Polarizable continuum solvation model analysis of halogen substituted 6-nitropyridines

S Mahalakshmi[a], R Raj Mohamed[b], V Kannappan[c*] & V Sathyanarayanamoorthi[d]

[a]Department of Physics, Aarupadai Veedu Institute of Technology, Chennai 603 104

[b]Post Graduate and Research Department of Physics, Jamal Mohamed College, Tiruchirapalli 620 020

[c]Post Graduate and Research Department of Chemistry, Presidency College, Chennai 600 005

[d]Post Graduate and Research Department of Physics, P S G College of Arts and Science, Coimbatore 641 014

*E-mail:vkannappan48@gmail.com

The conductor-like Polarizable Continuum Solvation Model (C-PCM) is applied to industrially important two halogen substituted pyridine derivatives, namely 2-chloro-6-nitropyridine and 2-bromo-6-nitropyridine in ten solvents with wide range of dielectric constants. The physical properties of the systems, such as free energies of solution, electrostatic interaction, dispersive energies, repulsive energies, dipole moments (μ) and first hyperpolarizability (β) of solute in pure state and in the presence of solvents are computed and discussed for these systems.

Keywords: PCM solvation analysis, 2-Chloro-6-nitropyridine, 2-Bromo-6-nitropyridine

1 Introduction

The nitrogen containing heterocyclic aromatic ring systems such as pyridines and pyrimidine derivatives are of biological importance as they are constituents of DNA and RNA and they play key role in the structure and properties of nucleic acids[1]. Pyridine ring system is present in several natural products, pharmaceutical and agrochemical compounds[2]. The two important pyridine containing vitamins, nicotinamide and pyridoxine are required for the biosynthesis of nicotinamide adenine dinucleotide phosphate (NADP+) and pyridoxal phosphate (PLP), respectively. In the past four decades, several organic substances have been used as corrosion inhibitors in steel industry. Of these, heterocyclic compounds containing one or more N, O or S atoms influence the inhibition of corrosion rate in aqueous acidic solutions of metals[3]. The significant criteria involved in the selection of inhibitors are hydrophobicity, molecular structure and electron density of the donor atoms, solubility and ability to disperse in solution[4,5]. Pyridine derivatives were found to be effective and efficient corrosion inhibitors for steel. The main aim of the present investigation is to study the solvation analysis of the two selected halo pyridine molecules. We have made an attempt to establish the theoretical property that contributes significantly for solvation in different solvents and hence responsible for inhibition of corrosion. Implicit solvation models are widely used to predict a variety of solvent effects including: Gibbs energy of solution, solubility and vapour pressure. In industrial, environmental and pharmacological applications, these properties are required over a range of temperatures. However, almost all implicit solvation models have been designed or tested only for predicting these quantities at room temperature[6-9].

2 Methodologies: Computational Details

Theoretical calculations have been carried out at the *ab-initio* level[10-12] on the two substituted pyridine molecules. In the present study, molecular geometry, optimized parameters are computed and the performance of the computational method for B3LYP at 6-31+G (d,p) basis set[13] has been studied. Solvation analysis is done using a wide range of solvents, which has been performed both in the pure state and media of different dielectric constants using Conductor-like Polarized Continuum Model (C-PCM) by GTO-6-31+G (d,p) basis set to interpret the solvent effect of the molecules. The modeling of water, methanol, ethanol, acetone, dichloromethane, chlorobenzene, chloroform, toluene, benzene, and carbon tetrachloride are considered as solvents in this study through the use of dielectric constants 78.35, 32.63, 24.85, 20.49, 8.93, 5.62, 4.90, 2.37, 2.27 and 2.23, respectively for the above mentioned solvents. The optimized structures of the two pyridine molecules are shown in Fig. 1.
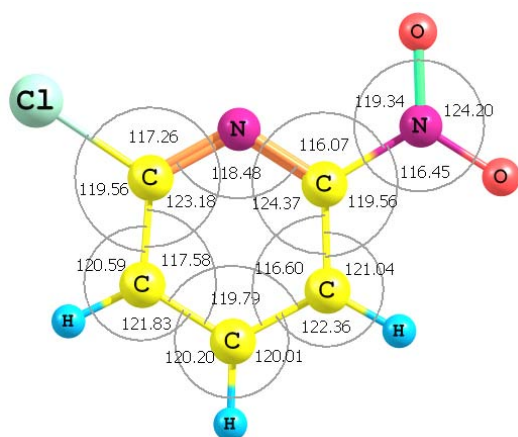
(a) 2-chloro-6-nitropyridine
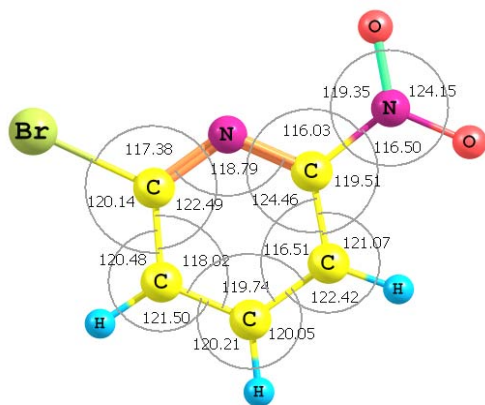
(b) 2-bromo-6-nitropyridine

Fig. 1 — Optimized structures of halogen substituted
(a) halo 2-chloro-6-nitropyridine and (b) 2-bromo-6-nitropyridine

3 Results and Discussion

Gibbs free energy of solvation is an important parameter among solution properties. It gives an idea about the solute–solvent interaction and it can be related to the work which necessarily builds up a solute in the solvent environment. Table 1 contains the list of solvent descriptors. Free energy of solution is computed by C-PCM method for the two substituted pyridines in different solvents. The computed free energies of solvation and its components of the two pyridine derivatives are listed in Tables 2 and 3. The data show how the different characteristics of each solvent affect the free energy of solvation of the two selected molecules. The free energy of solvation is the algebraic sum of the electrostatic interaction, gravitational energy, dispersion energy and repulsion energy. The electrostatic contribution to the free energies of solution depends partly on the dielectric constant of

Table 1 — Solvent Descriptors at 298 K

Solvent	ε	η	γ	$\alpha^`$	B
H_2O	78.35	1.33	71.99	0.82	0.35
CH_3OH	32.63	1.33	22.12	0.43	0.47
C_2H_5OH	24.85	1.36	31.62	0.37	0.48
Acetone	20.49	1.36	33.77	0.04	0.49
CH_2Cl_2	8.93	1.37	27.33	0.10	0.05
C_6H_5Cl	5.62	1.52	32.69	0	0.17
$CHCl_3$	4.90	1.45	26.53	0.15	0.02
$C_6H_5 CH_3$	2.37	1.50	40.20	0	0.14
C_6H_6	2.27	1.50	40.62	0	0.14
CCl_4	2.23	1.46	38.04	0	0

E is the dielectric constant at 298 K, n the index of refraction at optical frequencies at 298 K, γ the macroscopic surface tension at a liquid-air interface. $\alpha^`$ the Abraham's hydrogen bond acidity and b is the Abraham's hydrogen bond basicity acidity.

Table 2 — Free energy of solution and its components of 2-chloro-6-nitro pyridine at 298 K

Solvent of solution	Electrostatic Interaction kJ mole^{-1}	Dispersive energy kJ mole^{-1}	Repulsive energy kJ mole^{-1}	Free energy kJ mole^{-1}
H_2O	−64.18	−131.68	124.06	−71.52
CH_3OH	−61.53	−132.77	56.84	−137.62
C_2H_5OH	−60.45	−130.46	39.33	−161.29
Acetone	−59.86	−139.24	28.56	−171.24
CH_2Cl_2	−53.88	−143.14	35.78	−162.28
C_6H_5Cl	−47.96	−172.21	23.66	−205.96
$CHCl_3$	−46.02	−161.08	28.65	−179.82
$C_6H_5 CH_3$	−30.03	−168.54	21.34	−181.97
C_6H_6	−28.23	−168.34	25.61	−171.85
CCl_4	−27.98	−163.46	23.72	−169.08

Table 3 — Free energy of solution and its components of 2-bromo-6-nitro pyridine at 298 K

Solvent of solution	Electrostatic Interaction kJ mole^{-1}	Dispersive energy kJ mole^{-1}	Repulsive energy kJ mole^{-1}	Free energy kJ mole^{-1}
H_2O	−63.12	−134.43	188.24	−10.44
CH_3OH	−60.26	−133.86	87.36	−107.86
C_2H_5OH	−59.86	−141.66	60.96	−140.55
Acetone	−58.04	−141.74	44.55	−155.78
CH_2Cl_2	−52.38	−145.48	55.48	−143.24
C_6H_5Cl	−46.74	−175.14	37.06	−185.78
$CHCl_3$	−44.69	−163.86	44.68	−164.96
$C_6H_5 CH_3$	−29.04	−171.24	33.57	−167.46
C_6H_6	−27.44	−170.95	39.88	−159.44
CCl_4	−27.27	−166.13	36.96	−157.38

the solvent. The electrostatic contribution to the free energy of the solution increases with increase in the dielectric constant of the medium[15,16]. By comparing the electrostatic contribution values in different media, it is found that the electrostatic contribution is the least in CCl_4 which has a dielectric constant value of 2.23 while it is the highest in water which has a

dielectric constant of 78.35. The plot of electrostatic interaction energy against dielectric constant is shown in Fig. 2. The curve in this plot indicates that the electrostatic interaction energy is influenced by the dielectric constant. It may be pointed out here that the electrostatic contribution to the solution free energy in a given medium is higher for 2-chloro 6-nitro pyridine as compared to that of 2-bromo 6-nitro pyridine. This may be due to greater polarizability of bromine than chlorine which can be ascribed to the larger size of bromine atom. Increase in polarizability increases covalent character in the molecule. If we compare the free energy of solution of the molecules studied here in chlorinated solvents, dichloromethane provides less favourable free energy, which may be due to higher dielectric constant of solvent and hence, more negative electrostatic energy contribution. The free energy of solution of a substance in a solvent is a balance between the solvent – solute dispersive interactions and least macroscopic surface tension of the solvent molecule. Since the macroscopic surface tension of a particular solvent represents the energy required to make a surface in the solvent, a contribution to the free energy of solution is always unfavorable in a solvent of low surface tension.

Among the chlorinated solvents, the free energy of solution for the investigated molecules are higher in chlorobenzene. This may be due to smaller surface tension of this solvent and consequently higher dispersive energy. Since the free energy of solution in this solvent is more, the metallic iron can easily be corroded in chlorobenzene than in other chlorinated solvents. It may be pointed out that the free energy of solution of both the pyridine molecules which acts as corrosion inhibitors for iron, the feasibility of corrosion is easier in chlorobenzene. On the other hand, the free energy of solution of both the
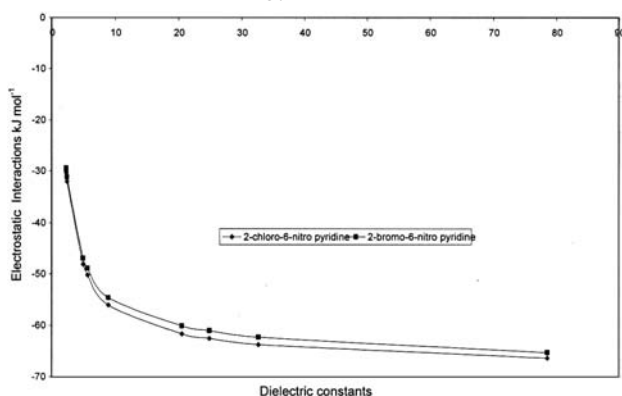
molecules in water is the least and hence these inhibitor molecules can act as effective inhibitors for the corrosion of iron in water.

The dispersion energies are mainly due to polarization of the solvent molecules by the solute molecules. This polarization, in turn, may depend on the refractive index and dipole moment of the solvent molecule [16]. From the data in Tables 2 and 3, it can be seen that the dispersion energy of both the solute molecules varies with the refractive indices of the solvent molecules. Thus, the dispersion energy of the molecules in different solvents may be correlated with the refractive index of the solvent. Plots of the refractive index versus dispersion energy for the two investigated compounds are shown in Fig. 3. The refractive index of water is the least among the solvents used for investigation and the dispersion energy is also the least. On the other hand, chlorobenzene has high refractive index and the dispersion energies for both the solutes in this solvent are high.

The repulsive energy of a solute molecule in a solution depends upon not only on the dielectric constant of the solvent but also on the Abraham's hydrogen bond acidity (α) and basicity (*b*) values. This is because the solute may be acidic, basic or amphoteric. The solute molecules used in the present investigation are almost neutral and hence, the repulsive energy may depend upon both these properties of the solvents. The repulsion energies of halogenated nitro pyridines in different solvents are given in Tables 2 and 3. These values indicate that the dielectric constants as well as the molecular size of the solvent molecules determine the repulsive energies. This is supported by the higher values of the repulsion energies of the bromo derivative in all the solvents as compared to the values for chloro derivative. The trend in the repulsive energies also

Fig. 2 — Plots of dielectric constant versus electrostatic interaction energy
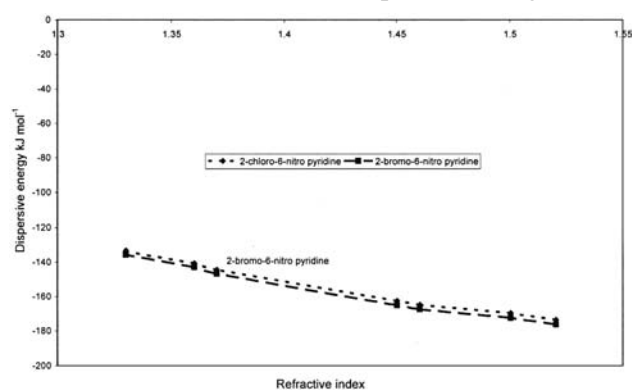

Fig. 3 — Plots of refractive index versus dispersive energy

suggests that the repulsive energy depends upon α and b values of the solvents. Abraham's acidity and basicity values are relatively high for water and hence the repulsion energies of the halogenated nitro pyridines in aqueous solution are much greater than those in other solvents. It can also be seen that α and b values of halogenated solvents are zero and hence the dispersive energies are minimum for both the solutes in these solvents. Plots of refractive index versus repulsion energy are shown in Fig. 4.

The free energy of solution can be used to compare the corrosion inhibiting property in different media. Of course the dipolar character of the solvent molecule is also equally important. The free energy of solution is the algebraic sum of the electrostatic, dispersive and repulsive energies. It can be seen from the data in the Tables 2 and 3 that the free energy of solution is the least negative in aqueous medium and hence, these solute molecules may be effective corrosion inhibitors in water. Further, the free energy of solution in a given solvent is less for bromo derivative than chloro derivative. This suggests that bromo compound may be a better corrosion inhibitor than chloro derivative in a given solvent. The dipole moment of the solute is also an important parameter to determine the solubility[17,18]. The experimental dipole moment values are not available and the dipole moment of pure solute in the presence of solvents are computed by *ab-initio* method and the values are given in Table 4. The induced dipole moment is proportional to polarizability which increases with increase of molar volume. It can be seen that the dipole moment of chloro derivative is slightly less than that of bromo derivative. This may be due to larger size of bromine than chlorine and consequently, the polarizability of chloro derivative is slightly less than that of bromo derivative. It may be seen from the dipole moment values that the values are slightly higher for bromo derivative. Further, the dipole moment values are higher for both the solutes in water. This may probably be due to higher dielectric constant value of water. The first hyperpolarizability is a third-rank tensor that can be described to 10 components by a 3×3×3 matrix due to Kleinmen symmetry[19,20]. In the present study, first hyperpolarizability β values for the two halogen substituted pyridine are computed by HF/6-31 +G (*d,p*) basis set using the finite-field approach. The complete equations for calculating the magnitude of the mean first hyperpolarizability β are given in literature[21]. Since hyperpolarizability is directly
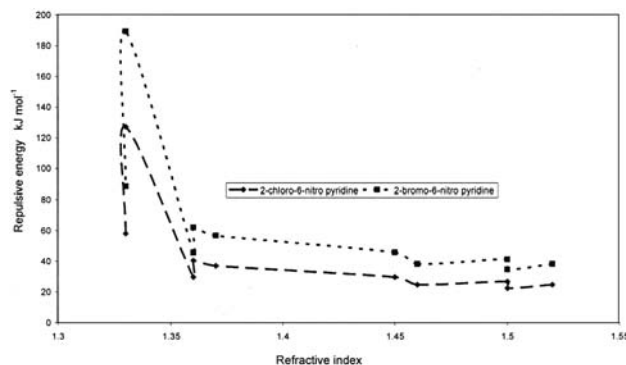

Fig. 4 — Plots of refractive index versus repulsive energy

Table 4 — Dipole moment and hyperpolarizability values of the solute molecules in different solvents at 298 K

Solvent	2-chloro-6-nitropyridine		2-bromo-6-nitropyridine	
	μ/D	$\beta/10^{-30}$ esu	μ/D	$\beta/10^{-30}$ esu
Solute	7.08	1.18	7.10	1.22
H_2O	9.18	1.33	9.36	1.36
CH_3OH	8.98	1.31	9.02	1.35
C_2H_5OH	8.94	1.30	9.01	1.35
Acetone	8.87	1.30	8.82	1.34
CH_2Cl_2	8.69	1.28	8.74	1.33
C_6H_5Cl	8.52	1.28	8.54	1.30
$CHCl_3$	8.43	1.26	8.61	1.30
$C_6H_5 CH_3$	7.85	1.22	7.97	1.27
C_6H_6	7.78	1.20	7.84	1.24
CCl_4	7.81	1.20	7.93	1.25

μ = Dipole moment in Debye units ; β = Hyperpolarizability in electro static units

correlated with the dipole moment, it is expected that the hyperpolarizability can be used to explain the solubilty property of these two compounds. The total first hyperpolarizability values of the pure solutes in the presence of different solvents are presented in Table 4. It can be seen that the first hyperpolarizability of chloro derivative is slightly less than that of bromo derivative. This may be due to larger size of bromine than chlorine. It may be seen from the hyperpolarizability values that the values are slightly higher for bromo derivative. Further, the hyperpolarizability values are higher for both the solutes in water. Thus, the hyperpolarizability values are also correlated with the free energy of solution of these two solutes in solvents of different dielectric constants in the same way as with dipole moment data.

4 Conclusions

Quantum mechanical solvation analysis is carried out for two industrially important corrosion inhibitors for iron, namely, 2-chloro-6-nitropyridine and 2-bromo-6-nitro-pyridine. The C-PCM model for

pyridine derivatives in different solvents lends itself to specific parameterization for more complicated condensed phases. The electrostatic interaction energy correlates well with the dielectric constant of the solvent. However, dispersion energy correlation is satisfactory with refractive index of the solvent. The repulsion energy of solute molecule depends upon more than one physical property of the solvent. Free energy of solution values also reported for the two solutes in ten different solvents. The free energy of solution is the least negative in aqueous solution for both the pyridine derivatives and hence, they may be effective coating for iron and inhibit corrosion of iron in aqueous medium. Further, it is still less negative for bromo derivative and hence, it may be a more efficient corrosion inhibitor than chloro derivative. It is anticipated that these features will make useful tools to develop the two halogenated nitro pyridines as effective corrosion inhibitors.

References

1 Hari Ji Singh & Priyanka Srivastava, *Indian J Pure & Appl Phys,* 47 (2009) 557.
2 Yadav B S, Israt Ali, Pradeep Kumar & Preeti Yadav, *Indian J Pure & Appl Phys,* 45 (2007) 979.
3 Hongfang Ma, Shenhao Chen, Zhibao Liu & Youmin Sun, *J Mol Struc Theochem,* 774 (2006) 19.
4 Bereket G, Ogretir C & Yurt A, *J Mol Struc Theochem,* 571 (2001) 139.
5 Bentiss F,Traisnel M, Vezin H & Lagrenee M, *Corrosion Sci,* 45 (2003) 371.
6 Tomasi J & Persico M, *Chem Rev,* 94 (1994) 2027.
7 Cramer C J & TruhlarD G, *Chem Rev,* 99 (1999) 2161.
8 Tomasi J, Mennucci B & Cammi R, *Chem Rev,*105 (2005) 2999.
9 Chamberlin A C, CramerC J & Truhlar D G, *J Phys Chem,* B 110 (2006) 5665.
10 Fuke K, Yoshiuchi H, Kaya K & Becke A D, *J Phys Chem,* 88 (1984) 5840.
11 Stephens P J, Devlin F J, Chabalowski C F & Frisch M J, *J Phys Chem,* 98 (1994) 11623.
12 Dewar M J S, Zoebisch E G, Healy E F & Stewart J J P, *J Am ChemSoc,* 107 (1985) 3902.
13 Musa E, Mohammed Christina Y, Ishak & Hajir I Wahbi, *Der Chemica Sinica*, 2 (2011) 133.
14 Schmidt M W, BaldridgeK K, Boatz J A, Elbert S T, Gordon M S, Jensen J H, Koseki Matsunaga S N, Nguyen K A, Su, S Windus T L, Dupuis M & Montgomery Jr J A, J *J Comput Chem,* 14 (1993) 1347.
15 Miertus S, Scrocco E & Tomasi J, *Chem Phys,* 55 (1981) 117.
16 Winget P, Thompson J D, Cramer C J & Thruhlar D J, *J Phys Chem A*, 106 (2002) 5160.
17 Sathyanarayanamoorthi V, Mahalakshmi S & Kannappan V, *J Mol Liq,* 154 (2010) 88.
18 Kikuchi K, *Quant Struct-Act Relat*, 6 (1987) 179.
19 Kleinman D A, *Phys Rev,* 126 (1962) 1977.
20 Karparm J, Sundaraganesan N, Sebastian S, Manoharan S & Kurt M, *J Raman Spectrosc,* 41 (2010) 53.
21 Prasad M V S, Udaya Sri N, Veeraiah A, Veeraiah V & Chaitanya K, *J Atom Mol Sci,* 4 (2013) 1.