (2)	0.47	0.3
p-Xylene (1) + 1-Propanol (2)	18.96	9.94
p-Xylene (1) + 1-Octanol (2)	29.17	15.9
Chlorobenzene (1) + 1-Propanol (2)	3.23	2.21
Chlorobenzene (1) + 1-Octanol (2)	31.81	18.75
1-Propanol (1) + 1-Octanol (2)	19.27	10.44

Average %AAD = 14.1

Table 4.20 (Cont'd): Test Results for the GC-UNIMOD Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 298.15 K.

Binary Systems	**GC-UNIMOD Model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2)	11.61	8.3
Cyclohexane (1) + Chlorobenzene (2)	10.4	8.72
Cyclohexane (1) + 1-Propanol (2)	9.57	6.84
Cyclohexane (1) + 1-Octanol (2)	11.68	6.11
p-Xylene (1) + Chlorobenzene (2)	0.56	0.42
p-Xylene (1) + 1-Propanol (2)	19.39	9.59
p-Xylene (1) + 1-Octanol (2)	29.37	12.17
Chlorobenzene (1) + 1-Propanol (2)	7.26	8.24
Chlorobenzene (1) + 1-Octanol (2)	33.62	17.36
1-Propanol (1) + 1-Octanol (2)	20.52	11.33

Average %AAD = 15.4

Table 4.21: Test Results for the GC-UNIMOD Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 293.15 K.

Ternary Systems	McAllister 3-Body Model	
	%AAD	%MAX
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	7.70	11.20
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	29.41	28
Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3)	32.42	26.9
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	25.83	28.31
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	20.52	19.44
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	7.08	12.56
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	21.49	29.4
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	10.79	18.68
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	4.76	1.21
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	5.87	9.30

Average %AAD = 16.6

Table 4.21 (Cont'd): Test Results for the GC-UNIMOD Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 298.15 K.

Binary Systems	GC-UNIMOD Model	
	%AAD	%MAX
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	7.3	10.13
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	10.59	4.21
Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3)	46.86	41.42
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	24.32	25.72
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	21.5	21.37
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	6.07	10.81
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	19.91	21.64
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	10.3	9.9
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	6.6	2.25
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	8.1	13.05

Average %AAD = 16.2

Table 4.22: Test Results for the GC-UNIMOD Model Employing the Experimental Kinematic Viscosity and Density Data of the Quaternary Systems.

T = 293.15 K		
Quaternary Systems	**GC-UNIMOD Model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	25.11	23.61
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	10.07	13.96
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	24.74	15.73
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	8.48	13.28
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	9.07	16.79

Average %AAD = 15.5

T = 298.15 K		
Quaternary Systems	**GC-UNIMOD Model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	24.86	22.45
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	19.7	27.56
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	25.27	17.17
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	9.24	11.98
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	9.93	17.93

Average %AAD = 17.8

Table 4.23: Test Results for the GC-UNIMOD Model Employing the Experimental Kinematic Viscosity and Density Data of the Quinary Systems.

T=293.15 K		
Quinary System	**GC-UNIMOD Model**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	42.14	27.83

T=298.15 K		
Quinary System	**GC-UNIMOD Model**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	39.59	23.53

4.5.4 Testing the predictive capability of the Grunberg and Nissan mixture law of viscosity

Grunberg and Nissan (1949) proposed an empirical equation for determination of the viscosities of binary solutions. In case of multicomponent liquid mixtures, a binary adjustable parameter G_{ij} was introduced by Irving (1977) to the Grunberg and Nissan equation.

The experimental data obtained in the present study were used to test the capability of the Grunberg and Nissan mixture law of viscosity. The data collected for the multicomponent regular solutions examined in the present at 293.15 K and 298.15 K were used in testing the Gruberg and Nissan equation. The results of testing are shown in Tables 4.24 through 4.27.

Table 4.24: Test Results for Grunberg and Nissan Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 293.15 K.

Binary Systems	**Grunberg and Nissan model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2)	10.55	22
Cyclohexane (1) + Chlorobenzene (2)	14	24
Cyclohexane (1) + 1-Propanol (2)	5.55	11
Cyclohexane (1) + 1-Octanol (2)	5.91	12
p-Xylene (1) + Chlorobenzene (2)	1.09	2
p-Xylene (1) + 1-Propanol (2)	14.55	25
p-Xylene (1) + 1-Octanol (2)	17.82	27
Chlorobenzene (1) + 1-Propanol (2)	4.55	8
Chlorobenzene (1) + 1-Octanol (2)	19	31
1-Propanol (1) + 1-Octanol (2)	15	24

Average %AAD = 10.8

Table 4.24 (Cont'd): Test Results for Grunberg and Nissan Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 298.15 K.

Binary Systems	Grunberg and Nissan model	
	%AAD	%MAX
Cyclohexane (1) + *p*-Xylene (2)	14.64	26
Cyclohexane (1) + Chlorobenzene (2)	18.82	30
Cyclohexane (1) + 1-Propanol (2)	6.09	11
Cyclohexane (1) + 1-Octanol (2)	6.91	13
p-Xylene (1) + Chlorobenzene (2)	0.27	1
p-Xylene (1) + 1-Propanol (2)	16.55	13
p-Xylene (1) + 1-Octanol (2)	16.18	29
Chlorobenzene (1) + 1-Propanol (2)	6.55	13
Chlorobenzene (1) + 1-Octanol (2)	19.82	32
1-Propanol (1) + 1-Octanol (2)	14.82	23

Average %AAD = 11.4

Table 4.25: Test Results for Grunberg and Nissan Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 293.15 K.

Binary Systems	Grunberg and Nissan model	
	%AAD	%MAX
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	12.6	26
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	30.5	52
Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3)	13.9	29
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	14.8	30
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	9.9	24
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	6.2	19
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	12.2	25
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	3.7	11
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	6.9	19
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	8.1	16

Average %AAD = 11.9

Table 4.25 (Cont'd): Test Results for Grunberg and Nissan Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 298.15 K.

Binary Systems	Grunberg and Nissan model	
	%AAD	%MAX
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	12.2	25
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	9.5	32
Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3)	23.6	41
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	17.8	31
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	11.7	31
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	6.4	18
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	11.6	21
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	3.4	10
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	6.4	18
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	8.3	18

Average %AAD = 11.1

Table 4.26: Test Results for Grunberg and Nissan Model Employing the Experimental Kinematic Viscosity and Density Data of the Quaternary Systems.

T = 293.15 K		
Quaternary Systems	**Grunberg and Nissan model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	12.8	29
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	11.1	26
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	16.4	82
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	4.3	14
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	4.8	15

Average %AAD = 9.9

T = 298.15 K		
Quaternary Systems	**Grunberg and Nissan model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	16.7	33
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	12.7	35
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	17.9	83
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	6	15
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	6.6	20

Average %AAD = 11.9

Table 4.27: Test Results for Grunberg and Nissan Model Employing the Experimental Kinematic Viscosity and Density Data of the Quinary Systems.

T=293.15 K		
Quinary System	**Grunberg and Nissan model**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	17	39

T=298.15 K		
Quinary System	**Grunberg and Nissan model**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	18.3	44

4.5.5 Testing the predictive capability of the Allan and Teja correlation

Allan and Teja (1991) reported their model for correlating the viscosities of multi-component liquid mixtures. Their model is a correlative model which requires experimental data in order to determine the interaction parameter.

Tables 4.28 through 4.31 summarize the results of testing the predictive capability of the Allan and Teja correlation for the liquid systems investigated in the present study at 293.15 K and 298.15 K.

Table 4.28: Test Results for the Allan and Teja Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 293.15 K.

Binary Systems	**Allan and Teja correlation**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2)	8.08	20.76
Cyclohexane (1) + Chlorobenzene (2)	16.15	39.03
Cyclohexane (1) + 1-Propanol (2)	8.65	16.03
Cyclohexane (1) + 1-Octanol (2)	14.97	38.36
p-Xylene (1) + Chlorobenzene (2)	30.2	39.13
p-Xylene (1) + 1-Propanol (2)	12.79	21.61
p-Xylene (1) + 1-Octanol (2)	33.9	40.65
Chlorobenzene (1) + 1-Propanol (2)	21.92	39.13
Chlorobenzene (1) + 1-Octanol (2)	43.27	48.09
1-Propanol (1) + 1-Octanol (2)	26	38.36

Average %AAD = 21.6

Table 4.28 (Cont'd): Test Results for the Allan and Teja Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 298.15 K.

Binary Systems	**Allan and Teja correlation**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2)	8.61	15.68
Cyclohexane (1) + Chlorobenzene (2)	13.36	38.79
Cyclohexane (1) + 1-Propanol (2)	10.07	17.7
Cyclohexane (1) + 1-Octanol (2)	15.20	34.57
p-Xylene (1) + Chlorobenzene (2)	29.72	38.48
p-Xylene (1) + 1-Propanol (2)	15.41	27.03
p-Xylene (1) + 1-Octanol (2)	33.1	39.08
Chlorobenzene (1) + 1-Propanol (2)	21.66	38.79
Chlorobenzene (1) + 1-Octanol (2)	42.86	48.17
1-Propanol (1) + 1-Octanol (2)	22.5	34.57

Average %AAD = 21.3

Table 4.29: Test Results for the Allan and Teja Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 293.15 K.

Ternary Systems	**Allan and Teja correlation**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	16.12	39.03
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	26.72	43.38
Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3)	13.33	38.36
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	11.2	39.13
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	13.67	39.15
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	12.18	38.36
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	14.82	42.54
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	29.89	45
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	16.53	38.36
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	31.89	45

Average %AAD = 18.6

Table 4.29 (Cont'd): Test Results for the Allan and Teja Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 298.15 K.

Ternary Systems	Allan and Teja correlation	
	%AAD	%MAX
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	12.65	34.82
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	36.83	131.52
Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3)	19.47	38.36
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	11.69	38.48
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	12.25	38.5
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	11.3	34.63
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	13.17	39.09
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	22.83	39.11
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	14.81	34.63
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	22.92	39.09

Average %AAD = 17.8

Table 4.30: Test Results for the Allan and Teja Model Employing the Experimental Kinematic Viscosity and Density Data of the Quaternary Systems.

T = 293.15 K		
Quaternary Systems	**Allan and Teja correlation**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	14.45	39.13
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	14.77	39.13
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	23.38	74.18
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	18.8	45
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	14.6	39.13

Average %AAD = 17.2

T = 298.15 K		
Quaternary Systems	**Allan and Teja correlation**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	15.2	38.48
8Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	13.63	36.29
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	23.59	74.56
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	13.09	38.4
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	15.55	34.82

Average %AAD = 16.2

Table 4.31: Test Results for the Allan and Teja Model Employing the Experimental Kinematic Viscosity and Density Data of the Quinary Systems.

T=293.15 K		
Quinary System	**Allan and Teja correlation**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	14.41	39.13

T=298.15 K		
Quinary System	**Allan and Teja correlation**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	17.57	34.82

4.5.6 Testing the predictive capability of the generalized corresponding states principle (GCSP) model

The generalized corresponding-states principle model was suggested by Teja and Rice (1981) for the prediction of the viscosity of multicomponent mixtures. The system requires the knowledge of the critical properties of pure components. The critical properties of the pure components are listed in Table 4.25.

Similar to the previous models the GCSP model is tested by employing the experimental data collected in the present study for ten binary, ten ternary, five quaternary subsystems of the quinary system at 293.15 K and 298.15 K. As it was indicated earlier, the selection of reference fluids affects the error of calculating the viscosity. Therefore, the reported results are those that pertain to the reference fluids that yield the lowest %AAD. Tables 4.32 through 4.35 show the results of testing the model.

Table 4.32: Test Results for the GCSP Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 293.15 K.

Binary Systems	**GCSP model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2)	7.00	11.96
Cyclohexane (1) + Chlorobenzene (2)	10.77	14.39
Cyclohexane (1) + 1-Propanol (2)	12.58	18.44
Cyclohexane (1) + 1-Octanol (2)	3.73	8.16
p-Xylene (1) + Chlorobenzene (2)	0.24	0.46
p-Xylene (1) + 1-Propanol (2)	19.44	26.45
p-Xylene (1) + 1-Octanol (2)	20.85	26.48
Chlorobenzene (1) + 1-Propanol (2)	1.47	4.81
Chlorobenzene (1) + 1-Octanol (2)	21.09	28.77
1-Propanol (1) + 1-Octanol (2)	12.55	17.75

Average %AAD = 10.9

Table 4.32 (Cont'd): Test Results for the GCSP Model Employing the Experimental Kinematic Viscosity and Density Data of the Binary Systems at 298.15 K.

Binary Systems	**GCSP model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2)	11.47	16.33
Cyclohexane (1) + Chlorobenzene (2)	14.53	18.69
yclohexane (1) + 1-Propanol (2)	11.43	16.29
Cyclohexane (1) + 1-Octanol (2)	5.36	15.3
p-Xylene (1) + Chlorobenzene (2)	0.29	0.58
p-Xylene (1) + 1-Propanol (2)	20.06	29.2
p-Xylene (1) + 1-Octanol (2)	20.43	29.91
Chlorobenzene (1) + 1-Propanol (2)	5.44	11.03
Chlorobenzene (1) + 1-Octanol (2)	23.54	31.11
1-Propanol (1) + 1-Octanol (2)	10.47	15.51

Average %AAD = 12.3

Table 4.33: Test Results for the GCSP Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 293.15 K.

Ternary Systems	**GCSP model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	2.84	9.91
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	13.06	21.32
Cyclohexane (1) + p-Xylene (2) + 1-Octanol (3)	20.86	49.52
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	7.68	14.37
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	12.37	24.55
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	12.63	44.95
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	10.62	21.24
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	16.93	28.93
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	39	71.89
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	18.18	41.78

Average %AAD = 15.4

Table 4.33 (Cont'd): Test Results for the GCSP Model Employing the Experimental Kinematic Viscosity and Density Data of the Ternary Systems at 298.15 K.

Ternary Systems	GCSP model	
	%AAD	%MAX
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3)	2.78	10.1
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3)	16.65	33.91
Cyclohexane (1) + *p*-Xylene (2) + 1-Octanol (3)	19.49	43.45
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3)	7.97	18.1
Cyclohexane (1) + Chlorobenzene (2) + 1-Octanol (3)	11.94	22.03
Cyclohexane (1) + 1-Propanol (2) + 1-Octanol (3)	12.97	37.69
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)	10.2	16.39
p-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)	16.15	28.88
p-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)	37.75	71.36
Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)	17.95	41.13

Average %AAD = 15.4

Table 4.34: Test Results for the GCSP Model Employing the Experimental Kinematic Viscosity and Density Data of the Quaternary Systems.

T = 293.15 K		
Quaternary Systems	**GCSP model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	7.67	24
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	14.67	27
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	23.33	91
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	28.33	65
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	30.83	64

Average %AAD = 20.9

T = 298.15 K		
Quaternary Systems	**GCSP model**	
	%AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)	7.67	23
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)	4	17
Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)	25	15.63
Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	26.5	62
p-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)	28	61

Average %AAD = 18.2

Table 4.35: Test Results for the GCSP Model Employing the Experimental Kinematic Viscosity and Density Data of the Quinary System.

T=293.15 K		
Quinary System	**GCSP model**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	16.6	44

T=298.15 K		
Quinary System	**GCSP model**	
	% AAD	**%MAX**
Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-propanol (4) + 1-Octanol (5)	16.4	33

*Table 4.36 : The Critical Properties of the Pure Components

Component	Molecular Weight	T_c (K)	P_c (atm)	Acentric Factor
Cyclohexane	84.162	553.5	40.7	0.212
p-Xylene	106.168	616.2	35.1	0.320
Chlorobenzene	112.559	632.4	45.2	0.249
1-Propanol	60.096	536.8	51.7	0.623
1-Octanol	130.231	652.5	28.6	0.587

*Reid, *et al*. (1987)

4.6 Summary of the Analysis of Results and Overall Comparison of the Models Tested

The predictive capabilities of six selected viscosity models: the generalized McAllister three-body interaction model, the *pseudo*-binary McAllister model, the GC-UNIMOD model, the Grunberg and Nissan law of viscosity, the Allan and Teja model and the GCSP model were tested using the experimental data obtained on the quinary system: cyclohexane + *p*-xylene + chlorobenzene + 1-propanol + 1-octanol and its binary, ternary and quaternary subsystems at 293.15 k and 298.15 K. Table 4.37 reports the values of the overall %AAD of each system.

The graphical comparisons of the predictive capabilities of the selected models for each system are depicted in Figures 4.1 through 4.4. Figure 4.1 shows the testing results of the selected models in case of binary systems at both 293.15 K and 298.15 K. The results show that the generalized McAllister model three-body interaction model and the *pseudo*-binary McAllister model have the lowest %AADs, 8.65 and 8.37 at 293.15 K and 298.15 K, respectively.

Figure 4.2 depicts the predictive capabilities for the ternary systems at 293.15 K and 298.15 K. The *pseudo*-binary McAllister model gives %AADs of 9.13 and 8.91 at 293.15 K and 298.15 K, respectively followed by the Grunberg and Nissan models with %AADs 11.88 and 11.09.

Figure 4.3 represents a comparison of the predictive capabilities of the selected viscosity models for the case of the quaternary systems at 293.15 K and 298.15 K. The *pseudo*-binary McAllister model shows the lowest %AAD of 10.27 and 11.58 whereas the Grunberg and Nissan model shows %AADs of 9.88 and 11.98 at 293.15 K and 298.15 K, respectively.

Figure 4.4 shows the graphical comparison of the overall predictive capabilities of all selected models which confirms that the *pseudo*-binary McAllister model gives the best predictive capability for predicting the viscosities of the multi-component mixtures.

Table 4.37: Overall Comparison of the Prediction Capabilities of the Tested Models

Temperature = 293.15 K						
Systems	McAllister 3-Body Model	Pseudo-Binary McAllister Model	GC-UNIMOD Method	(GCSP)	Allan and Teja Correlation	Grunberg and Nissan
	%AAD	%AAD	%AAD	%AAD	%AAD	%AAD
Quinary	20.84	7.94	42.14	16.6	14.41	17
Quaternary	21.67	10.27	15.49	20.97	17.2	9.88
Ternary	15.58	9.13	16.58	15.42	18.63	11.88
Binary	8.65	8.66	14.13	10.97	21.59	10.80
% Overall average	16.68	9	22.08	16	17.96	12.39

Temperature = 298.15 K						
Systems	McAllister 3-Body Model	Pseudo-Binary McAllister Model	GC-UNIMOD Method	(GCSP)	Allan and Teja Correlation	Grunberg and Nissan
	%AAD	%AAD	%AAD	%AAD	%AAD	%AAD
Quinary	20.82	7.83	39.59	16.40	17.57	18.30
Quaternary	19.13	11.58	17.80	18.23	16.21	11.98
Ternary	15.46	8.91	16.15	15.38	17.79	11.09
Binary	8.37	8.37	15.40	12.30	21.25	11.37
% Overall average	16	9.24	22.23	15.58	18.20	13.18

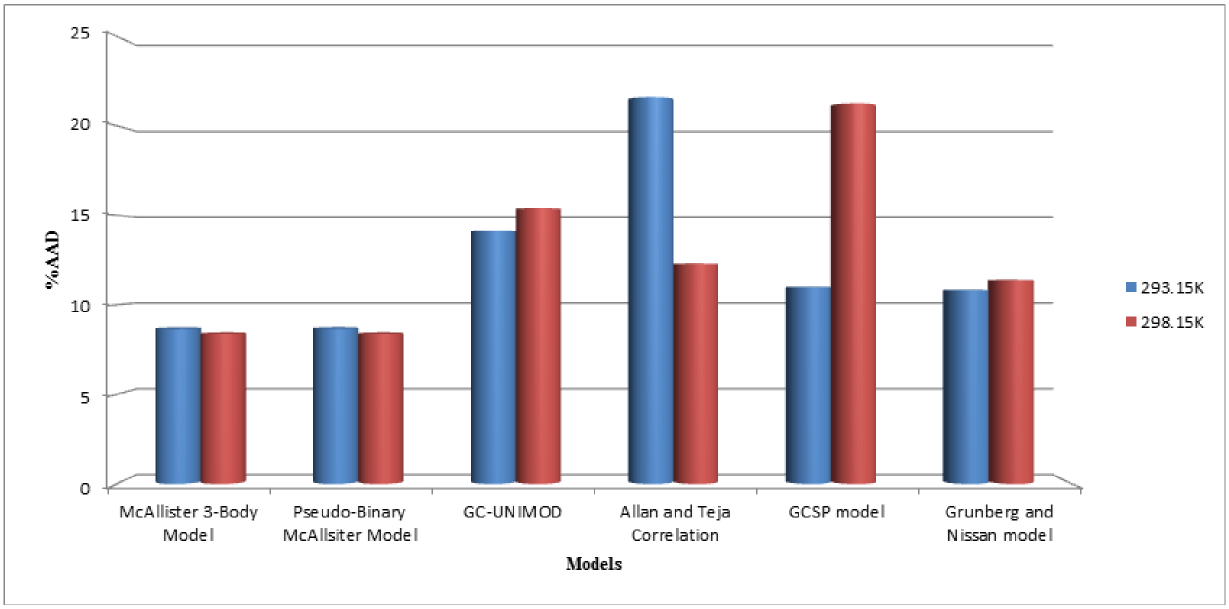


Figure 4.1: Graphical Representation of the Predictive Capabilities of the Viscosity Models Using Binary System Data.

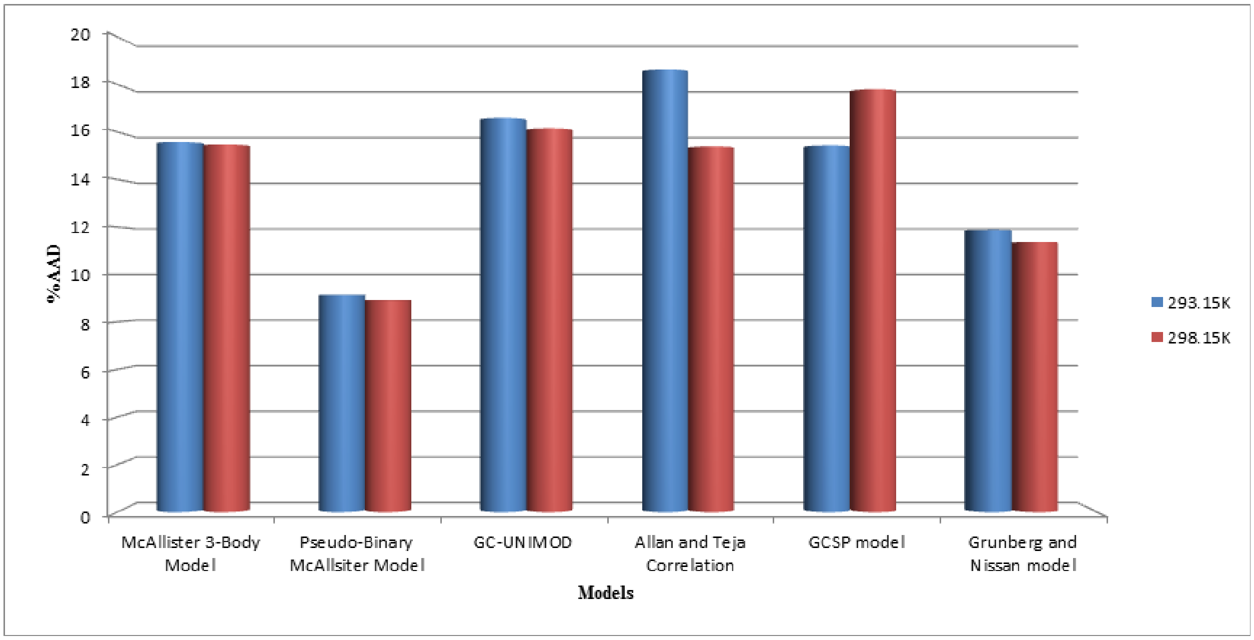


Figure 4.2: Graphical Representation of the Predictive Capabilities of the Viscosity Models Using Ternary System Data.

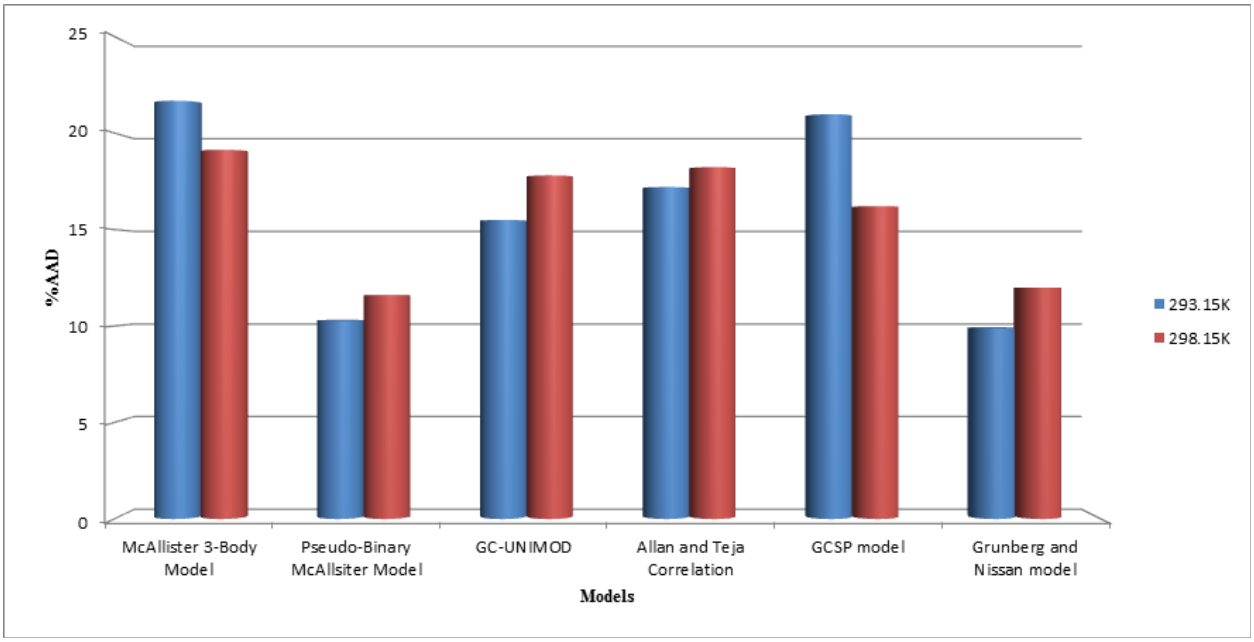


Figure 4.3: Graphical Representation of the Predictive Capabilities of the Viscosity Models Using Quaternary System Data.

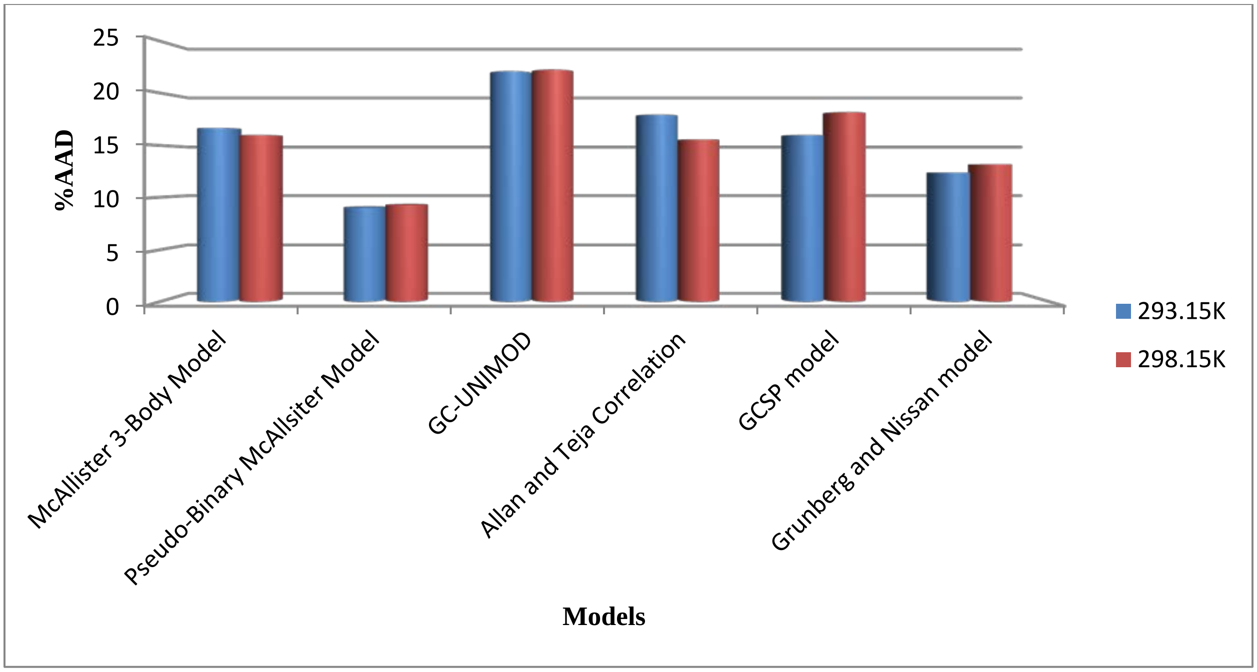


Figure 4.4: Overall Graphical Representation Capabilities of the Viscosity Models.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The densities and kinematic viscosities of the quinary regular solution system: cyclohexane, *p*-xylene, chlorobenzene, 1-propanol, and 1-octanol and all its binary, ternary and quaternary subsystems at 293.15 K and 298.15 K were accurately measured. The collected experimental data for the densities and the kinematic viscosities of the pure components are in notable agreement with the corresponding values reported in the literature.

The predictive capabilities of six selected models, reported in the literature, were tested by using the densities and the kinematic viscosities achieved in this study. The six models are:

- The generalized McAllister three-body interaction model.
- The *pseudo*-binary McAllister model.
- The group contribution GC-UNIMOD model.
- The Allan and Teja correlation.
- The generalized corresponding-states principle model
- The Grunberg and Nissan law of viscosity.

The percent average absolute deviation (%AAD) was determined for each model and the predictive capabilities were compared by using %AAD values.

The results show that the *pseudo*-binary McAllister model proposed by Nhaesi and Asfour (2000b) gives the lowest overall %AAD of 9 and 9.2 at 293.15 K and 298.15 K, respectively.

The Grunberg and Nissan ranked second with a %AAD of 12.4 and 13.2 at 293.15 K and 298.15 K, respectively. Those were followed by the generalized corresponding state principle and the generalized McAllister model with close values of %AAD at both temperatures. In case of the generalized corresponding state principle, the %AAD values were 16 and 15.6 at 293.15 K and 298.15 K, respectively. For the case of the generalized McAllister model the %ADD values were 16.7 and 16 at 293.15 K and 298.15 K, respectively.

In the procedure of calculation of the *effective carbon number* for the case of systems including cyclohexane, the final ECN values were multiplied by 0.75 as it was suggested by Al-Gherwi (2006), Cai (2004) and El-Hadad (2004). But contrary to expectations, the values of %AAD were higher after multiplication by 0.75. Therefore, the ECN values were calculated and employed as they were obtained with the help of the equation reported by Nhaesi and Asfour (1998); as indicated in Chapter 2.

The errors resulting from testing the generalized McAllister three-body interaction model using the experimental data collected in the present study were relatively higher than other studies conducted earlier by El-Hadad (2004), Cai (2004), and Al Gherwi (2006). This prompted the present author to calculate the relative sizes of the components constituting the systems that exhibited such relatively high errors. It was found out in all such cases that the size ratios of the molecules of the components constituting such mixtures were higher than 1.5. Consequently, as was suggested by McAllister (1960) that in such cases, a four-body interaction model should have been employed. Unfortunately, at this point of time such a generalized model is not available.

The other important factor that influences viscosity, besides molecular size, is the molecular shape. The molecular shapes of the pure components in the present study are very different from each other. For example, *p*-xylene is an aromatic hydrocarbon consisting of a benzene ring with two methyl groups, across from each other, attached to the ring. The 1-propanol and 1-octanol molecules are more or less “rod-like”. Cyclohexane is a cyclic hydrocarbon with different conformations as planar, boat, and chair which affects the molecular shape and hence the predictive capability of viscosity models.

Table 5.1: The size ratios of the molecules of pure components

Binary Systems	**Size Ratio**	**%AAD**
Cyclohexane + *p*-Xylene	1.14	3.06
Cyclohexene + Chlorobenzene	1.06	4.6
Cyclohexane + 1-Propanol	1.45	8.03
Cyclohexane + 1- Octanol	1.46	14.3
p-Xylene + Chlorobenzene	1.21	5.9
p-Xylene + 1-Propanol	1.65	26.9
p-Xylene + 1-Octanol	1.28	6.1
Chlorobenzene + 1-Propanol	1.36	7.1
Chlorobenzene + 1-Octanol	1.55	13.2
1-Propanol + 1-Octanol	2.11	7.4

The Allan and Teja correlation ranked fourth in terms of lowest overall %AAD values of 18 and 18.20 at 293.15 K and 298.15 K, respectively where in case of binary systems it gave the highest values of %AAD of 21.59 and 21.25.

The GC-UNIMOD model reported the highest overall %AAD values. It should be noted the residual part (R) was set equal to zero during the calculations involving the model, as this assumption may not impose a significant effect on the predictive capability of the GC-UNIMOD model as was indicated by Nhaesi (1998).

5.2 Recommendations

Considering the conclusions reached pursuant to the present study, the following recommendations can be made:

(i) A generalized four-body interaction model similar to the three-body interaction model that was developed and reported by Nhaesi and Asfour (2000a) should be developed.

(ii) Viscosity data for liquid mixtures with components having size ratios of more than 1.5 should be collected and used in testing the model developed under (i).

Nomenclature

a	Group interaction energy parameter
B	Constant generally used as a parameter
b	Constant generally used as a parameter
C	Constant generally used as a parameter
D	Constant generally used as a parameter
d	Constant generally used as a parameter
E	Constant generally used as a parameter
f	Shear force
G	Grunberg and Nissan binary interaction parameter
h	Planks's constant
i	Index number
j	Index number
k	Index number
M	Molecular weight, g/mol
n	Number of components of the mixture; number of interaction parameters; number of experimental points
N	Avogadro's number, carbon atoms number
P	Pressure
Q	Area parameter of molecules
R	Universal gas constant
R	Rate of a liquid molecule moving under shear stress
r_0	Rate of liquid molecule moving as a result of thermal fluctuation
t	Efflux time of viscometer

T	Temperature
V	Molar volume of the liquid
x	Mole fraction
Z	Compressibility factor

Greek Letters

μ	Absolute viscosity
λ	Center to center distance between molecule and a hole in Eyring's theory
$\lambda_1, \lambda_2, \lambda_3$	Intermolecular distance used in Eyring's theory
ν	Kinematic viscosity, m^2/s
ν_k	Number of groups in molecule
ν_{12}	McAllister three-body model binary interaction parameter
ν_{21}	McAllister three-body model binary interaction parameter
ν_{123}	McAllister three-body model interaction parameter
ν_{1112}	McAllister four-body model interaction parameter
ν_{2221}	McAllister four-body model interaction parameter
ν_{1122}	McAllister four-body model interaction parameter
ζ_{ij}	Binary interaction parameter in the Generalized Corresponding State Principle
ζ_{ij0}	Binary interaction parameter in the Generalized Corresponding State Principle for pure component
ρ	Density
τ	Oscillation period in seconds of the density, Shear stress
Φ	Shape factor, Volume fraction
Φ_{ji}	Local volume fraction of component j around central molecule i

ω	Acentric factor
Ξ	Group property in GC-UNIMOD model
Ψ_{ki}	Group residual viscosity in the GC-UNIMOD

Subscripts

1, 2, 3	Refer to various components in the mixture
123	Refer to interaction between three molecules
c	Critical properties
i, j	Refer to i^{th} and j^{th} component in the mixture, respectively
ij	Refer to interaction type i-j
ijk	Refer to interaction of type i-j-k
r_1	Refer to the reference fluid 1
r_2	Refer to the reference fluid 2
r	Reduced properties

Acronyms

AAD	Average absolute deviation, %
ECN	Effective carbon number
GC-UNIMOD	Group Contribution-Viscosity thermodynamics Model
GCSP	Generalized Corresponding States Principle
MAX	Maximum deviation, %

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APPENDICIES

APPENDIX A

Raw Kinematic Viscosity and Density Data

Table A.1 : Raw Kinematic Viscosity and Density Data for the Binary System: Cyclohexane(1) + *p*-Xylene(2)

Sample Composition		Viscometer number	T=293.15 (K)		T=298.15 (K)	
X_1	X_2		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1002	0.8998	25B349	426.70	0.730725	403.26	0.729676
0.2320	0.7680	25B366	403.33	0.728746	380.86	0.727695
0.3118	0.6882	25B350	443.65	0.727395	420.06	0.726339
0.3853	0.6147	25B366	416.27	0.726230	394.18	0.725164
0.4964	0.5036	25B349	467.02	0.724464	439.51	0.723392
0.5880	0.4120	25B350	489.96	0.723057	460.71	0.721978
0.7001	0.2999	25B366	489.30	0.721304	448.64	0.720215
0.8493	0.1507	25B349	601.67	0.719129	551.28	0.718026
0.8932	0.1068	25B350	629.55	0.7185	580.74	0.717383

Table A.1 (Cont’d) : Raw Kinematic Viscosity and Density Data for the Binary System: Cyclohexane (1) + Chlorobenzene(2)

Sample Composition		Viscometer number	T=293.15 (K)		T=298.15 (K)	
X_1	X_2		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.0949	0.9051	25B366	385.50	0.7700	366.23	0.7689
0.2088	0.7912	25B349	426.87	0.7630	398.25	0.7619
0.3096	0.6904	25B366	405.93	0.7569	383.74	0.75582
0.4169	0.5831	25B350	454.53	0.7509	431.22	0.7497
0.5047	0.4953	25B349	473.51	0.7453	445.68	0.7442
0.6137	0.3863	25B350	507.97	0.7398	476.33	0.7376
0.6722	0.3278	25B831	224.09	0.7354	214.58	0.7344
0.7966	0.2034	50B159	259.06	0.7292	241.29	0.7277
0.8606	0.1394	50B158	251.36	0.7245	238.98	0.7234

Table A.1 (Cont'd) : Raw Kinematic Viscosity and Density Data for the Binary System: Cyclohexane(1)+ 1-Propanol(2)

Sample Composition		Viscometer number	T=293.15 (K)		T=298.15 (K)	
X_1	X_2		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1115	0.8885	50B159	611.83	0.7208	538.28	0.7198
0.2058	0.7942	50B158	494.85	0.7200	468.85	0.7190
0.2922	0.7078	50B831	477.48	0.7195	428.53	0.7185
0.3907	0.6093	50B831	432.17	0.7189	390.39	0.7179
0.4946	0.5054	50B159	402.96	0.7184	364.07	0.7173
0.5870	0.4130	50B158	335.67	0.7180	324.70	0.7169
0.7048	0.2952	50B831	327.71	0.7173	305.80	0.7164
0.7992	0.2008	50B159	325.22	0.7173	304.66	0.7162
0.8926	0.1074	50B158	288.98	0.7170	290.23	0.7160

Table A.1 (Cont'd) : Raw Kinematic Viscosity and Density Data for the Binary System: Cyclohexane(1) + 1-Octanol(2)

Sample Composition		Viscometer number	T=293.15 (K)		T=298.15 (K)	
X_1	X_2		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1048	0.8952	100C334	530.66	0.7249	468.42	0.7240
0.1915	0.8085	100C335	506.2	0.7242	407.65	0.7233
0.2702	0.7298	100C336	371.16	0.7236	338.18	0.7227
0.3795	0.6205	100C334	310.56	0.7227	279.06	0.7217
0.5045	0.4955	100C335	264.61	0.7217	215.85	0.7207
0.6124	0.3876	100C336	175.84	0.7206	156.62	0.7196
0.6735	0.3265	75K95	282.75	0.7201	255.13	0.7190
0.7962	0.2038	50B158	488.26	0.7189	430.75	0.7179
0.8823	0.1177	50B159	363.00	0.7181	331.41	0.7170

Table A.1 (Cont'd) : Raw Kinematic Viscosity and Density Data for the Binary System : *p*-Xylene(1) + Chlorobenzene(2)

Sample Composition		Viscometer number	T=293.15 (K)		T=298.15 (K)	
X_1	X_2		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.0909	0.9091	50B831	179.63	0.7712	170.87	0.7701
0.2196	0.7804	50B159	187.23	0.7654	177.29	0.7643
0.3060	0.6940	50B158	168.48	0.7612	149.96	0.7601
0.4078	0.5922	25B349	417.33	0.7562	393.21	0.7551
0.4971	0.5029	25B350	422	0.7526	398.88	0.7515
0.6082	0.3918	25B366	392.01	0.7480	369.57	0.7469
0.7117	0.2883	50B158	181.55	0.7439	175.03	0.7428
0.8026	0.1974	50B159	172.95	0.7401	154.56	0.7390
0.9047	0.0953	25B349	191.17	0.7364	181.41	0.7354

Table A.1 (Cont'd) : Raw Kinematic Viscosity and Density Data for the Binary System : *p*-Xylene (1)+ 1-Propanol(2)

Sample Composition		Viscometer number	T=293.15 (K)		T=298 (K)	
X_1	X_2		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1135	0.8865	50B831	513.46	0.7237	459.51	0.7226
0.2034	0.7966	50B158	404.63	0.7250	369.18	0.7240
0.3057	0.6943	50B159	367.73	0.7263	313.3	0.7253
0.4150	0.5850	50B831	292.12	0.7275	267.47	0.7265
0.5079	0.4921	50B158	244.18	0.7284	224.73	0.7274
0.6084	0.3916	50B159	240.13	0.7293	222.68	0.7282
0.6886	0.3114	50B831	211.44	0.7300	200.29	0.7289
0.7988	0.2012	50B158	186.36	0.7308	174.36	0.7298
0.8961	0.1039	50B159	194.98	0.7323	183.79	0.7304

Table A.1 (Cont'd) : Raw Kinematic Viscosity and Density Data for the Binary System : *p*-Xylene (1)+ 1-Octanol (2)

Sample Composition		Viscometer number	T=293.15 (K)		T=298.15 (K)	
X_1	X_2		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1044	0.8956	100C334	582.15	0.7259	495.22	0.7253
0.1971	0.8029	100C335	573.50	0.7264	443.47	0.7257
0.2815	0.7185	100C336	422.60	0.7269	366.53	0.7262
0.4064	0.5936	100C336	304.20	0.7278	284.44	0.7270
0.4918	0.5082	75K96	462.40	0.7285	435.82	0.7275
0.5920	0.4080	75K95	331.62	0.7292	333.50	0.7282
0.6916	0.3084	75K96	262.97	0.7299	236.63	0.7289
0.7931	0.2069	50B158	386.13	0.7305	349.03	0.7295
0.8712	0.1288	50B159	331.87	0.7312	279.18	0.7302

Table A.1 (Cont'd) : Raw Kinematic Viscosity and Density Data for the Binary System: Chlorobenzene (1) + 1-propanol(2)

Sample Composition		Viscometer number	T=293.15 (K)		T=298.15 (K)	
X_1	X_2		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1028	0.8972	50B831	583.64	0.7290	535.41	0.7277
0.1574	0.8426	50B158	503.67	0.7333	505.80	0.7322
0.3057	0.6943	50B159	457.29	0.7427	415.05	0.7416
0.4011	0.5989	50B158	356.30	0.7484	359.90	0.7473
0.4906	0.5094	50B831	342.34	0.7533	313.83	0.7521
0.6071	0.3929	25B349	662.12	0.7589	611.15	0.7578
0.7094	0.2906	25B350	589.55	0.7638	577.53	0.7627
0.8164	0.1836	25B366	500.14	0.7690	493.44	0.7683
0.8922	0.1078	25B349	474.07	0.7716	469.74	0.7705

Table A.1 (Cont'd) : Raw Kinematic Viscosity and Density Data for the Binary System: Chlorobenzene (1)+1-octanol (2)

Sample Composition		Viscometer number	T=293.15 (K)		T=298.15 (K)	
X_1	X_2		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1063	0.8937	100C334	577.56	0.7284	500.6	0.7274
0.2008	0.7992	100C335	575.71	0.7320	447.75	0.7310
0.2934	0.7066	100C336	424.77	0.7355	368.29	0.7346
0.3913	0.6087	100C336	341.62	0.7395	299.6	0.7385
0.5031	0.4969	75K95	468.17	0.7449	437.16	0.7438
0.5960	0.4040	75K96	377.92	0.7509	349.78	0.7490
0.6818	0.3182	50B831	577.48	0.7553	593.85	0.7542
0.7835	0.2165	50B158	381.11	0.7611	419.43	0.7600
0.9003	0.0997	50B159	289.25	0.7689	263.58	0.7674

Table A.1 (Cont'd) : Raw Kinematic Viscosity and Density Data for the Binary System : 1-propanol(1) + 1-octanol(2)

Sample Composition		Viscometer number	T=293.15 (K)		T=298.15 (K)	
X_1	X_2		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1051	0.8949	100C336	580.3	0.7255	497.65	0.7246
0.2048	0.7952	100C335	608.66	0.7253	477.48	0.7244
0.3059	0.6941	100C334	482.61	0.7250	411.57	0.7241
0.3992	0.6008	100C336	412.52	0.7247	358.6	0.7238
0.4865	0.5135	75K95	705.03	0.7244	607.52	0.7235
0.6002	0.3998	75K96	615.89	0.7240	534.91	0.7231
0.6861	0.3139	75K95	529.56	0.7236	462.47	0.7227
0.7835	0.2165	75K96	467.52	0.7231	410.57	0.7221
0.8999	0.1001	50B831	816.96	0.7225	723.66	0.7215

Table A.2: Raw Kinematic Viscosity and Density Data for the Ternary System: Cyclohexane(1) +*p*-Xylene (2) + Chlororbenzene (3)

Sample Composition			Viscometer number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.0709	0.1054	0.8237	25B349	419.53	0.7663	396.09	0.7652
0.1755	0.5908	0.2337	25B350	435.70	0.7386	411.79	0.7375
0.2668	0.2943	0.4389	25B366	407.55	0.7460	384.74	0.7449
0.3423	0.4897	0.4897	25B349	443.93	0.7475	419.04	0.7463
0.4774	0.1713	0.1713	25B350	468.58	0.7316	441.93	0.7305
0.5271	0.2437	0.2437	25B366	443.03	0.7339	416.99	0.7328
0.6601	0.2515	0.2515	25B350	517.28	0.7323	485.63	0.7312

Table A.2 (Cont'd): Raw Kinematic Viscosity and Density Data for the Ternary System: Cyclohexane(1) +*p*-Xylene (2) + 1-Propanol (3)

Sample Composition			Viscometer number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1271	0.15082	0.7220	50B831	407.86	0.7230	368.01	0.7220
0.2218	0.62924	0.1490	50B159	205.48	0.7274	193.25	0.7264
0.3321	0.3327	0.3351	25B349	561.20	0.7236	520.85	0.7225
0.3904	0.2092	0.4005	50B158	270.31	0.7217	248.60	0.7206
0.4984	0.3917	0.1098	25B349	489.16	0.7232	458.49	0.7221
0.5837	0.2592	0.1571	25B350	538.79	0.7212	502.78	0.7201
0.6588	0.1270	0.2142	25B366	570.82	0.7193	528.33	0.7182

Table A.2 (Cont'd): Raw Kinematic Viscosity and Density Data for the Ternary System: Cyclohexane(1) + *p*-Xylene (2) + 1-Octanol (3)

Sample Composition			Viscometer number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.0807	0.1797	0.7396	100C334	316.65	0.7261	273.38	0.7252
0.1450	0.7033	0.1517	50B158	236.52	0.7288	220.36	0.7278
0.2513	0.3516	0.3970	75K95	228.85	0.7257	207.16	0.7247
0.3157	0.2435	0.4409	75K96	284.89	0.7245	255.56	0.7235
0.3787	0.4818	0.1395	50B159	276.51	0.7254	257.10	0.7243
0.4904	0.3270	0.1826	50B831	317.67	0.7234	293.41	0.7224
0.6105	0.1584	0.2311	50B831	410.54	0.7214	376.53	0.7204

Table A.2 (Cont'd): Raw Kinematic Viscosity and Density Data for the Ternary System: Cyclohexane(1) +chlorobenzene (2) + 1-Propanol (3)

Sample Composition			Viscometer number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.0912	0.2046	0.7042	50B158	379.72	0.7352	341.52	0.7341
0.1520	0.7221	0.1259	25B350	443.95	0.7611	417.77	0.7599
0.2315	0.4377	0.3308	25B366	509.46	0.7461	472.53	0.7449
0.2900	0.2968	0.4132	25B349	634.56	0.7379	586.64	0.7368
0.3500	0.5331	0.1169	25B350	469.45	0.7492	440.93	0.7481
0.4659	0.3817	0.1524	25B350	511.24	0.7402	478.06	0.7390
0.5535	0.2045	0.2419	25B349	594.35	0.7302	550.55	0.7290

Table A.2 (Cont'd): Raw Kinematic Viscosity and Density Data for the Ternary System: Cyclohexane(1) +chlorobenzene (2) + 1-Octanol (3)

Sample Composition			Viscometer number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1398	0.1346	0.7256	100C334	381.18	0.7267	326.33	0.7258
0.2019	0.6303	0.1678	50B158	264.68	0.7519	244.96	0.7508
0.3384	0.3081	0.3535	75K96	236.88	0.7357	213.93	0.7347
0.4073	0.2045	0.3882	75K95	270.01	0.7307	242.37	0.7297
0.4842	0.3963	0.1196	50B158	260.83	0.7394	241.92	0.7382
0.5914	0.2364	0.1722	50B159	363.67	0.7311	334.05	0.7300
0.6526	0.1235	0.2239	50B831	432.58	0.7255	394.01	0.7244

Table A.2 (Cont'd): Raw Kinematic Viscosity and Density Data for the Ternary System: Cyclohexane(1) + 1-Propanol (2) + 1-Octanol (3)

Sample Composition			Viscometer number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1207	0.1786	0.7007	100C335	445.51	0.7240	380.01	0.7231
0.2058	0.6406	0.1536	75K95	327.06	0.7209	289.99	0.7199
0.3280	0.3402	0.3318	75K96	418.56	0.7215	367.17	0.7205
0.3772	0.2298	0.3930	75K95	419.10	0.7217	366.52	0.7206
0.4839	0.3972	0.1189	50B831	503.20	0.7190	451.21	0.7280
0.5706	0.2585	0.1708	75K96	230.77	0.7196	207.25	0.7186
0.6517	0.1552	0.1932	75K95	224.42	0.7193	202.46	0.7183

Table A.2 (Cont'd): Raw Kinematic Viscosity and Density Data for the Ternary System: *p*-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3)

Sample Composition			Viscometer number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1206	0.1507	0.7287	50B158	364.24	0.7340	328.98	0.7329
0.2170	0.6117	0.1712	25B350	448.78	0.7579	421.27	0.7567
0.3344	0.3060	0.3595	25B366	486.34	0.7435	451.35	0.7424
0.4041	0.1949	0.4010	50B159	245.81	0.7381	227.55	0.7371
0.4880	0.3967	0.1153	25B349	435.38	0.7476	408.27	0.7465
0.5817	0.2407	0.1775	25B366	418.36	0.7410	392.74	0.7399
0.6684	0.0946	0.2368	25B350	446.44	0.7347	437.32	0.7337

Table A.2 (Cont'd): Raw Kinematic Viscosity and Density Data for the Ternary System: *p*-Xylene (1) + Chlorobenzene (2) + 1-Octanol (3)

Sample Composition			Viscometer number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1363	0.1504	0.7134	100C336	325.96	0.7311	277.42	0.7301
0.1946	0.6336	0.1718	75K95	127.84	0.7548	109.57	0.7537
0.3259	0.3324	0.3417	75K96	226.55	0.7406	200.33	0.7396
0.3898	0.1964	0.4138	100C335	176.52	0.7362	144.25	0.7352
0.4857	0.3856	0.1287	50B158	251.22	0.7448	225.80	0.7438
0.5699	0.2668	0.1633	50B159	293.36	0.7407	274.63	0.7397
0.6684	0.1071	0.2245	50B831	318.73	0.7343	297.11	0.7333

Table A.2 (Cont'd): Raw Kinematic Viscosity and Density Data for the Ternary System: *p*-Xylene (1) + 1-Propanol (2) + 1-Octanol (3)

Sample Composition			Viscometer number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.0867	0.1798	0.7334	100C336	431.05	0.7258	369.14	0.7249
0.1975	0.6546	0.1479	50B158	570.21	0.7254	520.54	0.7245
0.3011	0.3620	0.3369	75K95	363.36	0.7269	320.17	0.7259
0.3701	0.2349	0.3949	75K96	388.51	0.7276	346.02	0.7266
0.4567	0.4249	0.1184	50B159	421.51	0.7280	369.01	0.7270
0.5535	0.2717	0.1748	50B831	422.02	0.7289	373.73	0.7278
0.6226	0.1627	0.2147	50B158	408.22	0.7294	413.10	0.7284

Table A.2 (Cont'd): Raw Kinematic Viscosity and Density Data for the Ternary System: Chlorobenzene (1) + 1-Propanol (2) + 1-Octanol (3)

Sample Composition			Viscometer number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3		Efflux time (s)	Oscillation period (s)	Efflux time (s)	Oscillation period (s)
0.1178	0.1662	0.7160	100C336	437.47	0.7263	373.63	0.7255
0.1954	0.6522	0.1523	50B159	699.93	0.7338	624.27	0.7328
0.3062	0.3580	0.3358	75K95	356.88	0.7378	318.45	0.7368
0.4071	0.2278	0.3652	75K96	347.63	0.7409	313.85	0.7399
0.47248	0.4157	0.1118	50B831	375.97	0.7482	351.95	0.7471
0.5606	0.2743	0.1651	50B158	391.56	0.7513	352.29	0.7502
0.6408	0.1437	0.2155	75K95	208.69	0.7530	194.85	0.7519

Table A.3: Viscosity and Density Data for the Quaternary System: Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4)

Sample Composition				Viscometer Number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3	X_4		Efflux Time (s)	Oscillation Period (s)	Efflux Time (s)	Oscillation Period (s)
0.1302	0.0863	0.1037	0.6798	50B158	361.23	0.7290	330.83	0.7279
0.2581	0.2077	0.2406	0.2936	25B349	527.85	0.7363	490.72	0.7352
0.2887	0.1772	0.0571	0.4770	50B159	308.08	0.7255	282.15	0.7244
0.1678	0.2600	0.3975	0.1746	25B366	428.90	0.7450	402.45	0.7438
0.2518	0.2703	0.0924	0.3855	50B831	251.29	0.7288	232.39	0.7277
0.4892	0.1409	0.2662	0.1037	25B350	496.07	0.7348	464.45	0.7336

Table A.3 (Cont'd): Viscosity and Density Data for the Quaternary System: Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Octanol (4)

Sample Composition				**Viscometer Number**	**T=293.15 K**		**T=298.15 K**	
X_1	**X_2**	**X_3**	**X_4**		**Efflux Time (s)**	**Oscillation Period (s)**	**Efflux Time (s)**	**Oscillation Period (s)**
0.1230	0.1026	0.0920	0.6824	100C336	301.27	0.7282	261.57	0.7272
0.2265	0.2358	0.2554	0.2822	50B159	355.02	0.7346	325.82	0.7336
0.2830	0.2048	0.0677	0.4444	75K95	276.33	0.7273	248.49	0.7263
0.1415	0.2843	0.4313	0.2438	50B159	264.64	0.7440	245.56	0.7429
0.2403	0.2827	0.1051	0.3719	75K96	220.37	0.7296	199.42	0.7286
0.4500	0.1524	0.2838	0.1138	50B831	264.05	0.7355	245.04	0.7344

Table A.3 (Cont'd): Viscosity and Density Data for the Quaternary System: Cyclohexane (1) + *p*-Xylene (2) + 1-Propanol (3) + 1-Octanol (4)

Sample Composition				Viscometer Number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3	X_4		Efflux Time (s)	Oscillation Period (s)	Efflux Time (s)	Oscillation Period (s)
0.1208	0.0694	0.1543	0.6555	100C336	350.59	0.7248	301.20	0.7239
0.2241	0.2198	0.2755	0.2805	50B158	519.72	0.7243	465.94	0.7233
0.3113	0.1708	0.0852	0.4326	75K95	302.22	0.7240	269.42	0.7230
0.1670	0.2680	0.4360	0.1290	50B159	423.47	0.7247	383.21	0.7237
0.2868	0.2539	0.1170	0.3424	75K96	245.29	0.7245	220.76	0.7235
0.4655	0.1411	0.2943	0.0990	50B831	362.28	0.7211	330.33	0.7201

Table A.3 (Cont'd): Viscosity and Density Data for the Quaternary System: Cyclohexane (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)

Sample Composition				Viscometer Number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3	X_4		Efflux Time (s)	Oscillation Period (s)	Efflux Time (s)	Oscillation Period (s)
0.1538	0.0998	0.1370	0.6093	100C336	320.15	0.7281	276.18	0.7271
0.2551	0.2369	0.2802	0.2278	50B158	483.79	0.7334	433.95	0.7324
0.3156	0.1777	0.0936	0.4130	75K95	330.28	0.7304	292.21	0.7294
0.1678	0.2626	0.4623	0.1072	50B831	414.32	0.7366	374.33	0.7356
0.2658	0.2767	0.1330	0.3245	75K96	252.85	0.7348	226.89	0.7338
0.4698	0.1504	0.3049	0.0749	50B159	365.23	0.7278	333.35	0.7267

Table A.3 (Cont'd): Viscosity and Density Data for the Quaternary System: *p*-Xylene (1) + Chlorobenzene (2) + 1-Propanol (3) + 1-Octanol (4)

Sample Composition				Viscometer Number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3	X_4		Efflux Time (s)	Oscillation Period (s)	Efflux Time (s)	Oscillation Period (s)
0.1233	0.1293	0.1428	0.6046	100C336	282.41	0.7293	245.07	0.7284
0.2438	0.2312	0.2862	0.2389	50B158	411.82	0.7372	371.82	0.7361
0.2843	0.2128	0.0862	0.4167	75K95	272.44	0.7371	243.08	0.7360
0.1465	0.2702	0.4670	0.1167	50B159	402.97	0.7396	364.58	0.7385
0.2524	0.2673	0.1170	0.3632	75K96	233.69	0.7370	210.04	0.7361
0.4497	0.1346	0.3249	0.0908	50B831	281.28	0.7348	259.01	0.7337

Table A.4: Viscosity and Density Data for the Quinary System: Cyclohexane (1) + *p*-Xylene (2) + Chlorobenzene (3) + 1-Propanol (4) + 1-Octanol (5)

Sample Composition					Viscometer Number	T=293.15 K		T=298.15 K	
X_1	X_2	X_3	X_4	X_5		Efflux Time (s)	Oscillation Period (s)	Efflux Time (s)	Oscillation Period (s)
0.1438	0.2599	0.2557	0.1932	0.1474	75K95	137.19	0.7376	126.52	0.7366
0.1373	0.1271	0.2624	0.1152	0.3578	50B158	512.47	0.7360	460.05	0.7349
0.2205	0.1614	0.2664	0.0761	0.2756	75K96	190.12	0.7363	173.03	0.7352
0.2767	0.2521	0.1620	0.1865	0.1226	50B158	280.45	0.7319	258.88	0.7308
0.1534	0.3018	0.2093	0.3102	0.0251	50B159	250.97	0.7362	233.07	0.7351

APPENDIX B

Estimated Experimental Error

B.1 Density Measurement

The equation employed with the density meter for calculating the density of the liquid systems is:

$$\rho = \frac{A\tau^2}{1 - B\tau^2} - C \qquad \text{(B.1)}$$

The differential of equation (B.1) is applied to determine the maximum error of the density values. The differential equation with respect to the parameter τ is given by:

$$d\rho = \frac{2A\tau}{(1 - B\tau^2)^2} d\tau \qquad \text{(B.2)}$$

The maximum fluctuation in density meter is 1x10^{-5} second which is substitute in equation (B.2) as the value of $d\tau$ in equation (B.2). The value of τ is the maximum oscillation value obtained for pure component chlorobenzene equals 0.775881 at 293.15 K. The calibration constants value, A and B, substitute in equation (B.2) and the maximum predicted error is calculated as:

$$d\rho = \frac{2(3.6558)(0.775881)}{(1 - (.0186358 \times (0.775881)^2)^2} \times 1 \times 10^{-5} \qquad \text{(B.3)}$$

B. Viscosity Measurements

The equation used with the viscometer is given by:

$$\nu = Et - \frac{F}{t^2} \qquad \text{(B.4)}$$

Differentiating equation (B.3) with respect to the efflux time t, is:

$$d\nu = \left(E + \frac{F}{3t^3} \right) dt \tag{B.5}$$

The efflux time for each sample were calculated by taking the average of three measurements where the error in measuring did not exceed *0.1%*. Therefore the value of *dt* is set as 1% in order to determine the maximum error in the kinematic viscosity for each viscometer used.

Table B.1: The Maximum Predicted Error in the Measurement of the Kinematic Viscosity for Each Viscometer.

Viscometer No.	Temperature (K)	E x 10^9	F x 10^6	Maximum Efflux Time (s)	Maximum dν x 10^9
25B349	293.15	1.7699	434.7038	703.16	0.18
25B350	293.15	1.7535	226.0841	715.39	0.18
25B366	293.15	1.9037	734.8307	664.51	0.19
50B158	293.15	4.3520	243.3126	635.58	0.43
50B159	293.15	3.9386	246.8112	701.89	0.39
50B831	293.15	4.0933	1.2681	672.19	0.41
75K95	293.15	9.2671	1219.29	705.03	0.93
75K96	293.15	9.0045	2573.552	615.89	0.90
100C334	293.15	16.7546	781.6485	482.61	1.67
100C335	293.15	14.7091	655.4209	676.06	1.47
100C336	293.15	17.2850	614.2307	631.73	1.73

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