

Aromatic Compounds and Ester Polymeric Solvents Interactions

Edison Muzenda

Abstract—This work focused on the interactions that occur between ester polymeric solvents and simple aromatic volatile organic compounds (VOCs). Solutes were selected from various functional groups in their simplest form and computations of infinite dilution activity coefficients were performed using the Modified UNIFAC Dortmund group contribution model using a Microsoft Excel spreadsheet designed for this purpose. For polar aromatic VOCs, solubility decreased with increase in size of the ester solvent molecule and the opposite behavior was observed for non-polar VOCs. For all aromatic - ester solvent interactions, solubility increased with the increase in the degree of ester unsaturation.

Keywords—Activity coefficients, aromatic compounds, esters, solubility, van der Waals.

I. INTRODUCTION

THE release of volatile organic compounds (VOCs) into the atmosphere needs to be avoided at all costs where possible in order to limit the effect of these compounds on humans and the environment. Of the VOC abatement technologies available for treatment of industrial end-of-pipe emissions, physical absorption has shown to be particularly useful especially when the process is efficiently designed and profitable.

One area of particular concern in absorber design is finding a thermodynamically favourable absorbent, and thus a thorough understanding of solvent-solute interactions is required. Not all VOCs are soluble in water – thus suitable organic solvents are required. There is an increasing drive internationally for the use of ‘green’ solvents to replace traditional organic solvents. Biodiesel, which is a mixture of fatty acid esters, has been reported to possess all the properties of a good solvent and most importantly it is environmentally friendly [1], [2].

Another area of concern is ensuring that accurate thermodynamic data is selected to model the absorption process. Since VOCs are present in very dilute concentrations in the gaseous waste stream, it is essential to obtain phase equilibrium data in the very dilute region [3]. Measurements are laborious, expensive and time-consuming. Hence, the prediction of thermodynamic data such as activity coefficients

using group contribution methods is preferred for preliminary design and feasibility studies. Activity coefficients are important parameters in the computation of phase equilibrium data for absorption systems.

This work is a continuation of our focus on the use of biodiesel as a suitable solvent for the abatement of volatile organic compounds through physical absorption. The Modified UNIFAC Dortmund group contribution model of Weidlich and Gmehling [4] was selected to compute the required activity coefficient values using a Microsoft Excel spreadsheet designed for this purpose. The phase equilibrium fundamentals, the modified UNIFAC Dortmund group contribution method, relevant previous studies of interest, computational procedure as well as solvent and thermodynamic model selection have been previously discussed [4]–[8].

II. RESULTS & DISCUSSION

Infinite dilution activity coefficients were predicted for 12 aromatic compounds in 12 various methyl esters at 30°C. This temperature lies within a range which is considered practical for most absorption operations [1]. A mole fraction of 1×10^{-5} was chosen to represent infinite dilution conditions as recommended by Alessi *et al* [3]. The notation described by Van Gerpen *et al* [9] was adopted to describe the characteristics of the ester solvent chain, with the prefix ‘1-’ being used to identify the solvent as a methyl ester.

A. Overview

Table I shows the infinite dilution activity coefficient data of various aromatic solute/ saturated ester solvent interactions. The twelve aromatic compounds selected represent the simplest form of various functional groups. Table II represents infinite dilution activity coefficients of the same aromatic volatile organic compounds in monounsaturated and polyunsaturated esters. For ease of reference, the work is subdivided into three sections, namely polar, non-polar and miscellaneous aromatic compounds.

E. Muzenda is is a Professor of Chemical Engineering, Department of Chemical of Chemical Engineering as well as part-time Energy and Environmental Engineering Specialist and Consultant at the Process, Energy and Environmental Technology Station, Faculty of Engineering and the Built Environment, University of Johannesburg, Doornfontein, Johannesburg 2028, Tel: +27115596817, Fax: +27115596430, (Email: emuzenda@uj.ac.za).

TABLE I
INTERACTIONS BETWEEN ESTER SOLVENTS WITH SATURATED HYDROCARBON TAILS AND AROMATIC SOLUTES

		Activity Coefficients - Aromatic Solute/ Saturated Ester Interactions											
Ester Solvent	Designation	Aceto-phenone	Aniline	Anisole	Benzaldehyde	Benzoic Acid	Benzonitrile	Chlorobenzene	Ethynylbenzene	Phenol	Phenyl Acetate	Styrene	Toluene
M. Butyrate	1-C4:0	2.056	1.029	0.683	3.386	2.077	1.356	0.921	0.945	0.241	1.468	1.132	1.188
M. Caproate	1-C6:0	1.724	1.071	0.607	2.329	2.253	1.223	0.749	0.911	0.298	1.528	0.931	0.947
M. Octanoate	1-C8:0	1.627	1.179	0.608	1.927	2.507	1.233	0.678	0.930	0.368	1.653	0.854	0.842
M. Decanoate	1-C10:0	1.593	1.300	0.628	1.717	2.760	1.280	0.637	0.959	0.443	1.779	0.813	0.779
M. Laurate	1-C12:0	1.579	1.419	0.652	1.585	2.988	1.335	0.610	0.985	0.519	1.890	0.786	0.736
M. Myristate	1-C14:0	1.570	1.530	0.674	1.491	3.186	1.391	0.588	1.007	0.593	1.984	0.765	0.702
M. Palmitate	1-C16:0	1.563	1.631	0.694	1.418	3.355	1.442	0.570	1.023	0.665	2.061	0.747	0.674
M. Stearate	1-C18:0	1.554	1.723	0.710	1.358	3.496	1.487	0.554	1.035	0.733	2.122	0.731	0.650
M. Arachidate	1-C20:0	1.543	1.804	0.724	1.307	3.612	1.526	0.540	1.042	0.799	2.170	0.716	0.628

TABLE II
INTERACTIONS BETWEEN ESTER SOLVENTS WITH UNSATURATED HYDROCARBON TAILS AND AROMATIC SOLUTES

		Activity Coefficients - Aromatic Solute/ Unsaturated Ester Interactions											
Ester Solvent	Designation	Aceto-phenone	Aniline	Anisole	Benzaldehyde	Benzoic Acid	Benzonitrile	Chlorobenzene	Ethynylbenzene	Phenol	Phenyl Acetate	Styrene	Toluene
M. Stearate	1-C18:0	1.554	1.723	0.710	1.358	3.496	1.487	0.554	1.035	0.733	2.122	0.731	0.650
M. Oleate	1-C18:1	1.441	1.602	0.687	1.255	2.886	1.315	0.534	0.933	0.691	1.881	0.707	0.643
M. Linoleate	1-C18:2	1.349	1.501	0.673	1.170	2.458	1.182	0.518	0.861	0.656	1.690	0.692	0.641
M. Linolenate	1-C18:3	1.275	1.416	0.667	1.100	2.145	1.077	0.506	0.811	0.627	1.539	0.683	0.643

B. Polar aromatic solutes

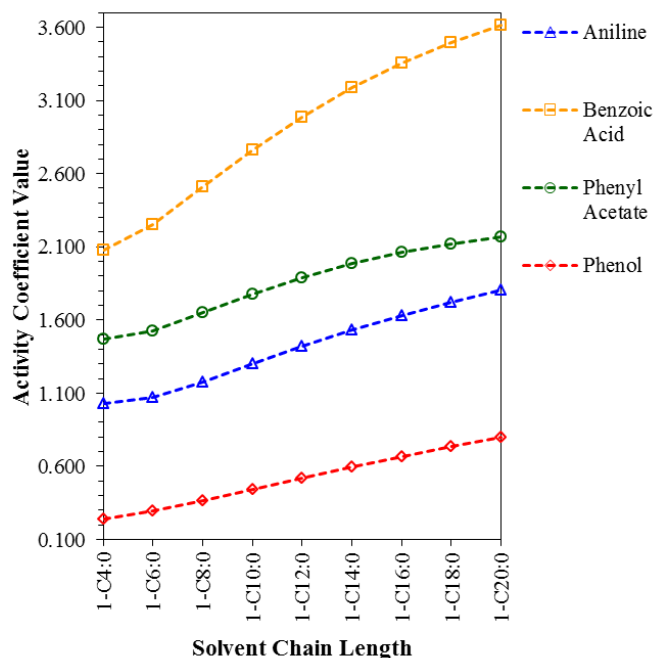


Fig. 1 Interactions between polar aromatic solutes and saturated ester solvents.

Four polar aromatic solutes with the ability to hydrogen-bond with other polar solutes were studied. Activity coefficients increased with an increase in the solvent chain length. Fig. 1. This behavior can be explained as follows – in addition to London dispersion forces and dipole-dipole interactions, esters are capable of hydrogen bonding. This is attributed to the lone electron pairs on the oxygen atoms in the ester chain. Esters do not contain hydrogen atoms attached to the electronegative oxygen atoms and can therefore only act as hydrogen bond (H-bond) acceptors. Thus one of the slightly positive hydrogen atoms contained in each of the above solutes (which can act both as H-bond donors and as H-bond acceptors) can be attracted to one of the lone pairs on one of the oxygen atoms in an ester for a hydrogen bond to be formed. The energy released in these attractions provides the energy required to separate solute molecule from solute molecule and ester molecule from ester molecule to allow mixing. However an increase in ester chain length results in an increase in interference from the non-polar hydrocarbon part of the ester molecules. These chains force themselves between the polar solutes, thereby breaking the hydrogen bonds. The greater the length of the ester hydrocarbon tail, the more evident the above effect becomes, hence the increase in insolubility of the solute with increased solvent chain length.

Phenol was the most soluble of the four solutes. This is mainly because one of the lone pairs of electrons of the oxygen

atom are delocalized across the benzene ring, thereby reducing the polarity of the –OH group. This reduction in the polarity of the hydroxyl group allows phenol to be very miscible with the predominantly non-polar esters. The same principle applies for aniline where the single lone electron pair is delocalized across the benzene ring. This accounts for the relative solubility of aniline in the ester solvents in relation to benzoic acid and phenyl acetate. These two compounds contain two oxygen molecules in their functional groups, making them strongly polar as these molecules possess high dipole moments. These molecules are more soluble in polar solvents such as the alcohol and ether groups.

C. Non-polar aromatic compounds

Fig.2 shows the solubility of relatively non-polar aromatic solutes in the ester solvents studied.

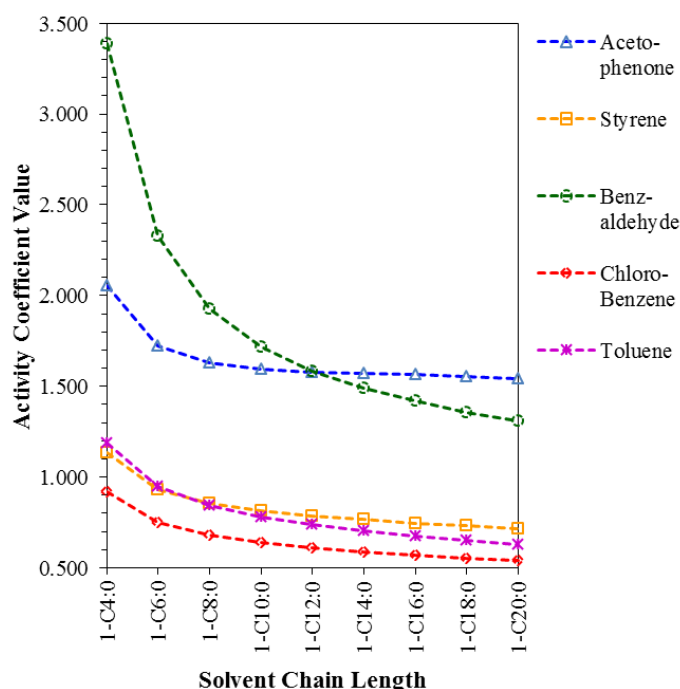


Fig. 2 Interactions between non-polar aromatic solutes and saturated ester solvents.

It is evident that, unlike the polar solvents, these solute-solvent interactions display an increase in solubility with an increase in solvent chain length. This can be attributed to an increase in the attractive London dispersion forces with an increase in solvent molecule size, since hydrogen bonding is absent in these interactions and dipole-induced dipole interactions would remain more or less constant.

Chlorobenzene is the most soluble of the five solutes. As with phenol and aniline, there is an interaction between the delocalized electrons in the benzene ring and one of the lone electron pairs on the chlorine atom creating an overlap. This results in a movement of electrons away from the chlorine towards the benzene ring. Whilst chlorine is itself quite electronegative, the polarity of the chlorine-carbon bond is

much reduced by the delocalization.

Whilst acetophenone and benzaldehyde can partake in hydrogen bonding in that they have electronegative oxygen atoms, they have no hydrogen bonded to an electronegative atom and can only act as H-bond acceptors. Since the ester solvents are also only H-bond acceptors, no hydrogen bonding can take place and thus the only van der Waals forces dominating in these interactions are London dispersion forces and attractive dipole - induced dipole forces. Both these molecules will possess a high dipole moment due to the presence of their highly electronegative polar oxygen atom. The effect of these molecules' ability to polarize the solvent molecules does however decrease with increasing ester chain length due to the increase in strength of the dispersion forces. It should be mentioned however that these two molecules are much less miscible than the other three aromatic solutes in non-polar ester solvents due to the high polarity of these solutes.

D. Miscellaneous aromatic compounds

The solubility of anisole, benzonitrile and ethynylbenzene is described in Fig.3.

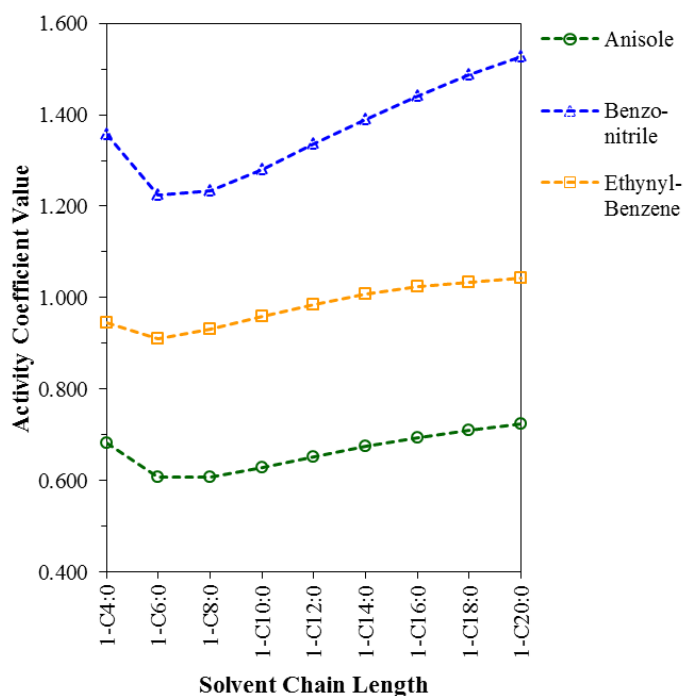


Fig. 3 Interactions between miscellaneous aromatic solutes and saturated ester solvents.

It can be seen from Fig.3 that all three solute-solvent interactions experienced a marked decrease in activity coefficients followed by an increase in activity coefficients with increasing solvent chain length. It is presumed that the initially high activity coefficients could be attributed to the small size of the methyl butyrate solvent. Being small, it is possible that the methyl butyrate molecule would find it difficult to orientate itself in such a way that a strong mutual

attraction could take place between itself and the predominantly linear solvents. This is especially true if one considers the weak London forces the solvent molecule would possess. Methyl caproate on the other hand possesses a large enough London force to cause a more significant dipole-induced dipole to occur between the solvent and solute molecules. Since the solute molecules are all linear in nature, it is assumed that the increase in activity coefficients is due to the increased difficulty in aligning themselves with increasing solvent chain lengths for maximum bond interactions to occur. In other words, the longer the solvent chain length, the more loosely the solutes will arrange themselves with the solvent molecules.

Anisole was the most soluble of the three molecules in the ester solvents. Its alkane tail allows for miscibility in non-polar solvents even though its electronegative oxygen atom allows for miscibility in polar solvents (it is an H-bond acceptor). The miscibility of anisole in non-polar solvents is attributed to the shielding effect afforded to the oxygen atom by the alkyl and aryl groups. Benzonitrile, on the other hand, was the least soluble due to the high polarity exerted by the unshielded lone nitrogen electron pairs, which can facilitate hydrogen bonding.

E. Interactions between unsaturated esters and aromatic solutes

Thermodynamic interactions for unsaturated ester solvents and aromatic solutes are shown in Fig.4, 5 and 6.

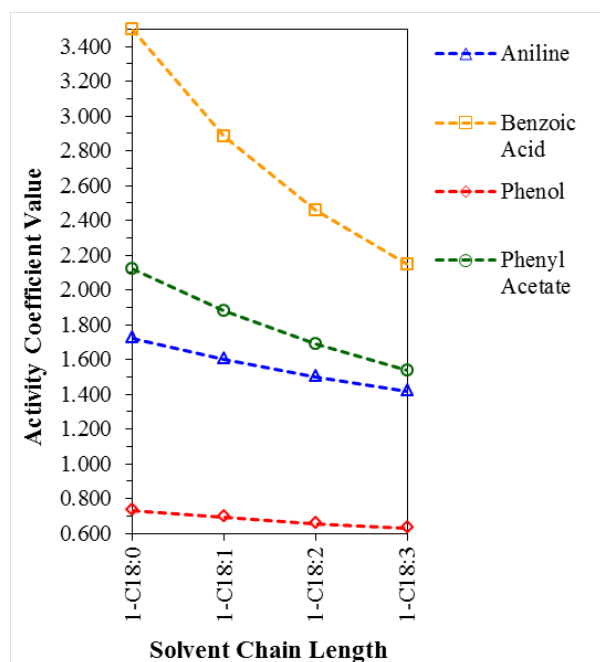


Fig. 4 Interactions between unsaturated esters and polar aromatic compounds

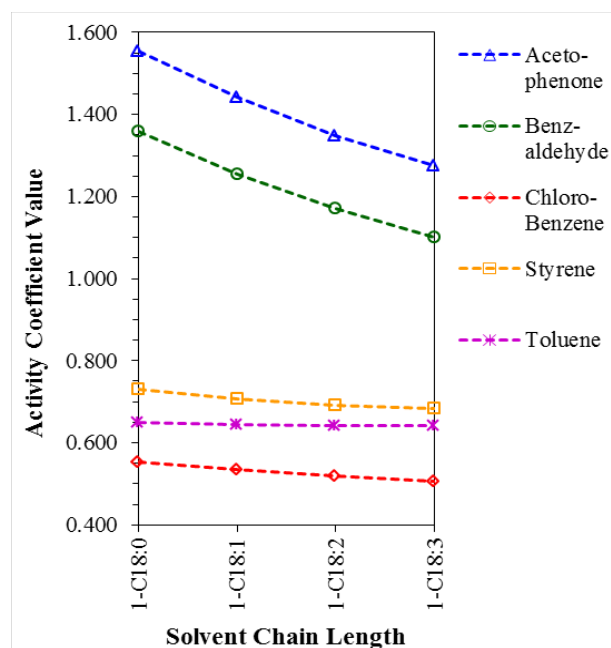


Fig. 5 Interactions between unsaturated esters and non-polar aromatic compounds

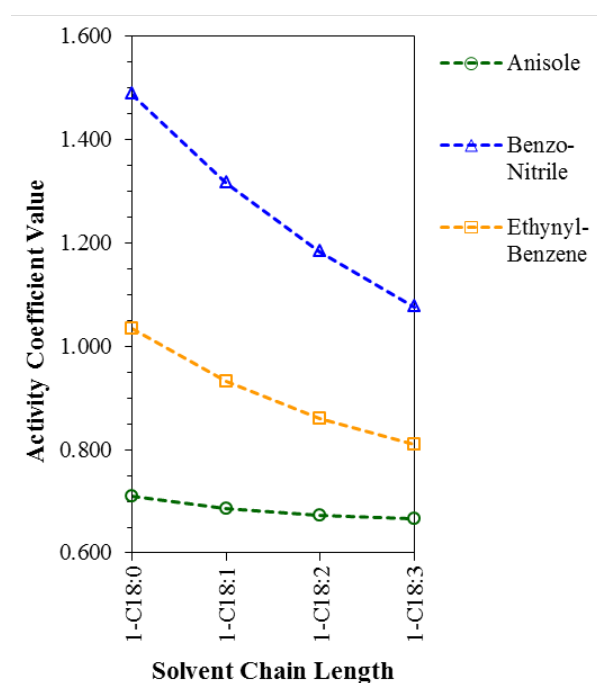


Fig. 6 Interactions between unsaturated esters and miscellaneous aromatic compounds

All of the ester/ aromatic interactions experienced a decrease in activity coefficient with an increase in the degree of solvent unsaturation. This was not the case with the alkanes and alkenes studied [6]–[8], where an increase in activity coefficient was experienced with an increase in solvent unsaturation. The latter case is the more likely behavior because the more closely packed the solute and solvent are, the better the van der Waals interactions. Saturated solvents are

much straighter than the unsaturated solvents, which leads to closer packing. The fact that aromatic compounds are more soluble in increasingly unsaturated ester solvents could perhaps be attributed to an increase in the freedom to move around in a more loosely packed solvent structure. This freedom of movement would allow the aromatic molecules to rearrange themselves in such a way as to experience maximum van der Waals interactions, especially since the benzene ring is planar in structure.

ACKNOWLEDGMENT

The author is very grateful to the University of Johannesburg's Research Committee for financial and technical support.

REFERENCES

- [1] K. Bay, H. Wanko, and J. Ulrich, "Absorption of Volatile Organic Compounds in Biodiesel: Determination of Infinite Dilution Activity Coefficients by Headspace Gas Chromatography," *Chem. Eng. Res. Des.*, vol. 84, no. A1, pp. 22–27, Jan. 2006.
- [2] K. Bay, H. Wanko, and J. Ulrich, "Biodiesel - Hoch Siedendes Absorbens für die Gasreinigung," *Chemie Ingenieur Technik*, vol. 76, no. 3, pp. 328–333, Mar. 2004.
- [3] P. Alessi, M. Fermeglia, and I. Kikic, "Significance of Dilute Regions," *Fluid Phase Equilibria*, vol. 70, no.2-3, pp. 239 – 250, Dec. 1991.
- [4] U. Weidlich and J. Gmehling, "A Modified UNIFAC Model. 1. Prediction of VLE, hE, and γ^∞ ," *Ind. Eng. Chem. Res.*, vol. 26, no. 7, pp. 1372–1381, Jul. 1987.
- [5] J. J Scheepers, E. Muzenda, and M Belaid, "Influence of Temperature and Molecular Structure on Organics-Biodiesel Interactions using Group Contribution Methods", The 2012 International Conference of Manufacturing Engineering and Engineering Management, *World Congress on Engineering 2012*, IAENG, London, UK, 4-6 July 2012.
- [6] J.J. Scheepers, E. Muzenda, and M. Belaid, "Influence of Structure on Fatty Acid Ester-Alkane Interactions," in *Internat. Conf Proc. PSRC Internat. Conf. Educ. Humanities. Chemical. Environ. Sciences*, Bangkok, Sept. 2012, pp. 93–102.
- [7] J.J Scheepers and E Muzenda, "Alkenes – ester polymeric solvents thermodynamic interactions – Part 1" International Conference on Ecology, Agriculture and Chemical Engineering,, in *International Conference Proceedings of the Planetary Scientific Research Centre*, Thailand, Phuket, 18-19 Dec. 2012, pp. 229-232.
- [8] J.J Scheepers, E Muzenda, and M. Belaid, "Alkenes – ester polymeric solvents thermodynamic interactions – Part 2" International conference on Nanotechnology and Chemical Engineering, in *International Conference Proceedings of the Planetary Scientific Research Centre*, Thailand, Bangkok, 21-22 Dec. 2012, pp. 54-57.
- [9] J. van Gerpen, B. Shanks, R. Pruszko, D. Clements, and G. Knothe, "Biodiesel Production Technology: August 2002–January 2004," National Renewable Energy Laboratory (NREL), Colorado, Subcontractor Report July 2004, p. 2.