Studies on Volumetric and Viscometric Properties on N-Acetylcysteine in Acetic acid-Water binary and ternary mixtures

by

(Banamali Vattya)

A thesis submitted in partial fulfillment of the requirements for the degree of
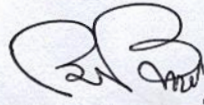M.Sc in Department of Chemistry

Khulna University of Engineering & Technology
Khulna-9203, Bangladesh
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Dedicated

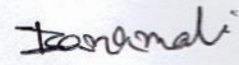**To**

My Beloved Parents

Declaration

This is to certify that the thesis work entitled **"Studies on Volumetric and Viscometric Properties on N-Acetylcysteine in Acetic acid-Water binary and ternary mixtures"** has been carried out by **Banamali Vattya** in the Department of Chemistry, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

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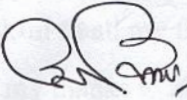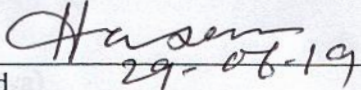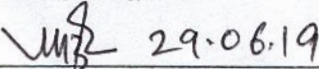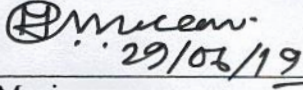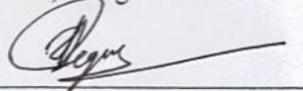Signature of Supervisor
(Prof. Dr. Mohammad Abu Yousuf)

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Signature of Candidate
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Approval

This is to certify that the thesis work submitted by **Banamali Vattya** entitled **"Studies on Volumetric and Viscometric Properties on N-Acetylcysteine in Acetic acid-Water binary and ternary mixtures"** has been approved by the board of examiners for the partial fulfillment of the requirements for the degree of Masters of Science in the Department of Chemistry, Khulna University of Engineering & Technology, Khulna, Bangladesh in 29 June, 2019.

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(Banamali Vattya)

Abstract

The density and viscosity of NAC ($\sim$0.10 to $\sim$1.00) $mol.L^{-1}$ in H_2O, CH_3COOH and $H_2O–CH_3COOH$ mixed solutions were measured and analyzed over the whole concentration range at (298.15, 303.15, 308.15, 313.15 and 318.15) K temperatures. The apparent molar volumes were obtained from the experimental density data. In the NAC–H_2O and NAC in [9:1] [$H_2O–CH_3COOH$] solvent systems the apparent molar volume of NAC increases, whereas in the NAC–CH_3COOH and NAC in [4:1], [7:3] and [3:2] [$H_2O–CH_3COOH$] solvent systems it decreases. With the help of experimental density data apparent molar volume at infinite dilution, and S_v values were also calculated. The apparent molar volume at infinite dilution gives an idea about the presence of solute−solvent interactions while Sv is the experimental slopes which give an idea about the prevailing solute−solute interactions in the mixtures. The calculated data indicate that there may be solute-solute and solute-solvent interactions present in the binary and ternary solutions. Binary and ternary systems showed rapid increase of viscosity values with the increase in NAC concentration but the values of viscosity decreased with the increase of temperature for all the experimented system. The viscosity data were employed to find out the viscosity (A, B) coefficients, change of free energy, ΔG^*, change of enthalpy, ΔH^* as well as change of entropy, ΔS^*. From these thermodynamic parameters state of the spontaneity of the investigated systems were identified. Moreover, negative A and positive B co-efficient values suggesting that weak solute-solute but strong solute-solvent interaction present in the binary and ternary solution. On the basis of this data, the predominant molecular interactions occurring between NAC–H_2O and NAC in [9:1] [$H_2O–CH_3COOH$] solvent systems were found to be solute-solute interaction, whereas in NAC–CH_3COOH and NAC in [4:1], [7:3] and [3:2] [$H_2O–CH_3COOH$] solvent systems solute-solvent interaction were predominant.

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Symbols/ Abbreviations	Explanation
K_d	Dissociation Constant
λ_i	Ionic conductance
η	Viscosity
λ_1^0	Limiting Ionic conductance
A	Area of contact between the two layers
f	Tangential force
ϕ	Fluidity
l	Length
Pa.s	Pascal-Second
cP	centipoise
mPa.s	Milli-Pascal-second
v	Velocity
r	Radius
P	Pressure
t	Flow time
ρ	Density of the liquid/solution
φ_v	Apparent molar volume
φ_E^0	Apparent molar expansivity at infinite dilution
φ_E	Apparent molar expansivity
ΔG^*	Free energy
ΔH^*	Change of Enthalpy
ΔS^*	Change of Entropy
h	Difference in height of the surface of the two reservoirs
g	Acceleration due to gravity
NAC	N-Acetylcysteine
IUPAC	The International Union of Pure and Applied Chemistry

CHAPTER I

Introduction

1.1 General

Viscometric and volumetric properties of solution provide a lot of information on the structures and molecular interactions of liquid mixtures. There is a certain relationship among viscometric and volumetric properties of solution as well as thermodynamic properties. So by determining and studying them together, relatively more realistic and comprehensive information of solution might be obtained.

In interpreting the composition, the structure of molecules and the molecular interaction in the binary and ternary systems, it is inevitable to find out the size and the shape of the molecules and the geometry of the arrangement of their constituent atoms. The measurement of bulk properties like, density, surface tension, viscosity etc. are also have gained increased importance during the recent years, because not only of their great usefulness in elucidating the composition and structure of molecules, but also the molecular interaction in binary and ternary systems. Viscometric and volumetric properties provide valuable tools in elucidating the composition and structure as well as interaction of solute and solvent in solution.

1.2 The phenomena of solute-solvent interaction

Revelation of the nature of ion-solvent interaction and interpretation of the thermodynamic and transport processes in terms of such parameters as effective size of the solvated ions in solutions have been two of the most difficult problems in the understanding of electrolytic solutions. This is because there is not satisfactory model to represent the various phenomena that occur in solution and the incompleteness in the understanding of the structure of the liquids in general. There are a number of evidences of solvation of ions [1–2] or solute molecules a number of studies have discussed the effect of solvation on the equilibrium properties of liquids.

The process of solvation and the process of dissolution are known to be closely related. When ionic crystal is added to a solvent, the electrostatic forces of attraction between the oppositely charged ions in the crystal have to overcome by interposing solvent layers around each of the ions. The ability of a solvent to dissolve a crystal is reflected by the

following properties, its dielectric properties, polarity, degree of self-association and its ability to solvate. Studies on the phenomena of solvation have led to the conclusions that:

(i)   The ionic compounds are moderately soluble in dipolar aprotic solvents of relatively high dielectric constant but are much more soluble in water and other hydroxylic solvents like methanol. A number of inorganic salts are dissociated in acetonitrile, which is otherwise known to solvate cations and anions rather poorly [3].

(ii)   The dielectric constant alone is not an adequate measure of solvating ability and may even play a major role in determining the solvation of ionic species. Cations should be better solvated in solvents having atoms with an unshared electron pair like nitrogen and oxygen. The cations have been found to be strongly solvated in highly polar solvents with the negative charge localized on an oxygen atom, e.g. in sulphur dioxide, dimethylsulfoxide, phosphorus oxide, dimethylformamide [4]. Potassium iodide is less soluble than sodium iodide in methanol or water [5], but in dimethylsulfoxide or dimethylformamide the reverse is true, which could be due to differences of cation solvation.

The anions have been found to be solvated in two ways:
(i)   Small ions are mostly solvated by hydrogen bonding which is superimposed upon solvation by ion-dipole interactions, and

(ii)   Large ions are solvated by interaction due to mutual polarizability of the anions and the solvent superimposed upon solvation by dipole interactions. Thus while the anions are more strongly solvated in hydrogen bonding solvents than in dipolar aprotic solvents, the cations are better solvated in the latter type of solvents.

The solubility of halides in various solvents generally follows the order:

Iodides > bromides > chlorides > fluorides.

The alkaline halides are more soluble in hydroxylic solvents than in the dipolar aprotic solvents like acetonitrile and acetone. These are found to be more soluble in acetonitrile than in acetone [6]. Electrolytes may be divided into two categories: ionophores and ionogens. While the former are ionic in character in the crystalline state as well as in the fused state and in highly dilute solutions, the latter have molecular crystal lattice and ionize in solution only if suitable interaction occurs with the solvent molecules.

The ionophores may exist in solution as an equilibrium mixture containing ion-pairs and free ions [7].

$$M^+X^- \rightleftharpoons M^+ + X^-$$
$$\text{Solvated} \quad \text{Solvated}$$
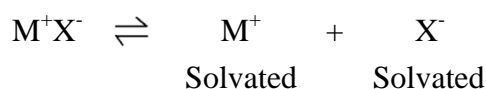
The ion-pairs are of oppositely charged ions having life terms sufficiently long to be recognized as kinetic entities in solution and in which only electrostatic forces are assumed [1]. Fuoss *et al.* [8] have studied intensely the dependence of the dissociation constant, K_d, on the dielectric constant, the temperature and the nature of the salt. It was found to be large for solvents having high dielectric constant. It has also been found to be dependent on the distance of closest approach of the ions in the ion pairs. For hydroxylic solvents, large ions have larger K_d values and lower conductance values than smaller ions, which doesn't hold for other solvents.

Interaction of the ions with the solvent molecules causes low conductance. Na^+ ion behaves as a large ion as the K_d of iodides of Bu_4N^+ and Na^+ are found to be of the same order. Small ions like Li^+, F^- have low conductance in acetone but have low K_d values which have been attributed to the loss of the solvent molecules from the ion-pairs [9]. Solute-solvent interactions have been studied in details by various methods; some important ones may be listed as follows:

    (i)   Study of the solute-solvent interactions through transference experiments.

    (ii)   The effect of solvation on the ionic conductance.

    (iii)   The experiments applying stoke's law and their relevance to the nature of solvation.

    (iv)   Polarographic measurements of solutions.

    (v)   The spectral results due to the presence of the ions in solutions.

A relationship between the values of the limiting equivalent ionic conductance, λ_i and the viscosity, η value was advocated and utilized by Walden and others to study the solute-solvent interactions [10]. In one approach which assumes the constancy of the product $\lambda_i\eta$ the effects of variation of temperature, viscosity and variation of the solvent were studied. For large organic ions [10], the temperature co-efficient was found to be nearly constant in water as well as other non-aqueous solvents, while for the other ions it showed variations. For changing solvents, the product was found to vary widely in the case of inorganic ions which have been interpreted to be due to differences in solvation numbers of the ion in the various solvents. In another approach to this study Pure and Sherrington [11] used the relation between viscosity η_i, and limiting ionic conductance λ_i^0, to measure the radii of interaction of solvent and solute, called stoke's law radii, r. They compared the crystallographic radii of some cations and anions with stoke's law radii in the case of diethylamide and dimethylsulphoxide solvents. They found the degree of solvation to decrease from lithium to cesium and to be less for silver and ammonium ions which have nearly comparable crystallographic radii. They postulated the anions to be unsolvated in dipolar aprotic solvents as the radii obtained are of the same order as that of the crystallographic radii, and that the negative end of the dipole in the solvent molecule is unshielded while the positive end is protected by two methyl groups, so that the cations, but not the anions are solvated by these solvents. Volumetric and viscometric measurement provides valuable tool for the determination of interaction among solutes and solvents.

1.3 Viscosity

Viscosity means viscous ability. Simply, viscosity of a material is resistance to flow. The internal friction which opposes the relative motion of the adjacent layers of a fluid causes for the resistance to flow. When a fluid is flowing through a cylindrical tube, this internal friction arises because of intermolecular friction. Molecules are a slower moving layer try to decrease the velocity of the molecules in a faster moving layer and vice versa.

Viscosity is really a frictional effect experienced by one layer of a liquid in moving past another in much the same way as an object experiences frictional resistance when dragged on a surface. The friction force, *f*, resisting the flow of one layer of fluid past the

adjacent layer is proportional to the area, A, of the interface between the layers and to$\frac{du}{dr}$, the velocity gradient. This is Newton's lawand is given by

$$f = \eta A \frac{du}{dr}$$

Whereη (eta, a Greek letter), the constant of proportionality, is called the co-efficient of viscosity. When the velocity gradient is unity and the area is 1 sq-cm, η is equal to the force; or the co-efficient of viscosity,η may be defined as the force per 1 sq-cm required to maintain a difference of velocity of 1 cm per second between two parallel layers 1 cm apart. The reciprocal of the co-efficient of viscosity is known as the fluidity, $\varnothing$, or

$$\varnothing = \frac{1}{\eta}$$

Fluidity is a measure of the ease with which a liquid can flow. The connection between these quantities was first derived by J.L.M. Poiseuille in 1844, known as the Poiseuille equation [12]. If a liquid with a coefficient of viscosity (η) flows with a uniform velocity, at a rate of v cm^3 in t seconds through a narrow tube of radius r cm, and length 1 cm under a driving pressure of P dynes cm^{-2} then [12]:

$$\eta = \frac{\pi P r^4 t}{8lv} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1.1.1)$$

This equation known as Poiseuille's equation holds accurately for stream-line flow but not for the turbulent flow which sets as higher velocities; where, η is a proportionality constant, known as the coefficient of viscosity or simply viscosity of the liquid. The CGS unit of viscosity i.e., dynes sec cm^{-2} = g cm^{-1}sec^{-1} is called poise, in honor of J.L.M. Poiseuille who is the pioneer in the study of viscosity. The SI unit of viscosity is the Pascal-second (Pa.s). Since viscosity of liquid is usually very small, it is usually expressed in millipoise (mP) or centipoise (cP) or mPa.s.

1.3.1   Factors affecting viscosity

Viscosity is first and foremost function of material. Most ordinary liquids have viscosities on the order of 1 to 1000 mPa·s, while gases have viscosities on the order of 1 to 10μPa·s. Pastes, gels, emulsions, and other complex liquids are harder to summarize.

Some fats like butter or margarine are so viscous that they seem more like soft solids than like flowing liquids.

Temperature: The viscosity of a simple liquid decreases with increasing temperature (and vice versa). As temperature increases, the average speed of the molecules in a liquid increases and the amount of time they spend "in contact" with their nearest neighbors decreases. Thus, as temperature increases, the average intermolecular forces decrease. The exact manner in which the two quantities vary is nonlinear and changes abruptly when the liquid changes phase.

Pressure: Viscosity is normally independent of pressure, but liquids under extreme pressure often experience an increase in viscosity. Since liquids are normally incompressible, an increase in pressure doesn't really bring the molecules significantly closer together. Simple models of molecular interactions won't work to explain this behavior and, to my knowledge, there is no generally accepted more complex model that does. The liquid phase is probably the least well understood of all the phases of matter.

While liquids get runnier as they get hotter, gases get thicker. The viscosity of gases increases as temperature increases and is approximately proportional to the square root of temperature. This is due to the increase in the frequency of intermolecular collisions at higher temperatures. Since most of the time the molecules in a gas are flying freely through the void, anything that increases the number of times one molecule is in contact with another will decrease the ability of the molecules as a whole to engage in the coordinated movement. The more these molecules collide with one another, the more disorganized their motion becomes.

Cohesive forces: Cohesive forces are the intermolecular forces (such as those from hydrogen bonding and Van Der Waals forces) which cause a tendency in liquids to resist separation. These attractive forces exist between molecules of the same substance. For instance, rain falls in droplets, rather than a fine mist, because water has strong cohesion which pulls its molecules tightly together, forming droplets. This force tends to unite molecules of a liquid, gathering them into relatively large clusters due to the molecules' dislike for its surrounding. The materials having stronger cohesive forces normally exhibit lower viscosities and vice-versa.

Adhesive force: Adhesive forces are the attractive forces between unlike molecules. They are caused by forces acting between two substances, such as mechanical forces (sticking together) and electrostatic forces (attraction due to opposing charges). In the case of a liquid wetting agent, adhesion causes the liquid to cling to the surface on which

it rests. When water is poured on clean glass, it tends to spread, forming a thin, uniform film over the glasses surface. This is because the adhesive forces between water and glass are strong enough to pull the water molecules out of their spherical formation and hold them against the surface of the glass, thus avoiding the repulsion between like molecules. The materials having stronger adhesive forces normally reveal higher viscosities and vice-versa.

1.4 Properties of Acetic Acid
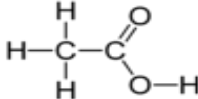
Acetic acid, also known as ethanoic acid or methane carboxylic acid, is a colorless liquid that has a strong and distinct pungent and sour smell. It is an organic chemical compound best recognized for giving vinegar. It is one of the simplest carboxylic acids (the second-simplest, after formic acid) and has the chemical formula CH_3COOH. Acetic acid is classified as a carboxylic acid. A carboxylic acid, shown as RCOOH, is a group of organic compounds that contain a carboxyl group. Here, the R group in the carboxylic acid structure may contain one or more carbon and/or hydrogen atoms.

It is produced by fermentation and synthesis methods. In both these methods, acetic acid must be separated from dilute aqueous solutions. Because the separation of acetic acid by a distillation process is quite difficult and expensive, the liquid−liquid extraction process can be used by means of an appropriate organic solvent. It is also well known for its ability to form dimers in the gas phase, whereas in the liquid phase or in a solution the point is not so clear. Infrared and Raman spectroscopic study of aqueous solutions of acetic acid, at low concentrations the acid is largely a hydrated monomer. As acid concentration increases, the hydrated monomer is gradually replaced by a hydrated linear dimer and then by the cyclic dimer. At higher concentrations, longer oligomers coexist with cyclic dimers. Presence of hydrogen bonds in acetic acid is the reason for its high boiling temperature, even though its dipole moment is less than 2 D. Indeed, it is known that acetic acid (and other acids) dimerize in the vapor phase, while the liquid phase may contain both dimers and higher oligomers.

Acetic acid is an excellent polar proteic solvent. It is frequently used as a solvent for recrystallization to purify organic compounds. Acetic acid is used as a solvent in the production of terephthalic acid, the raw material for polyethylene terephthalate. It is often used as a solvent for reactions involving carbocations, such as Friedel-Crafts alkylation. For example, one stage in the commercial manufacture of synthetic camphor

involves a Wagner-Meerwein rearrangement of camphene to isobornyl acetate; here acetic acid acts both as a solvent and as a nucleophile to trap the rearranged carbocation. Glacial acetic acid is used in analytical chemistry for the estimation of weakly alkaline substances such as organic amides. Glacial acetic acid is a much weaker base than water, so the amide behaves as a strong base in this medium. It then can be titrated using a solution in glacial acetic acid of a very strong acid, such as perchloric acid. It is used in many industries such as the production of acetic ester and pharmaceuticals. It is an effective antiseptic when used as a 1% solution, with broad spectrum of activity against streptococci, staphylococci, pseudomonas, enterococci and others. It may be an option for skin infections caused by pseudomonas resistant to typical antibiotics. A brief description of properties of acetic acid is given in Table 1.1.

Table 1.1.: Properties of Acetic Acid

Chemical formula	$C_2H_4O_2$ or CH_3COOH
Molar mass	60.05 g·mol^{-1}
Appearance	Colorless liquid
Structure	
Odor	Pungent/Vinegar-like
Density	1.049 g.cm^{-3}
Melting point	16 to 17 °C; 61 to 62 °F; 289 to 290 K
Boiling point	118 to 119 °C; 244 to 246 °F; 391 to 392 K
Solubility in water	Miscible
Acidity (pK$_a$)	4.76
Basicity (pK$_b$)	9.24 (basicity of acetate ion)
Viscosity	1.22 mPa.s
Dipole moment	1.74 D

1.5 Properties of N-Acetylcysteine

N-Acetyl-L-Cysteine (NAC), the preacetylysed form of simple amino acid cysteine, a synthetic precursor of cysteine and reduced glutathione has been in clinical use for more than 40 years. It is a powerful intracellular antioxidant, antitoxin improves immunity. NAC is a thiol compound which is also called Acetylcysteine, is an amino acid with the molecular formula $C_5H_9NO_3S$, Molar mass of acid 163.195 g/mole.The melting point and boiling point of NAC are 106 °C and 407.7°C respectively. It is a white crystalline powder with a slightly acidic odor and characteristic sour tasting. It is a solid at room temperature, but melts easily with water, 4ml ALC; practically insoluble in chloroform and ether. The vapor pressure of NAC is estimated 1.1×10^{-5} mm Hg at 25 °C and stable of Stable in ordinary light; stable at temperature up to 120 °C; nonhygroscopic (oxidizes in moist air). The pH of NAC is 2 to 2.75 (1 in 100 mL) and dissociation constants pKa= 3.24 (carboxylic acid moiety) and Spectral Properties is Specific optical rotation: +5 °C at 20 °C (concentration = 3 g/100 mL).

NAC is not found naturally in food sources; however cysteine is present in most high protein foods. NAC converts into cysteine. Cysteine is a nonessential amino acid produced by the body. Cysteine is primarily found in animal protein, along with the other ten essential amino acids. Meats such as pork, chicken, sausage, turkey and duck all contain the amino acid cysteine. Fish and lunch meats also contain cysteine. Dairy sources of cysteine include ricotta cheese, cottage cheese, yogurt and eggs. Cysteine can be found in some plant sources plant sources for vegetarians and vegans. Cysteine is found in granola and oat flakes. Vegetables like broccoli, red pepper and onion are significant sources of cysteine. Other plant sources include bananas, garlic, soy beans, linseed and wheat germ. Cysteine is important amino acid, but deficiency is relatively rare. Low levels of cysteine can cause slow growth in children and lowered immunity. Muscle loss, weakness, apathy and liver damage may also be a result of low cysteine in the diet. NAC is not found naturally in food sources; however cysteine is present in most high protein foods. NAC converts into cysteine. Cysteine is a nonessential amino acid produced by the body. Cysteine is primarily found in animal protein, along with the other ten essential amino acids. Meats such as pork, chicken, sausage, turkey and duck all

contain the amino acid cysteine. Fish and lunch meats also contain cysteine. Dairy sources of cysteine include ricotta cheese, cottage cheese, yogurt and eggs. Cysteine can be found in some plant sources plant sources for vegetarians and vegans. Cysteine is found in granola and oat flakes. Vegetables like broccoli, red pepper and onion are significant sources of cysteine. Other plant sources include bananas, garlic, soy beans, linseed and wheat germ. Cysteine is important amino acid, but deficiency is relatively rare. Low levels of cysteine can cause slow growth in children and lowered immunity. Muscle loss, weakness, apathy and liver damage may also be a result of low cysteine in the diet. NAC is a therapeutic medicine frequently used as a mucolytic agent and for treating acetaminophen hepato toxicity. It increases the cell reserves of free radicals and acts as an antioxidant. It also inhibits the replication of HIV and prevents apoptosis in neurons. NAC prevents endotoxin-induced degeneration of oligodendrocyte progenitors and hypomyelination in developing rat brain. NAC may have a direct chelating effect on lead asseen by lowered serum lead levels. It prevents lead toxicity and reduces oxidative sequel of lead exposure. NAC crosses cell membranes and is rapidly consumed in producing intracellular glutathione. By reducing extracellular cysteine to cysteine, it acts as a source of SH groups and it can stimulate glutathione synthesis enhance glutathione-S-transferase activity promote detoxification and act directly on reactive oxidant radicals. NAC corrects the reduction in glutathione concentration and results in significant preservation of fluidity of membranes and of the activities of catalase, mitochondrial superoxide dismutase and different forms of glutathione peroxidase in biliary obstructed rats. NAC is a powerful scavenger of hypochlorous acid and is capable of reducing hydroxyl radicals and hydrogen peroxide. SH groups are essential for defense against reactive oxygen species. NAC can also prevent apoptosis caused by oxidative stress and promote cell survival by activating signal regulating pathways. Recently, volumetric and viscometric study of NAC ethanol-water and DMSO-water systems were performed [13-14]. From the results it was seen that NAC showed more interaction in ethanol-water mixture than those for individual solvents. Similar results were obtained in DMSO-water systems. So to get more information of NAC, this research is devoted to solution properties of NAC in CH_3COOH solution. Mixed solutions were prepared by varying the ratio of acetic acid in water. Effect of addition of NAC in H_2O-CH_3COOH system has also been explored which hasn't been done before to the best of my knowledge.

1.6 Physical Properties and chemical constitutions

In interpreting the composition, the structure of molecules and the molecular interaction in the binary and ternary systems, it is inevitable to find out the size and the shape of the molecules and the geometry of the arrangement of their constituent atoms. For this purpose the important parameters are bond lengths or interatomic distance and bond angles. The type of atomic and other motions as well as the distribution of electrons around the nuclei must also be ascertained; even for a diatomic molecule a theoretical approach for such information would be complicated. However, the chemical analysis and molecular mass determination would reveal the composition of the molecules, and the study of its chemical properties would unable one to ascertain the group or sequence of atoms in a molecule. But this cannot help us to find out the structures of molecules, as bond length, bond angles, internal atomic and molecular motions, polarity etc. cannot be ascertained precisely.

For such information it is indispensable to study the typical physical properties, such as absorption or emission of radiations, refractivity, light scattering, electrical polarization, magnetic susceptibility, optical rotations etc. The measurement of bulk properties like, density, surface tension, viscosity etc. are also have gained increased importance during the recent years, because not only of their great usefulness in elucidating the composition and structure of molecules, but also the molecular interaction in binary and ternary systems.

The various physical properties based upon the measurement of density, viscosity, surface tension, refractive index, dielectric constant etc., have been found to fall into the following four categories [15].

> (i) **Purely additive properties:** An additive property is one, which for a given system, is the sum of the corresponding properties of the constituents. The only strictly additive property is mass, for the mass of a molecule is exactly equal to

the sum of the masses of its constituent atoms, and similarly the mass of a mixture is the sum of the separate masses of the constituent parts. There are other molecular properties like molar volume, radioactivity etc. are large additive in nature.

(ii) **Purely constitutive properties:** The property, which depends entirely upon the arrangement of the atoms in the molecule and not on their number is said to be a purely constitutive property. For example, the optical activity is the property of the asymmetry of the molecule and occurs in all compounds having an overall asymmetry.

(iii) **Constitutive and additive properties:** These are additive properties, but the additive character is modified by the way in which the atom or constituent parts of a system are linked together. Thus, atomic volume of oxygen in hydroxyl group (−OH) is 7.8 while in ketonic group (=CO) it is 12.2. The molar refraction, molecular viscosity etc. are the other examples of this type.

(iv) **Colligative properties:** A colligative property is one which depends primarily on the number of molecules concerned and not on their nature and magnitude. These properties are chiefly encountered in the study of dilute solutions. Lowering of vapor pressure, elevation of boiling point, depression of freezing point and osmotic pressure of dilute solutions on the addition of non-volatile solute molecules are such properties.

1.7 Molarity

Molarity, (C) is defined as the number of moles of solute per liter of solution. If n is number of moles of solute and V liters is the volume of the solution then,

$$\text{Molarity (C)} = \frac{\text{Number of moles of solute}}{\text{Volume of Solution}}$$

Or $C = \dfrac{n}{V}$ ………………………………………………………………...(1.2.1)

The unit of molarity is $mol.L^{-1}$.

1.8 Molar volume of Mixtures

The volume in mL occupied by 1 mole of any substance is called the molar volume. On the other hand, if ρ is the density and M be the molar mass, molality of a solution is defined as the number of moles of the solute per 1000 g of solvent. Mathematically,

$$Molality\,(\text{m}) = \frac{\text{Number of moles of solute}}{\text{Weight of solvent in gram}} \times 1000$$

$$\text{or, } m = \frac{\dfrac{a}{M_2} \times 1000}{\text{Volume of solvent in mL.} \times \text{density of solvent in g cm}^{-3}}$$

$$\text{or, } m = \frac{a}{M_2} \times \frac{1000}{V_1 \times \rho_0} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (1.2.2)$$

Where, a   = weight of solute in gram.

M_2 = molecular weight of solute in gram.

V_1 = volume of solvent in mL.

ρ_0 = density of solvent in g.cm^{-3}.

$$\text{Specific volume, (V)} = \frac{1}{\rho}\,\text{mL}g^{-1} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (1.2.3)$$

$$\text{Molar volume, } (V_m) = \frac{M}{\rho}\,m\;Lmol^{-1} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (1.2.4)$$

When two components are mixed together, there may be either a positive or a negative deviation in volume. One of cause of positive deviation in volume i.e. volume expansion has been explained by the disruption of the mode of association through H–bonding of liquids. The negative deviation in molar volume i.e. volume contraction has been thought of by many observers, as arising from the

     I.   compound formation through association

    II.   decrease in the intermolecular distance between the interacting molecules

   III.   interstitial accommodation of smaller species in the structural network of the larger species and

   IV.   change in the bulk structure of either of the substance forming the mixture.

1.9 Apparent molar volume

The apparent molar volume of a solute in solution, generally denoted by φ_v [16]

$$\varphi_v = \frac{V - n_1 \overline{V}_1^{\,0}}{n_2} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1.2.5)$$

Where, V is the volume of solution containing n_1 moles of solvent and n_2 moles of solute and $\overline{V}_1^{\,0}$ is the molar volume of the pure solvent at specified temperature and pressure. For binary solution, the apparent molar volume φ_v of an electrolyte in an aqueous solution is given by,

$$\varphi_v = \frac{1}{n_2} \left[\frac{n_1 M_1 + n_2 M_2}{\rho} - n_1 \overline{V}_1^{\,0} \right] \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1.2.6)$$

Where, $V = \dfrac{n_1 M_1 + n_2 M_2}{\rho}$ and

n_1 and n_2 are the number of moles, M_1 and M_2 are molar masses of the solvent and solute respectively and ρ is the density of the solution. For molar concentration, $n_2 = m$, the molality and n_1, the number of moles of solvent in 1000 g of solvent, the equation for apparent molar volume takes the form [17-18]

$$\varphi_v = \frac{1}{m} \left[\frac{1000 + m M_2}{\rho} - \frac{1000}{\rho_0} \right]$$

$$\text{or, } \varphi_v = \left[\frac{M_2}{\rho} - \frac{1000(\rho - \rho_0)}{m \rho \rho_0} \right] \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1.2.7)$$

where, ρ_0 and ρ are the densities of the solvent and solution.

If the concentration is expressed in molarity the equation (1.2.7) takes the form [19]:

$$\varphi_v = \left[\frac{M_2}{\rho_0} - \frac{1000(\rho - \rho_0)}{C \rho_0} \right] \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1.2.8)$$

1.10 Viscosity

Viscosity means viscous ability. The internal friction opposes the relative motion of adjacent layers of a fluid. When a fluid is flowing through a cylindrical tube, layers just touching the sides of the tubes are stationary and velocities of the adjacent layers increases towards the center of the tube, the layer in the center of the tube having the maximum velocity. There thus exists a velocity gradient. Molecules are a slower moving layer try to decrease the velocity of the molecules in a faster moving layer and vice versa, with a result that some tangential force is required to maintain uniform flow. This tangential force will depend upon two factors,

(i) Area of contact 'A' between the two layers and

(ii) Velocity gradient $\dfrac{dv}{dx}$

Thus, $f \infty A \dfrac{dv}{dx}$

Or $\qquad f = \eta A \dfrac{dv}{dx}$ .... (1.2.9)

Where, η is a proportionality constant, known as the coefficient of viscosity or simply viscosity of the liquid. Thus, the coefficient of viscosity may be defined as the force per unit area required to maintain unit difference in velocity between two parallel layers of liquid unit distance apart.

The reciprocal of viscosity called the fluidity (φ) is given by the relation.

$\phi = \dfrac{1}{\eta}$ .... (1.2.10)

If a liquid with a coefficient of viscosity (η) flows with a uniform velocity, at a rate of V cm^3 in t seconds through a narrow tube of radius r cm, and length 1 cm under a driving pressure of p dynes cm^{-2} then according to J.L.M. Poiseuille [20]:

$\eta = \dfrac{\pi \, Pr^4 \, t}{8lv}$ .... (1.2.11)

This equation known as Poiseuille's holds accurately for stream-line flow but not for the turbulent flow which sets as higher velocities. After correction for kinetic energy, the equation becomes,

$$\eta = \frac{\pi \, Pr^4 t}{8lv} - \frac{\rho V}{8\pi lt} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1.2.12)$$

Where, ρ represents the density of the liquid/solution. However, in practical purposes, the correction factor is generally ignored.

The driving pressure $P=h\rho g$, where h is the difference in height of the surface of the two reservoirs, since the external pressure is the same at the surface of both reservoirs, $g =$ acceleration due to gravity and $\rho=$ the density of liquid. Thus the equation (1.2.11) becomes,

$$\eta = \frac{\pi h \rho g r^4 t}{8vl} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1.2.13)$$

For a particular viscometer h, l, r and v are fixed, so the equation (1.2.13) becomes,

$$\eta = A\rho t \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1.2.14)$$

where $A = \dfrac{\pi h g r^4}{8vl}$, called the calibration constant of the viscometer used.

Putting the values of A, ρ and t o f the investigated liquid in equation (1.2.15), the coefficient of viscosity can be obtained for a liquid at a definite temperature.

The CGS Unit of viscosity is poise, in honor of J.L.M. Poiseuille. The SI unit of viscosity is the pascal-second (Pa·S). Since viscosity of liquid is usually very small, it is usually expressed in centipoise (cP) or mPa.s.

1.11 Viscosity and temperature

The viscosity of a liquid generally decreases with the increase of temperature. Evaluation of energy of activation for viscous flow can be stated by the Arrhenius equation as follows:

$$\eta = Ae^{-\epsilon_a/RT} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1.2.16)$$

Where, A is Arrhenius constant and ϵ is energy of activation for viscous flow. The linear form of the equation 1.2.26 is as follows:

$$ln\eta = lnA - \frac{\epsilon_a}{RT} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1.2.17)$$

$ln\eta$ against $\frac{1}{T}$ offer straight line. From the slope and intercept the energy of activation and Arrhenius constant can be determined.

1.12 Different thermodynamic parameters

Eyring and co-workers [21] using absolute reaction rate theory and partition functions corrected viscosity, η as follows:

$$\eta = \frac{hN}{V} \cdot e^{\frac{\Delta G^*}{RT}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (1.2.28)$$

Where, ΔG^* is the change of free energy of activation per mole for viscous flow, V_m is the molar volume for liquids or solutions and h, N, R and T have usual meaning. The values of change of free energy of activation (ΔG^*) can be calculated by using the Nightingle and Benck equation [22],

$$\Delta G^* = RT\ln\left(\frac{\eta V}{hN}\right) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (1.2.29)$$

And values for the corresponding thermodynamic parameters, enthalpy of activation, ΔH^* and entropy of activation ΔS^* for per mole for viscous flow of the liquids or solutions have been calculated from the relationship (1.2.28) [22]

$$\ln\frac{\eta V}{hN} = \frac{\Delta H^*}{RT} - \frac{\Delta S^*}{R} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (1.2.30)$$

Assuming ΔH^* and ΔS^* to be almost independent in the temperature range studied, a plot of $\ln\frac{\eta V_m}{Nh}$ against $\frac{1}{T}$, will give a straight line. From the slope and intercept ΔH^* and ΔS^* can be determined respectively.

1.13 Viscosity Coefficients A and B Measurement

The Jones-Dole coefficient, A, reflects the effect of solute-solute interaction and B, is a measure of structural modifications induced by the solute-solvent interaction. The co-efficient A and B for the electrolyte solutions can be measured by using the empirical equations of Jones-Dole [23].

$$\eta_r = 1 + A\sqrt{C} + BC \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots ..(1.2.31)$$

where, η_r is the relative viscosity.

Relative viscosity, $\eta_r = \frac{\text{viscosity of solution, } \eta}{\text{viscosity of solvent, } \eta_0}$

The values of the coefficients *A* and *B* were obtained from the intercept and slope of the plot $\frac{\eta_r - 1}{\sqrt{C}}$ against $\sqrt{C}$ respectively.

Chapter II

Literature Review

2.1 Literature review

NAC a sulfhydryl substance is a derivative of amino acid L-cysteine widely used as medicine. Mucolytic activity of NAC was used for the first time in the treatment of some respiratory diseases (e.g. chronic bronchitis) over 40 years ago [24]. Detoxifying properties of NAC were discovered in the 1970s and since then NAC was being used as an antidote in aminophen intoxication [25]. Currently it is known mainly as an antioxidant displaying direct and indirect activities [26]. Oxidative stress, the imbalance between reactive oxygen species (ROS) and actions of the antioxidant network which takes part in pathogenesis of a broad spectrum of diseases including cancer, cardiovascular, arthritis, diabetes, influenza-like symptomatology as well as some lung disturbances namely pulmonary oxygen toxicity, adult respiratory distress syndrome, chronic obstructive pulmonary disease, idiopathic pulmonary fibrosis [27] and cystic fibrosis. Increasing number of publications confirm efficacy of using NAC in the above mention diseases [26-29]. Antioxidant properties of NAC come from its specific structure. NAC contains amino acid L-cysteine plus an acetyl ($-OCCH_3$) group attached to the amino (NH_2) group. All amino acids including L-cysteine with sulphur group are characterized by antioxidant properties. Since L-cysteine is a precursor of reduced glutathione (GSH), synthesis of NAC contributes to augmentation of the level of this major intracellular antioxidant [26]. Depleted pool of GSH is often caused by oxidative stress and inflammation. NAC can therefore normalize disturbed redox status of the cells and thus influence redox – sensitive cell signaling and transcription pathways. Sulfhydryl group (–SH) in the NAC molecule make possible also to directly scavenge ROS such as superoxide radical (O_2), hydrogen peroxide, regulation of protein phosphorylation and regulation of calcium level inside the cells as well as phagocytosis process [30-31].

Diversity of applying NAC is the source of broad spectrum of used dosage and routes of administrations. Oral administration (tablet or inhalations) can range from 250 to 1800 mg/day and is used mainly in lung diseases [27]. Toxicological data shows that intakes of NAC per day orally could be consumed without causing significant adverse effects

[32]. Application of NAC (7 mg/ml) diminished UV induced ROS in melanocyte cell line and protects these cells from UV – induced oxidative damage. NAC reduced formation of 8-oxoguanine in mice skin protecting melanocytes from UV induced melanoma [33-35]. Most of anticancer therapies are based on growth of ROS production in cancer cells leading to their apoptosis [36-40]. The efficiency of vitamin E and NAC as an antioxidant adjuvant therapy was shown in chemotherapy/radiotherapy course during acute lymphoblastic leukemia in 40 children study. Toxicity of chemo- and radiotherapy measured as a diminished level of malondialdehyde, as well as increased level of glutathione peroxidase and decreased occurrence of toxic hepatitis was significantly reduced [41-43].

NAC as a muco active, anti-inflammatory and antioxidant agent was expected to have a benefit therapeutic effect in Cystic fibrosis patients. In 4 weeks trial [44-46] NAC was administered orally to 18 Cystic fibrosis patients in a high doses (600-1000 mg) three times daily. Endometriosis is known as a common gynaecological disorder affecting about 10% of women in a reproductive age. It is characterized by presence of endometrial tissue outside of the uterine cavity, resulting in pelvic pain, infertility and dysmenorhea. Development of the disease is caused by implantation of endometrial cells in the peritoneal cavity and their proliferation leading to invade peritoneum and disease progression. Pathophysiology of endometriosis includes chronic inflammation within oxidative stress and pathological angiogenesis [47-48]. A cataract is a cloudiness or opacity in the normally transparent crystalline lens of the eye. This cloudiness can cause a decrease in vision acuity and sometimes may lead to hand movements behind the eye or blindness. The leading riskfactor of cataract is aging .As glutathione is an important antioxidant in the lens it has been suggested that increasing GSH level NAC supplementation could be used to reduce cataract risk [49]. Diabetes elevates the risk of cataract formation. This form of cataract can result from sorbitol accumulation in the lens. Pathophysiology of early cataract development and the potential benefit of supplementation with vitamin B6 and NAC among the diabetic population were studied by Jain *et. al.*[50]. High-glucose concentrations can cause the oxidation and modification of proteins in the lens. Vitamin B6 (pyridoxine) and NAC supplementation may be helpful in slowing the oxidation of lens proteins. The study of Liebermann [51] raised the possibility that administration of NAC may reverse early cataracts. Zhang et al. [52] evaluated the effect of NAC and glutathione ethyl ester (GSH-EE) eye drops on the progression of diabetic cataract formation in rats. Author concluded that NAC and GSH-

EE can slightly inhibit the progression of the diabetic cataract at the earlier stage. NAC, used as an ophthalmic drug is promising in the treatment of a range of ophthalmic disorders with oxidative stress component involved in pathogenesis including cataract, glaucoma, dry eye syndrome, vitreous floaters, inflammatory disorders, corneal, retinal and systemic diseases and its ophthalmic complications.

NAC is widely used as medicine also a scavenging agent. So investigation of effect of NAC in H_2O-CH_3COOH mixture could be quite interesting and might have medicinal application as well as that has not been investigated earlier so far.

2.2 Aim of the research

NAC is a molecule of extremely fast medicinal career and wide therapeutic profile. To date, at least 12 distinct biological activities have been attributed to NAC. In view of the fact that NAC is one of the smallest drug molecules, with a total of 19 atoms, the above pharmacological versatility is undoubtedly unique, indicating that the background of its biological complexity must be sought at the sub-molecular level. NAC is an acetylated amino acid with antioxidant and mucolytic properties. NAC is the most widely used mucolytic agent worldwide. Further indications for its use include rheumatoid arthritis, plasma hyperlipoproteinaemia and adult respiratory distress syndrome. NAC has also been reported to support repair processes after cytotoxic and radioactive damages in cancer therapy to remove atherosclerotic plaques. Its mode of action has generally been assumed to be related to the thiol (or thiolate) site, as the key moiety of the molecule. The reported thiolate-involved mechanisms are free radical scavenging, rupture of disulfide bonds in cross-linked mucous proteins, metal complex formation. It is obvious that NAC has some crucial properties that govern its viability and activity in biological media. So its solution behavior and the related protonation state and medium-dependent physicochemical interaction and thermodynamic properties are the discussion point at this time.

Water is universal solvent used in daily life. At the same time acetic acid is very much soluble in water. So solution of NAC in acetic acid and water mixed solvent might have

potential application. To the best of our knowledge, still there is no explicit data of rheological and volumetric properties of NAC in H_2O-CH_3COOH are available. The purpose of this study was to evaluate the miscibility of NAC in H_2O-CH_3COOH mixed solution systems. Physico-chemical study recognized useful tool in getting sound information about the structure of various solution system. The specific aims of this study are:

i)   to be aware of the probable interaction of NAC in H_2O-CH_3COOH solution;

ii)   to explore the data on physico-chemical properties of the systems mentioned above;

iii)   to explore the role of NAC in physico-chemical interactions of all the systems and

iv)   to understand the change in thermodynamic properties of NAC in H_2O-CH_3COOH mixture.

CHAPTER III

Experimental

3.1 General

During the course of the present work a number of techniques were involved which were in general standard ones. Constant efforts for attaining the ideal conditions for the experiments were always attempted.

The thoroughly cleaned glass pieces were dried in electric oven. The smaller pieces of apparatus were dried in electric oven and stored in desiccators, while larger pieces of apparatus were used directly from the oven.

Cannon-Fenske Opaque Viscometers were used for measurement of viscosity. The inside wall of the viscometer was cleaned thoroughly with warm chromic acid so that there was no obstruction in the capillary and the liquid could run clearly without leaving any drop behind. It was then rinsed thoroughly with distilled water followed by rectified spirit and finally with acetone and dried.

3.2 Apparatus

Viscosities of various liquids were measured using Cannon-Fenske Opaque Viscometers. And the densities were measured by Density and Sound Velocity Meter (DSA 5000M) Anton Paar, Austria. Electronic balance (HR 200, made in Japan) with an accuracy of$\pm$ 0.0001g was used for weighing. The flow time of liquids were recorded by a stop-watch capable to read up to 0.01 seconds. The temperature was controlled by water thermostat (Fisher Scientific ET-150, HAKKE, Germany) with an accuracy of $\pm$ 0.05°C. The experimental temperatures were 298.15 to 323.15K at 5K intervals. Viscometers were calibrated with doubled-distilled water at the studied temperature. Calibrated volumetric flask, pipette and burette were used for necessary volume measurement.

3.3 Preparation and Purification of Reagents

High quality analytical grade reagents were used in all the experiments and where necessary further purifications were done.

3.4 Distillation of water

First time water was distilled by water distillation apparatus. First time distilled water was further purified by a quick-fit glass made distillation apparatus. About 1.5 L water was taken in a round bottom reservoir of which the capacity was 2.0 L. Then it was distilled in presence of $KMnO_4$. Distilled water was collected at only 100°C. Other liquids of which the temperatures were below and above the mentioned boiling point were discarded. In all the experiments double distilled water was used.

3.5 Chemicals

N-acetylcysteine was collected from Sigma Aldrich, USA. Acetic acid,(CH_3COOH) (HPLC Grade) was collected from E-Merck, Germany. All chemicals and reagents were of analytical grade and were used without further purification.

3.6 Preparation of solution

Solutions were prepared by mixing appropriate amount of NAC in H_2O-CH_3COOH mixed solvents using measuring flask. NAC was weighed by electronic balance (HR 200, made in Japan) with an accuracy of $\pm$ 0.0001g. The volume taken by using pipette was corrected up to 0.1 cm^3. The volume of each component used as taken converted into molar solution.Stopper of measuring flask was kept closed to prevent evaporation and introduction of moisture into the solution.

3.7 Density measurement

The densities were measured byDensity and Sound Velocity Meter (DSA 5000M) Anton Paar, Austria. The densities of solvents and solutions were measured separately. For this solvent and solutions were poured into the Density and Sound Velocity Meter through injection by syringe. The investigated temperatures were selected manually and the experimental data of density values were recorded automatically in the machine. Then the results were collected from the data memory. Precautions were taken in every injection and after each ejection machine was cleaned properly by ethanol, acetone on the basis of inorganic and organic solvents used.

3.8 Viscosity measurement

Viscosity of water, acetic acid and several solutions were measured by using the Cannon-Fenske Opaque Viscometers. The interior of the viscometer was cleaned thoroughly with warm chromic acid and then with distilled water, so that there was no obstruction in the capillary and the liquid could run freely without leaving any drop behind. It was then rinsed with acetone and dried in an oven at about 85°C. The viscometer was then clamped vertically in the thermostatic water bath such that the upper mark of the top bulb was well below the water level. 10.0 mL of doubled-distilled water was poured into the viscometer by a pipette.Then it was allowed to keep in the thermostatic bath for about 30 minutes to attain the bath temperature. With the help of pipette filler attached to the narrower limb of the viscometer, the water was sucked up above the upper mark of the bulb. The water of bulb was then allowed to fall into the capillary and the time of fall between the two marks was noted with the help of stop-watch capable of reading up to 0.01 second. The reading at each temperature was repeated three/four even more times, in order to check the reproducibility of the flow time, the temperature being maintained at the same value. Since the accurate viscosity and density of water at different temperatures are known (from literature) calibration constant A of the viscometer for different temperature were obtained by using equation,

$$\eta = A\rho t \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1.2.16)$$

Where, $A = \dfrac{\eta_{H_2O}}{\rho_{H_2O} \cdot t_{H_2O}}$

Like water, the flow time of different solutions were determined. Then putting the values of the calibration constant, density and time of flow of the experimental solutions, the viscosities of the solutions were determined by using the equation 1.2.16.

3.9 Apparent Molar Volume measurement:

Apparent molar volumes were determined from measured densities of solvent and solution by using the following equation 1.2.8.

$$\varphi_v = \left[\frac{1000(\rho_0 - \rho)}{C\rho_0}\right] + \frac{M_2}{\rho_0} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1.2.8)$$

Where φ_v is the apparent molar volume, C is the molarity, M_2 is the molecular mass of the solute (NAC), and ρ_0 and ρ are the densities of the solvent and the solution respectively. In general, φ_v was found to vary linearly with concentration for the systems studied. Thus, φ_v data were fitted into equation1.2.13 and 1.2.18.

$$\varphi_v = \varphi_v^0 + S_v \sqrt{c} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1.2.13)$$

$$\varphi_v = \varphi_v^0 + S_v \sqrt{C} + b_v C \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1.2.18)$$

Where φ_v is the apparent molar volume at infinite dilution and b_v is an experimentally determined parameter.

3.10 Determination of Thermodynamic Parameters

The activation energy for viscous flow is determined from logarithmic form of Eyring equation as:

$$ln\eta = lnA - \frac{\epsilon_a}{RT} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1.2.27)$$

The slope and intercept of the straight line of plot of $ln\eta$ vs $\frac{1}{T}$ presented the values of activation energy for viscous flow and Arrhenius constant respectively.

Values of enthalpy of activation, ΔH^* and entropy of activation, ΔS^* for per mole for viscous flow of solutions have been calculated from the relationship (1.2.30)

$$ln\frac{\eta V}{hN} = \frac{\Delta H^*}{RT} - \frac{\Delta S^*}{R} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1.2.30)$$

CHAPTER-IV

Results and Discussion

4.1 Investigated Systems

The whole research work has been designed within six investigated systems to identify the change of interaction in various concentrations of NAC in different binary and ternary solution of CH_3COOH and water, which will provide the change of information in volumetric, viscometric and thermodynamic properties of solutions to determine the molecular interactions among NAC, CH_3COOH and water. The investigated systems are:

   i) $NAC-H_2O$
   ii) $NAC-CH_3COOH$
   iii) NAC in [9:1] [$H_2O -CH_3COOH$]
   iv) NAC in [4:1] [$H_2O -CH_3COOH$]
   v)   NAC in [7:3] [$H_2O -CH_3COOH$]
   vi) NAC in [3:2] [$H_2O -CH_3COOH$]

4.2 Volumetric Properties

4.2.1 Density of Pure Solvent

The density at different temperatures of the pure solvents; CH_3COOH and water have been tabulated in Table 4.1 with the literature values [53-54] for possible comparison. The larger density values of CH_3COOH indicate that CH_3COOH is denser than water at all investigated temperatures. From the table it is also seen that densities of the solvents decreased with the increasing temperature as expected and provide almost same results as mentioned in the cited literatures. It indicates that the solvents being used in the experiments were pure and analytical grade as declared by suppliers.

Table 4.1: Density, ρ values of CH$_3$COOH and Water at 298.15 to 318.15 K at 5 K interval

Temperature (K)	Density (g.cm^{-3}) of CH$_3$COOH		Density (g.cm^{-3}) of Water	
	Literature Value	Experimental Value	Literature Value	Experimental Value
298.15	1.0480 [53]	1.0479	0.9971 [54]	0.9970
303.15	1.0422 [53]	1.0423	0.9957 [54]	0.9956
308.15	1.0368 [53]	1.0367	0.9940 [54]	0.9940
313.15	1.0314 [53]	1.0311	0.9922 [54]	0.9921
318.15	1.0257 [53]	1.0255	0.9902 [54]	0.9901

4.2.2 Density of NAC−H$_2$O Binary System

The density values, ρ of different concentration of NAC (0.1004, 0.3005, 0.5004, 0.702 and 1.0008) M the in water solutions have been investigated at 298.15, 303.15, 308.15, 313.15 and 318.15 K temperatures. The density values are shown in Table 4.2. The density values of (NAC−H$_2$O) systems at 5 investigated temperatures are higher than those of water even the values increased with increasing the amount of NAC in water. It is seen from the result that densities of aqueous NAC solution increased with increasing concentration within the investigated composition (~0.10 to ~1.00) M of NAC in water. Comparing the results in Table 4.1 with the density values of water it can be stated that density values of solution of NAC in water are higher than those of pure water. Density values of the NAC−H$_2$O in Table 4.2 have fitted in Figure 4.1. From the Figure 4.1 it is seen that density values of NAC in water increased linearly with the concentration of the NAC within the temperature range of 298.15 K to 318.15 K at 5 K interval. This increase in density in NAC−H$_2$O binary system may be due to solute-solute, solute-solvent interaction through strong hydrogen bond, dipole-dipole as well as acid-base interaction between NAC and water. Detail mechanism of dissolution of NAC in water is still unknown. With increasing temperature internal energy of the molecules present in the systems is increased. As we know from the first law of thermodynamics, if energy of a

system is increased then work is done on the system and changed it mode of dimension blindly, *e.g.,* increase in volume, plus some heat is absorbed. In other words, heat and work are equivalent ways of changing a system's internal energy [55]. So with increasing temperature as well as the internal energy solute–solvent interaction may be weaken and the volume is increased; the resultant is the lessen of densities.Possible interactions which occurred when NAC is dissolved in aqueous solution can be described as below:

The possible interactions between NAC and Water

NAC molecules in aqueous solution behave as weak acid because of its –COOH functional group that releases proton and exhibits negative charge and producing H_3O^+ ion in solution.

$$C_5H_9NO_3S + H_2O \rightleftharpoons C_5H_8NO_3S^- + H_3O^+$$
$$\text{NAC} \qquad\qquad [\text{NAC}]^-$$

The amide and thiol group of NAC may form H–bond as well as dipole-dipole interaction with water. The solvation system has shown above.

Table 4.2: Density values, ρ of N-Acetylcysteine in water system at 298.15 to 318.15 K at 5 K interval

Name of the system	Conc. (mol.L^{-1})	Density, ρ (g.cm^{-3})				
		298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
NAC−H$_2$O	0.1004	1.0015	1.0000	0.9983	0.9964	0.9943
	0.3005	1.0102	1.0086	1.0067	1.0046	1.0024
	0.5004	1.0187	1.0169	1.0149	1.0126	1.0103
	0.7020	1.0271	1.0251	1.0229	1.0205	1.0181
	1.0008	1.0393	1.0371	1.0347	1.0321	1.0296
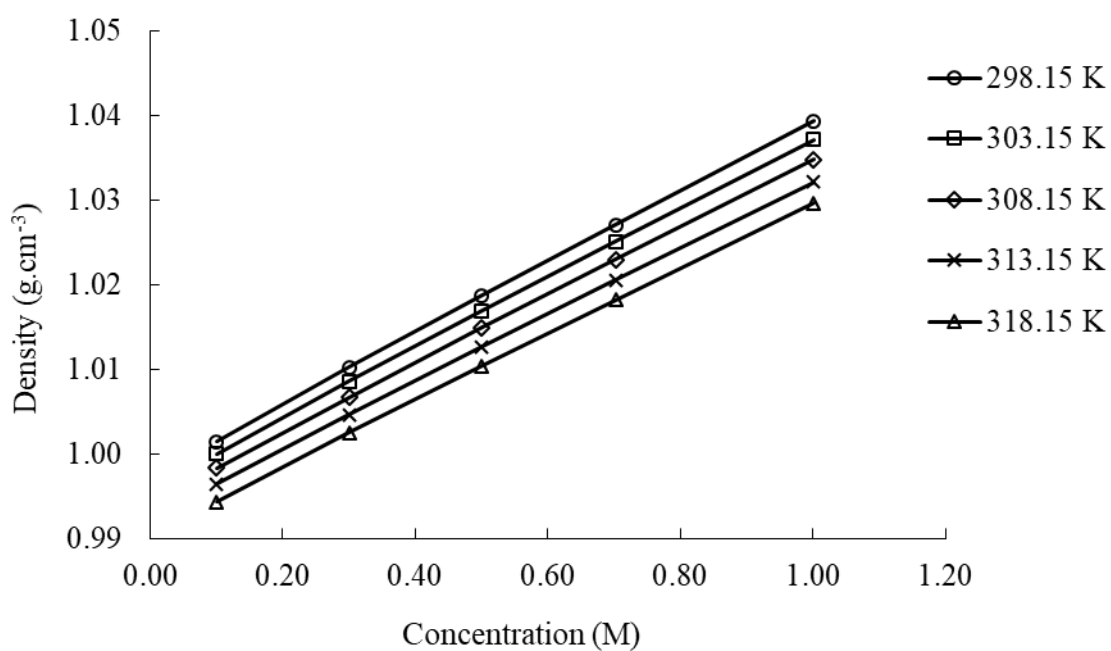
Figure 4.1: Densities, ρ vs concentration (M) of N-Acetylcysteine in water system at 298.15 to 318.15 K at 5 K interval

4.2.3 Density of NAC–CH₃COOH Binary System

The density values, ρ of different concentration of NAC (0.1006, 0.3004, 0.5007, 0.7011, and 1.001) M in CH_3COOH have been investigated at 298.15, 303.15, 308.15, 313.15 and 318.15 K temperatures. The density values of NAC–CH_3COOH binary systems have been shown in Table 4.3 at different temperatures. Composition of NAC in CH_3COOH were increased from (~0.10 to ~1.00) M. From the results shown in Table 4.3 and 4.1 it can be stated that density values of NAC–CH_3COOH binary solution are higher than those of the pure CH_3COOH. It is also seen that the density values of NAC solutions in CH_3COOH increased remarkably with increasing concentration at all the temperatures. The data of the Table 4.3 has been fitted in Figure 4.2. From the Figure 4.2 it is seen that density values of NAC in CH_3COOH has increased linearly with the increase in the concentration of the NAC. This increase in density of NAC–CH_3COOH binary system may be due to the solute–solvent interaction through hydrogen bond, dipole-dipole interaction between NAC and CH_3COOH. Comparing Table 4.2 and 4.3 we can see that the density values of NAC–CH_3COOH is higher than NAC–H_2O binary system. It is also seen that density values of the investigated binary systems decreased with increasing temperature at a specific concentration as shown in Figure 4.2. With increasing temperature as well as the internal energy; solute–solvent interaction may be weaken and the volume is increased; the resultant is the lessen of densities have been discussed in the earlier section 4.2.2.

Table 4.3: Density values, ρ of N-Acetylcysteine in CH₃COOH system at 298.15 to 318.15 K at 5 K interval

| Name of the system	Conc. $(mol.L^{-1})$	Density, ρ $(g.cm^{-3})$				
		298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
NAC–CH₃COOH	0.1006	1.0519	1.0462	1.0406	1.0351	1.0294
	0.3004	1.0599	1.0543	1.0487	1.0430	1.0374
	0.5007	1.0683	1.0627	1.0570	1.0514	1.0458
	0.7011	1.0771	1.0715	1.0658	1.0602	1.0546
	1.0010	1.0901	1.0846	1.0790	1.0732	1.0678
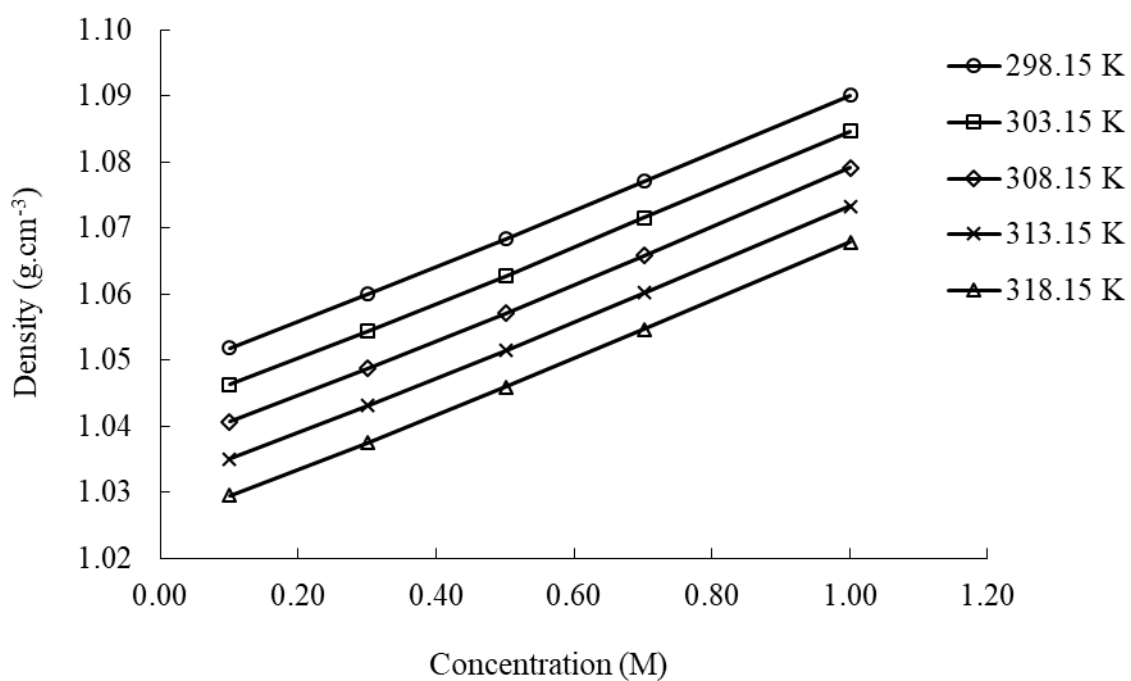
Figure 4.2: Density values, ρ vs concentration (M) of N-Acetylcysteine in CH₃COOH system at 298.15 to 318.15K at 5 K interval

4.2.4 Density of $CH_3COOH–H_2O$ Binary System

$H_2O–CH_3COOH$ mixtures are very important systems exhibiting properties that are of great interest in physics, chemistry and biology. These include several thermodynamic and physico-chemical properties. The density values for $H_2O–CH_3COOH$ have also been identified for further calculations as shown in the Table 4.4. With the increasing amount of CH_3COOH in the binary mixture of $H_2O–CH_3COOH$; the density increases. The values are larger than CH_3COOH but smaller than water.

Table 4.4: Experimental density values, ρ of [9:1], [4:1], [7:3] and [3:2] [$H_2O–CH_3COOH$] systems at 298.15 to 318.15 K at 5 K interval

Name of the system	Experimental Value, ρ (g.cm^{-3})				
	298.15K	303.15K	308.15K	313.15K	318.15K
[9:1] [$H_2O–CH_3COOH$]	1.0033	1.0018	1.0009	1.0007	1.0005
[4:1] [$H_2O–CH_3COOH$]	1.0240	1.0213	1.0184	1.0154	1.0121
[7:3] [$H_2O–CH_3COOH$]	1.0406	1.0372	1.0336	1.0292	1.0268
[3:2] [$H_2O–CH_3COOH$]	1.0601	1.0556	1.0511	1.0478	1.0422

4.2.5 Density of $NAC−CH_3COOH−H_2O$ Ternary System

The densities, ρ of the five specific concentration of NAC in [9:1], [4:1], [7:3] and [3:2] [$H_2O–CH_3COOH$] systems at 298.15K to 318.15 K at 5K interval has been investigated. The density values have shown in Table 4.5. The density values of NAC in [3:2] [$H_2O−CH_3COOH$] ternary systems are the highest than all other ternary and also than those of both $NAC−H_2O$ and $NAC−CH_3COOH$ binary systems. The density values increased with increasing concentration of NAC in $H_2O−CH_3COOH$ at the entire investigated composition range, (~0.10 to ~1.00) M NAC in mixed solvents. Comparing the results in Table 4.1, 4.2, 4.3, 4.4 and 4.5 it can be stated that densities of NAC in $H_2O−CH_3COOH$ increased remarkably with concentration at all the temperatures. The values of the Table 4.5 are fitted in Figure 4.3-4.6. From the figures it is seen that the

densities of NAC in [9:1], [4:1], [7:3] and [3:2] [H_2O–CH_3COOH] systems increased linearly with the concentration of the NAC within the temperature range of 298.15 K to 318.15 K at 5 K interval. It is seen that with increasing amount of water in NAC–CH_3COOH–H_2O systems density values increased. At the same time NAC is also a polar organic solute (with –COOH, –SH, CH_3CONH–functional groups). So with increasing the ratio of CH_3COOH in H_2O–CH_3COOH systems amount of solvation with strong interaction took place between NAC and increased amount of water as a result densities increased. It is also seen that density values of the investigated ternary systems decreased with increasing temperature at a specific concentration as shown in Table 4.5 and Figure 4.3-4.6. It is already mentioned that with increasing temperature internal energy increased which affect or increase the vibrational, rotational and translational state of the system. As a result volume of the system increased and density values decreased.

In case of ternary systems, the highest densities observed for NAC in [3:2] [H_2O–CH_3COOH] system, probably highest dipole-dipole interactions in addition to other forces. On the other hand NAC in [9:1] [H_2O– CH_3COOH] system showed lowest interaction might be due to minimum dipole-dipole forces, comparison to other ternary systems. In ternary systems the interaction increased with the increase of the ratio of CH_3COOH and the order is:

NAC in [3:2] [H_2O–CH_3COOH] > NAC in [7:3] [H_2O–CH_3COOH] > NAC in [4:1]
[H_2O–CH_3COOH] > NAC in [9:1] [H_2O–CH_3COOH]
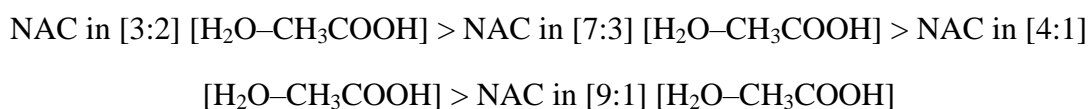
In presence of NAC in polar mixtures hydrophilic and hydrophobic interaction in solvent-solvent, solvent-solute; H-bond and other forces of interaction, like van der Waal's forces increased the interactions among the molecules and increased the density than those of the binary systems e.g., CH_3COOH–H_2O, NAC–CH_3COOH, NAC–H_2O; even the pure systems. The order density of different systems may be as follows:

NAC in [3:2] [H_2O–CH_3COOH] > NAC–CH_3COOH > NAC in [7:3] [H_2O–CH_3COOH] > NAC in [4:1] [H_2O–CH_3COOH] > NAC–H_2O > NAC in [9:1] [H_2O–CH_3COOH]

Table 4.5: Density values, ρ of N-Acetylcysteine in [9:1], [4:1], [7:3] and [3:2] [H_2O–CH_3COOH] systems at 298.15 to 318.15 K at 5 K interval

Name of the system	Conc. (mol.L^{-1})	Density, ρ (g.cm^{-3})				
		298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
NAC in [9:1] [H_2O– CH_3COOH]	0.1005	1.0085	1.0069	1.0059	1.0057	1.0054
	0.3005	1.0186	1.0168	1.0157	1.0153	1.0149
	0.5019	1.0285	1.0265	1.0253	1.0247	1.0241
	0.7026	1.0383	1.0361	1.0347	1.0338	1.0328
	1.0003	1.0524	1.0498	1.0479	1.0467	1.0454
NAC in [3:2] [H_2O– CH_3COOH]	0.1018	1.0279	1.0251	1.0222	1.0192	1.0159
	0.3009	1.0359	1.0331	1.0302	1.0272	1.0240
	0.5019	1.0445	1.0416	1.0387	1.0357	1.0325
	0.7027	1.0531	1.0503	1.0474	1.0445	1.0413
	1.0020	1.0662	1.0635	1.0606	1.0576	1.0545
NAC in [7:3] [H_2O– CH_3COOH]	0.1001	1.0436	1.0401	1.0365	1.0320	1.0296
	0.3012	1.0497	1.0461	1.0425	1.0380	1.0355
	0.5012	1.0560	1.0524	1.0486	1.0441	1.0415
	0.7009	1.0624	1.0587	1.0549	1.0504	1.0476
	1.0002	1.0721	1.0684	1.0645	1.0599	1.0569
NAC in [1:4] [H_2O– CH_3COOH]	0.1008	1.0621	1.0577	1.0531	1.0498	1.0442
	0.3017	1.0665	1.0621	1.0574	1.0540	1.0485
	0.5003	1.0712	1.0667	1.0620	1.0585	1.0530
	0.7026	1.0760	1.0715	1.0668	1.0632	1.0577
	1.0020	1.0833	1.0788	1.0742	1.0705	1.0650

Figure 4.3: Densities, ρ vs concentration (M) of N-Acetylcysteine in [9:1] [H_2O–CH_3COOH] system at 298.15 to 318.15 K at 5 K interval

Figure 4.4: Densities, ρ vs concentration (M) of N-Acetylcysteine in [4:1] [H_2O–CH_3COOH] system at 298.15 to 318.15 K at 5 K interval

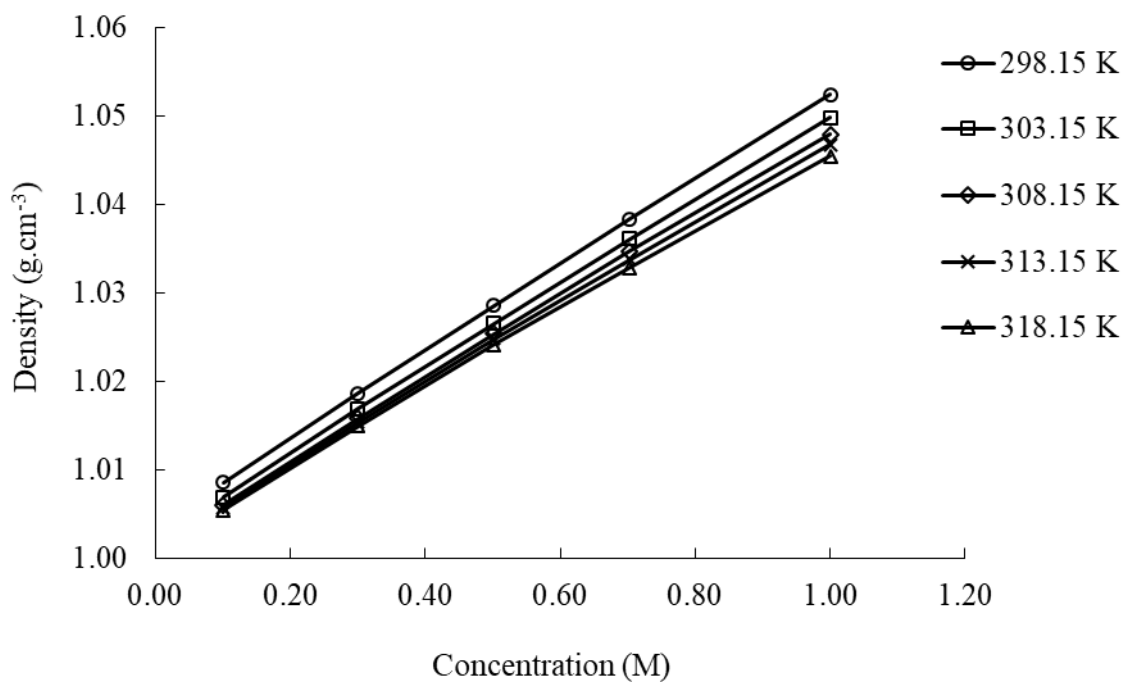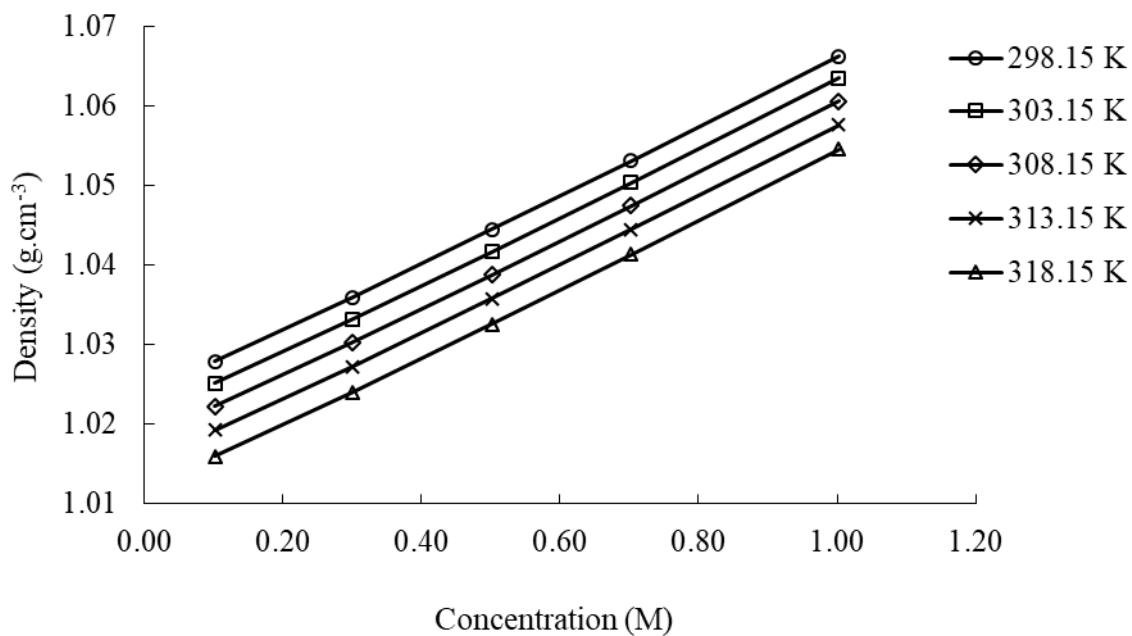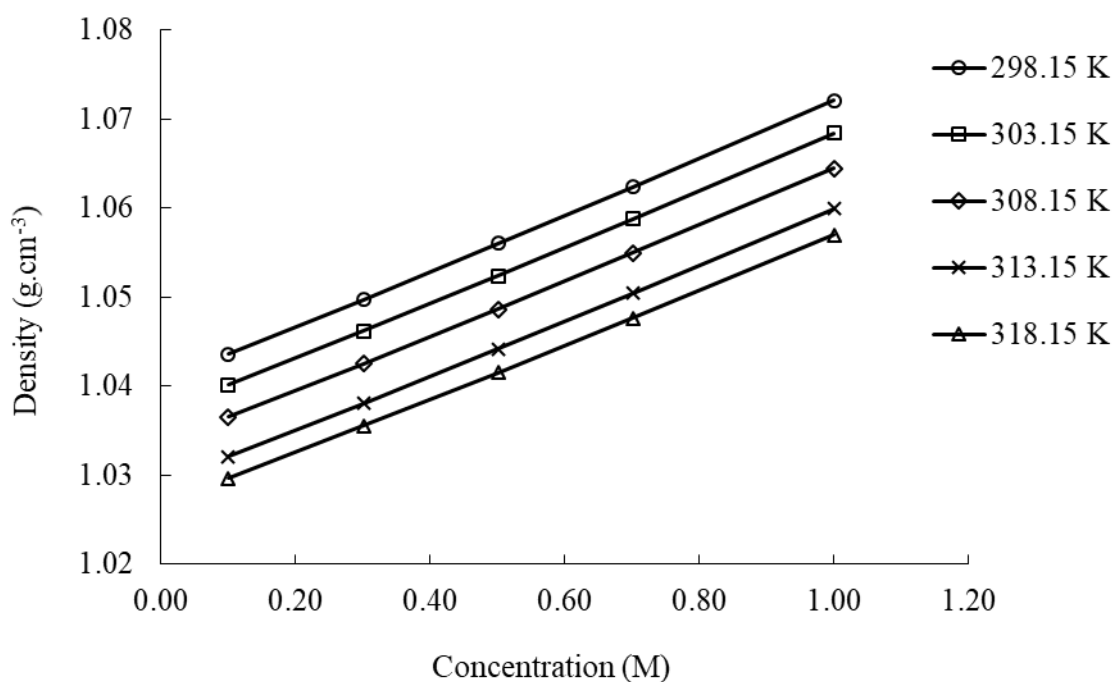Figure 4.5: Densities, ρ vs concentration (M) of N-Acetylcysteine in [7:3] [H_2O–CH_3COOH] system at 298.15 to 318.15 K at 5 K interval
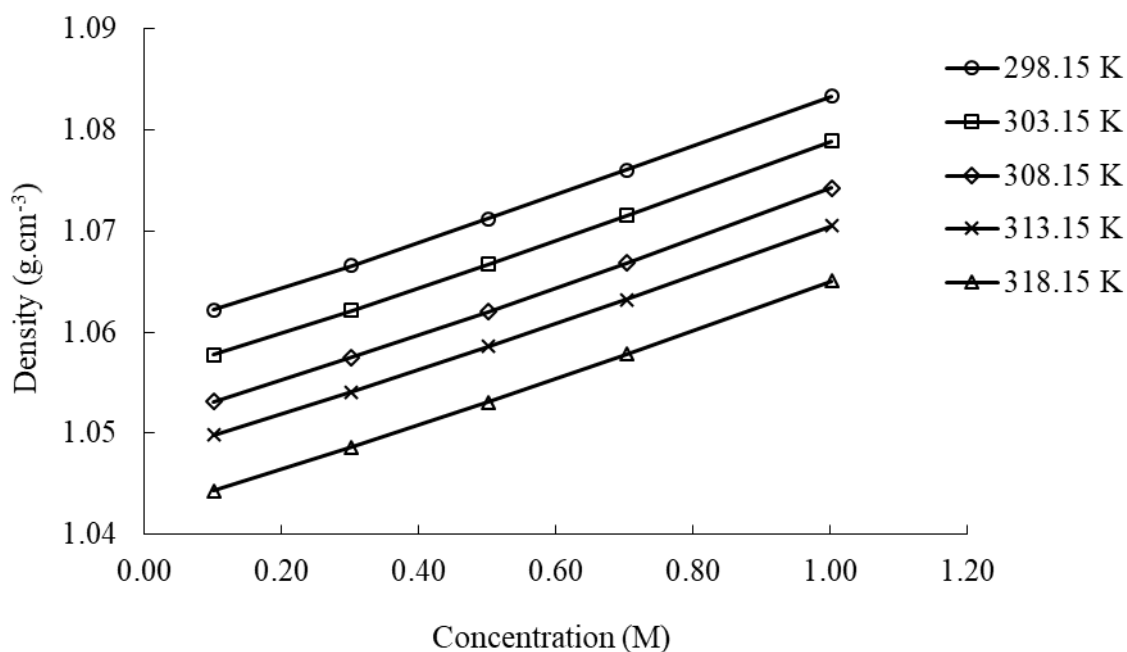
Figure 4.6: Densities, ρ vs concentration (M) of N-Acetylcysteine in [3:2] [H_2O–CH_3COOH] system at 298.15 to 318.15 K at 5 K interval

4.3 Apparent Molar Volume

The volumetric properties of NAC in solution can provide useful information in elucidating the interactions which occur in water, CH_3COOH as well as H_2O–CH_3COOH mixed solutions. NAC possessing both polar and non-polar groups have potential effects on the structure or molar volume of water, CH_3COOH as well as H_2O–CH_3COOH mixed solutions exhibit interactions of particular important applications. Hydrophobic interactions between the organic parts of NAC and CH_3COOH may play an important role in the stability in the mixture even when water is added to it. From a theoretical point of view, the most useful quantities are the limiting values of the apparent molar volume since these values depend only on the intrinsic size of the ion and on ion-solvent interaction. Moreover, the interactions of solutes with water may influence their accession to, and binding with, receptor sites, thus influencing their perception properties. In order to investigate the nature of the solute-solute and solute–solvent interactions of NAC in aqueous CH_3COOH solution, the apparent molar volume and apparent molar volume at infinite dilution were determined.

4.3.1 Apparent Molar Volume of NAC–H_2O Binary System

The apparent molar volume of different concentration (~0.10 to ~1.00) M of NAC in water solution has been determined at 298.15 to 318.15 K temperatures at 5K interval by using equation 1.2.8. The values of apparent molar volume of NAC–H_2O binary system has been shown in the Table 4.6. The graphical representation of the φ_v values of NAC–H_2O binary system has been shown in Figure 4.8. The apparent molar volume values vary linearly with square root of concentration of NAC solution.

It is seen that apparent molar volume is dependent upon the concentration of NAC as well as on temperature. The values have been found to be positive throughout the whole concentration range for NAC in water medium. The apparent molar volumes of NAC in water were found to be increased with the increasing concentration at all temperatures. Moreover the increase in magnitude of φ_v values with an increase in molarities of NAC suggest that the presence of ion-ion or solute-solute interactions [56].

The increase of apparent molar volume values of NAC with concentrations may be attributed to the increase in solvent-solvent, solute-solvent and the solute-solute interactions. In the case of solvent-solvent interaction: in H_2O–H_2O there are H-bond and

dipole-dipole interaction might be present. When the concentration of NAC is increased in NAC–H_2O system it is assumed that in addition to solute-solvent interactions NAC molecules may interact through S⋯S linkage that link two molecules together, commonly termed as solute–solute interaction [57-58]. Every S⋯S linkage is made between two molecules of NAC serves as a "staple" holding them in a more steady position.

However the φ_v values of NAC in water also increase with a rise in temperature in the system which suggests that at higher temperature significant solute-solvent interactions present in the mixtures.

Table 4.6: Apparent molar volume, φ_v of NAC in water system at 298.15 to 318.15 K at 5 K interval

Name of the system	Conc. (mol.L^{-1})	Apparent molar volume, φ_v (cm^3.mol^{-1})				
		298.15K	303.15 K	308.15 K	313.1 K	318.15 K
NAC–H_2O	0.1004	119.17	119.96	121.17	122.16	122.98
	0.3005	119.65	120.55	121.70	122.81	123.53
	0.5004	120.23	121.17	122.17	123.31	124.07
	0.7020	120.73	121.68	122.65	123.71	124.53
	1.0008	121.24	122.23	123.19	124.23	124.96
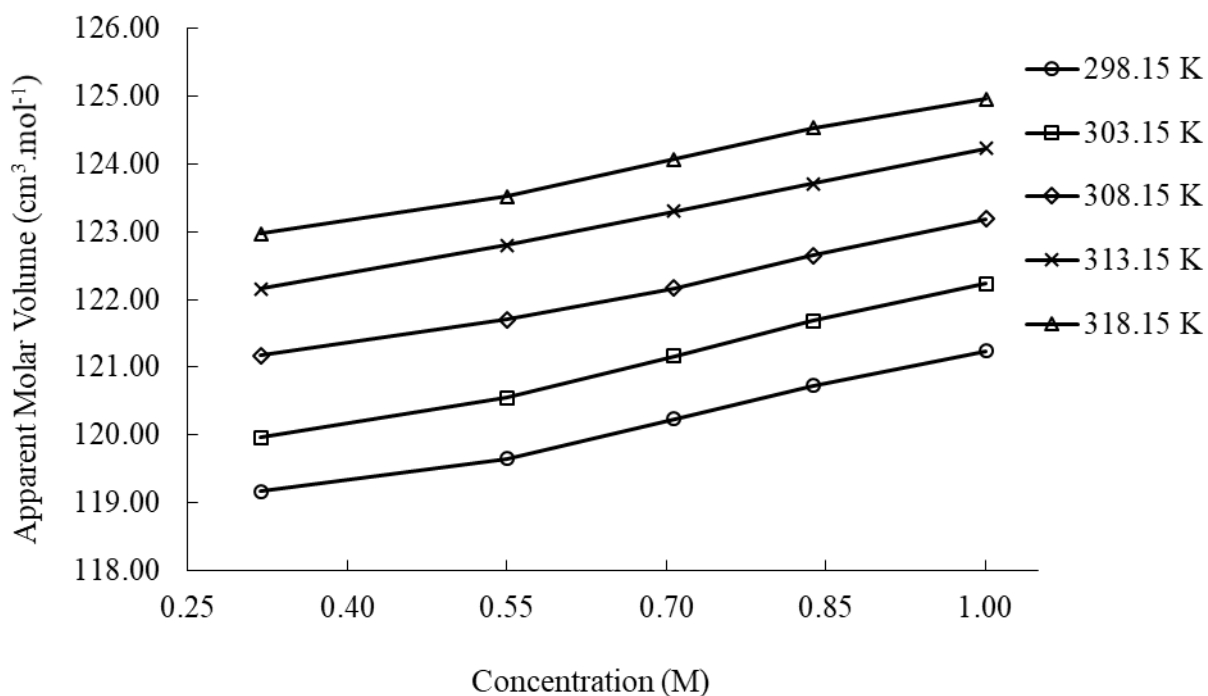
Figure 4.7: Apparent molar volume, φ_v vs concentration (M) of N-Acetylcysteine in water
system at 298.15 to 318.15 K at 5 K interval

4.3.2 Apparent Molar Volume of NAC−CH₃COOH Binary System

The apparent molar volume of NAC−CH₃COOH binary system has been determined in
different concentration (~0.10 to ~1.00) M of NAC from 298.15 to 318.15 K temperature
at 5K interval by using equation 1.2.8. The values of apparent molar volume of
NAC−CH₃COOH binary system has been shown in the Table 4.7. The graphical
representation of the φ_v values of NAC−CH₃COOH binary system has been shown in
Figure 4.9. The apparent molar volume decreased linearly with square root of
concentration of NAC solution.

It is seen that apparent molar volume is dependent upon the concentration of NAC as
well as on temperature. The values have been found to be positive throughout the whole
concentration range for NAC in CH₃COOH. The apparent molar volume of NAC in
CH₃COOH has been found to be decreased with the increasing concentration at all
temperatures. As we know a decrease in magnitude of φ_v values with an increase in
molarities of NAC suggest that the presence of ion−dipole interactions [56].

The decrease of apparent molar volume values of NAC with concentrations may be attributed to the increase in solvent-solvent and solute-solvent interactions. In the case of solvent-solvent: in CH_3COOH–CH_3COOH there are dipole-dipole and van der Waal's force of attraction might be present. It also contains hydrophobic group which interact with the hydrophobic group of NAC. As a result solute-solvent interactions increases in NAC–CH_3COOH binary system.

However the φ_v values increase with a rise in temperature in NAC–CH_3COOH system which suggests that at higher temperature significant solute-solvent interactions are present in the mixtures. It is clearly seen that, the φ_v values of NAC–CH_3COOH is the highest between binary systems at all the temperatures. The apparent molar volume, φ_v of NAC in all concentrations and temperatures in water and CH_3COOH has been found in the order of:

$$NAC–CH_3COOH > NAC–H_2O$$

Table 4.7: Apparent molar volume, φ_v of NAC in CH_3COOH system at 298.15 to 318.15 K at 5 K interval

| Name of the system	Conc. $(mol.L^{-1})$	Apparent molar volume, φ_v $(cm^3.mol^{-1})$				
		298.15K	303.15 K	308.15 K	313.1 K	318.15 K
NAC–CH_3COOH	0.1006	118.48	119.18	119.86	120.55	121.28
	0.3004	117.57	118.26	119.03	119.75	120.48
	0.5007	116.88	117.48	118.33	118.89	119.52
	0.7011	116.12	116.65	117.40	118.07	118.65
	1.0010	115.56	116.04	116.62	117.44	117.92
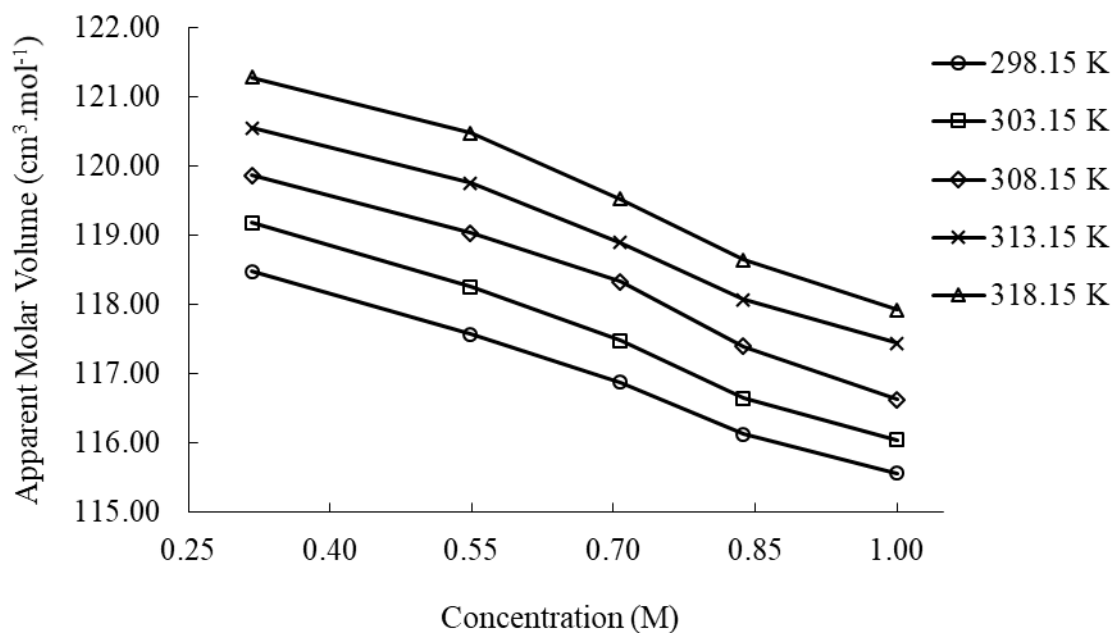
Figure 4.8: Apparent molar volume, φ_v vs concentration (M) of N-Acetylcysteine in CH$_3$COOH system at 298.15 to 318.15 K at 5 K interval

4.3.3 Apparent Molar Volume of NAC−CH$_3$COOH−H$_2$O Ternary System

The apparent molar volume of NAC in CH$_3$COOH−H$_2$O mixture systems have been determined at various concentration (∼0.10 to ∼1.00) M of NAC from 298.15 to 318.15 K temperature at 5 K interval by using equation 1.2.8. The values of apparent molar volume of the ternary systems have been shown in the Table 4.8. It is seen that like binary systems, apparent molar volume is also dependent upon the concentration of NAC as well as on temperature. The values have been found to be positive throughout the whole concentration range for NAC in all ternary solution. The apparent molar volume of NAC−CH$_3$COOH−H$_2$O system has found to be decreased at [4:1], [7:3] and [3:2] [H$_2$O−CH$_3$COOH] solvent systems with increasing the concentration of NAC which suggested that in addition to ion-dipole interaction, ion-ion interaction might be supplemented there but solute-solvent interaction became predominant in [4:1], [7:3] and [3:2] [H$_2$O−CH$_3$COOH] solvent systems [56]. But in case of [9:1] [H$_2$O−CH$_3$COOH]

solvent systems apparent molar volume of NAC has found to be increased which suggests that the presence of ion-ion interactions [56].

Moreover, apparent molar volumes were found to be increased with increasing temperature at any concentration of the solution and the reason has been discussed earlier for the binary systems in section 4.3.1 and 4.3.2.

The φ_v values have also found to be increased with the increase in the ratio of acetic acid in ternary systems. The graphical representation of the φ_v values of ternary systems has been shown in Figure 4.9-4.12. It is seen from the Figure 4.9-4.12, the stacked line of apparent molar volumes, φ_v versus concentration of NAC in CH_3COOH–H_2O solutions; represent the trend of the contribution of each apparent molar volume over concentration. From the Figure 4.10-4.12 it is seen that φ_v values decrease against concentration of NAC and from Figure 4.9 it is seen that φ_v values increase against concentration of NAC in all cases of NAC–CH_3COOH–H_2O ternary solutions. But a remarkable increase of the φ_v properties have been seen in case of temperature.

From the above discussion about apparent molar volume reveals the following characteristics:

➢ Solute–solvent interaction in the NAC–CH_3COOH systems happened significantly

➢ Solute-solute interaction predominant in NAC–H_2O system at higher concentration of NAC

➢ Significant presence of solute–solute, solute–solvent interaction in the ternary systems

➢ H–bonding between NAC and solvents, *e.g.,* water and CH_3COOH ensued

➢ The apparent molar volume, φ_v are positive and large in magnitude

➢ φ_v increases with increasing temperature *i.e.,* temperature effect on φ_v is quite significant

Table 4.8: Apparent molar volume, φ_v of N-Acetylcysteine in [9:1], [4:1], [7:3] and [3:2] [H$_2$O–CH$_3$COOH] systems at 298.15 to 318.15 K at 5 K interval

Name of the system	Conc. (mol.L^{-1})	Apparent molar volume, φ_v (cm^3.mol^{-1})				
		298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
NAC in [9:1] [H$_2$O– CH$_3$COOH]	0.1005	111.56	112.16	112.90	113.62	114.53
	0.3005	112.05	112.89	113.73	114.45	115.27
	0.5019	112.63	113.63	114.41	115.18	116.11
	0.7026	113.03	114.15	114.99	116.01	117.12
	1.0003	113.76	115.00	116.10	117.10	118.24
NAC in [4:1] [H$_2$O– CH$_3$COOH]	0.1018	121.78	122.57	123.03	123.65	124.02
	0.3009	120.50	121.11	121.53	121.86	122.24
	0.5019	119.49	120.04	120.40	120.70	121.00
	0.7027	118.90	119.24	119.68	119.94	120.22
	1.0020	118.16	118.52	118.88	119.20	119.42
NAC in [7:3] [H$_2$O– CH$_3$COOH]	0.1001	128.22	129.02	129.84	130.61	131.29
	0.3012	127.74	128.46	129.25	130.05	130.74
	0.5012	127.31	128.03	128.81	129.54	130.33
	0.7009	126.96	127.62	128.40	129.16	129.96
	1.0002	126.57	127.21	128.00	128.71	129.54
NAC in [3:2] [H$_2$O– CH$_3$COOH]	0.1008	134.27	135.04	135.79	136.72	137.19
	0.3017	133.60	134.23	135.12	135.91	136.47
	0.5003	132.90	133.60	134.48	135.27	135.82
	0.7026	132.52	133.14	133.94	134.82	135.35
	1.0020	132.05	132.62	133.28	134.12	134.75

Figure 4.9: Apparent molar volume, φ_v vs concentration (M) of N-Acetylcysteine in [9:1] [H_2O–CH_3COOH] system at 298.15 to 318.15 K at 5 K interval
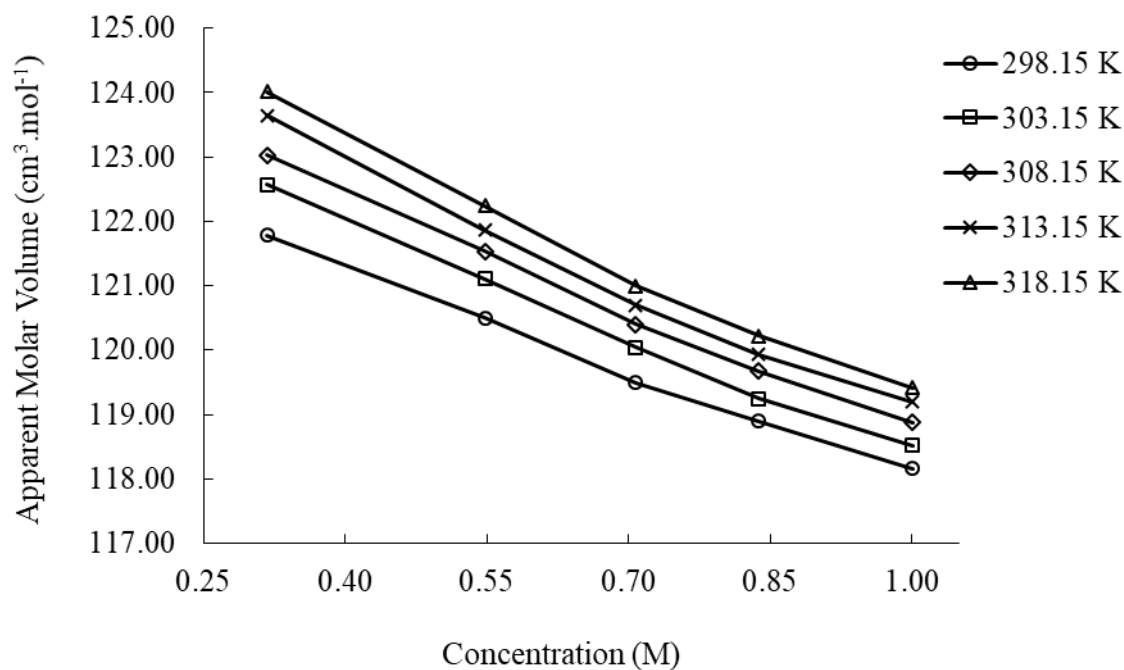
Figure 4.10: Apparent molar volume, φ_v vs concentration (M) of N-Acetylcysteine in [4:1] [H_2O–CH_3COOH] system at 298.15 to 318.15 K at 5 K interval
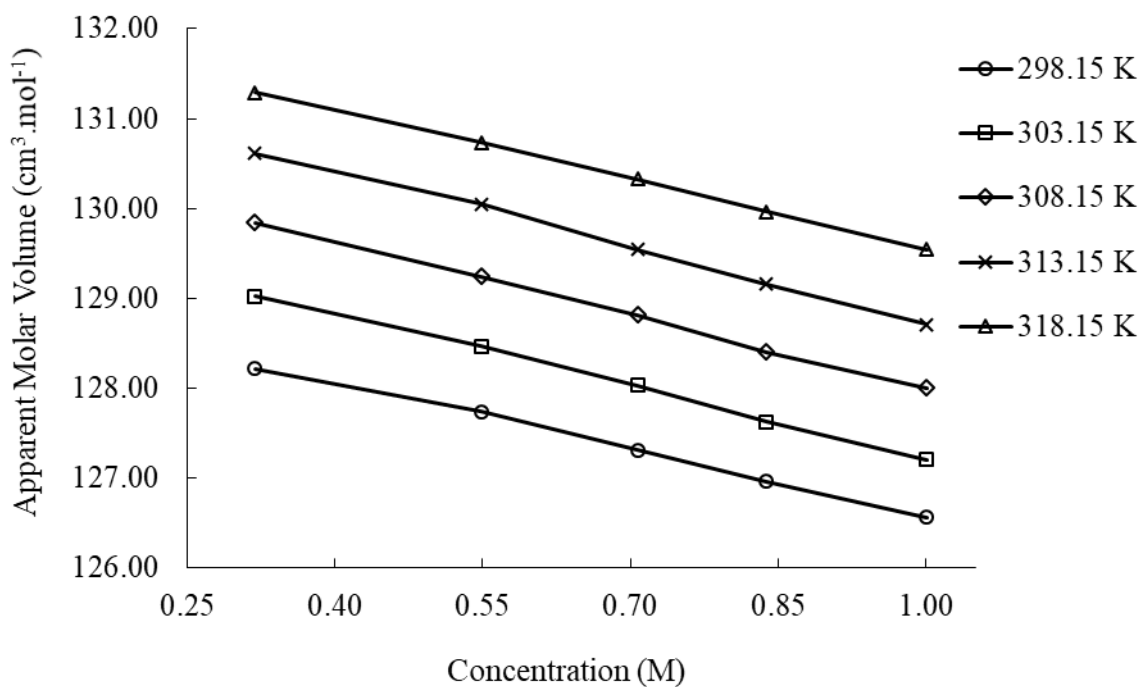
Figure 4.11: Apparent molar volume, φ_v vs concentration (M) of N-Acetylcysteine in [7:3] [H$_2$O–CH$_3$COOH] system at 298.15 to 318.15 K at 5 K interval

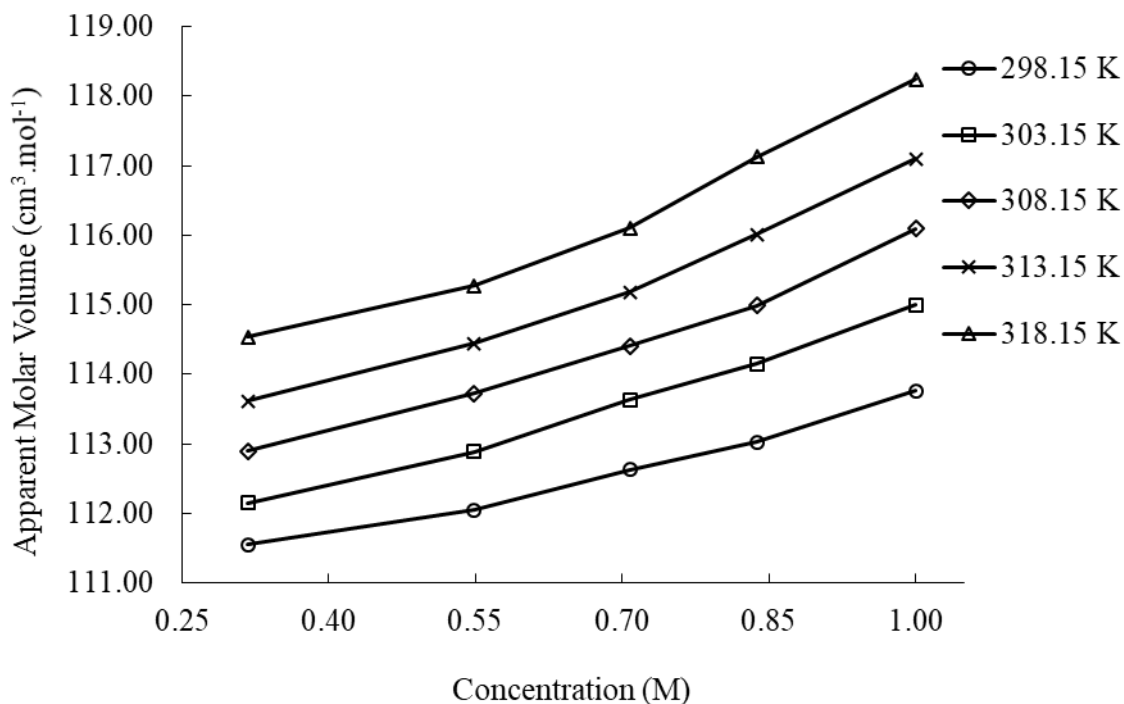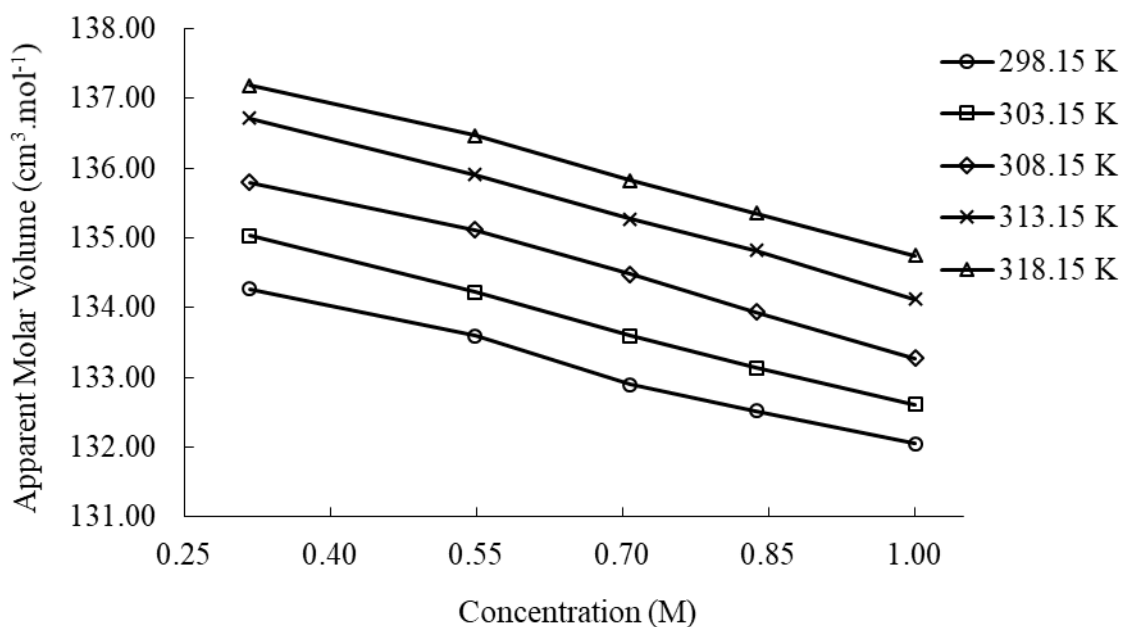Figure 4.12: Apparent molar volume, φ_v vs concentration (M) of N-Acetylcysteine in [3:2] [H$_2$O–CH$_3$COOH] system at 298.15 to 318.15 K at 5 K interval

4.4 Apparent molar volume at infinite dilution

Apparent molar volume at infinite dilution, φ_v^0 varies with the molarity of NAC as represented by the following equation. The apparent molar volume at infinite dilution gives an idea about the presence of solute−solvent interactions. The S_v is the experimental slopes which give an idea about the prevailing solute−solute interactions in the mixtures. The apparent molar volumes at infinite dilution, φ_v^0 values of NAC in water, CH_3COOH and $H_2O–CH_3COOH$ mixtures have been tabulated in Table 4.9. The results can be revealed as a function of both temperature and the structure of NAC. The φ_v^0 values of NAC reflect the true value of NAC at the specified temperatures. Apparent molar volumes at infinite dilution were computed from intercept of the plot between φ_v and $C^{1/2}$ as per following Masson equation 1.2.13.

$$\varphi_v = \varphi_v^0 + S_v \sqrt{c}$$

The apparent molar volumes, φ_v and square root of concentration, $C^{1/2}$ have been computed formerly to evaluate the value of apparent molar volume at infinite dilution which is the experimental intercept of graph between φ_v and $C^{1/2}$ and is a function of ion−solvent interactions. In case of NAC−H_2O and NAC in [9:1] [$H_2O–CH_3COOH$] solution the increase in φ_v^0 values with an increase in NAC molarity represents the volume expansion [56] due to less hydrophobic interactions. In the remaining systems the decrease in the φ_v^0 values with an increase in NAC molarity represents the volume contraction [56] due to increase of hydrophobic nature of the systems. However the φ_v^0 values increase with a rise in temperature in all systems due to weaken all sorts of interactions at higher temperatures present in the mixtures.

Table 4.9: Apparent molar volume, φ_v^0 at infinite dilution of NAC in CH$_3$COOH, water and [9:1], [4:1], [7:3] and [3:2] [H$_2$O–CH$_3$COOH] systems at 298.15 to 318.15 K at 5 K interval

Temperature (K)	Apparent molar volume at infinite dilution, φ_v^0 (cm^3.mol^{-1})					
	NAC–H$_2$O	NAC–CH$_3$COOH	NAC in [9:1] [H$_2$O–CH$_3$COOH]	NAC in [4:1] [H$_2$O–CH$_3$COOH]	NAC in [7:3] [H$_2$O–CH$_3$COOH]	NAC in 3:2] [H$_2$O–CH$_3$COOH]
298.15	118.0766	119.9116	110.4104	123.4387	129.0294	135.3376
303.15	118.8047	120.7529	110.7277	124.4269	129.9008	136.1657
308.15	120.1420	121.5517	111.3006	124.9199	130.7171	137.0562
313.15	121.1663	122.1686	111.8108	125.5790	131.5351	137.946
318.15	121.9773	123.052	112.5094	126.0463	132.1203	138.3791

4.5 S$_v$ parameter

The S$_v$ parameter is the resultant of experimental slope of graph between φ_v and C$^{1/2}$ and is a function of ion–ion interactions. Sign of S$_v$ gives information about the structural influence of solute on solvent system that is, whether solute acts as a structure promoting or structure breaker [59] of solvent or solvent mixture. The values of experimental slopes (S$_v$) have been represented in Table 4.10.

The positive values of S$_v$ in NAC–H$_2$O and NAC in [9:1] [H$_2$O–CH$_3$COOH] solution predicts there is a strong solute-solute interaction present here whereas negative values of S$_v$ in NAC and CH$_3$COOH mixtures indicate the presence of weak solute-solute interaction [60].

It is found that values of S$_v$ are positive for NAC–H$_2$O and negative for NAC in CH$_3$COOH and [4:1], [7:3] and [3:2] solution. It suggests that in NAC–H$_2$O and NAC in

[9:1] [H_2O–CH_3COOH] solution system having more solute–solute interactions in comparison to all other systems.

Table 4.10: S_v parameter of N-Acetylcysteine in water, CH_3COOH and [9:1], [4:1], [7:3] and [3:2] [H_2O–CH_3COOH] systems at 298.15 to 318.15 K at 5 K interval

Temperature (K)	NAC–H_2O	NAC–CH_3COOH	NAC in [9:1] [H_2O–CH_3COOH]	NAC in [4:1] [H_2O–CH_3COOH]	NAC in [7:3] [H_2O–CH_3COOH]	NAC in 3:2 [H_2O–CH_3COOH]
298.15	3.1204	-4.3825	3.2159	-5.3728	-2.4481	-3.3308
303.15	3.3944	-4.7381	4.1613	-6.0464	-2.6856	-3.5828
308.15	2.9828	-4.8409	4.5773	-6.1711	-2.7196	-3.7173
313.15	3.0418	-4.7333	5.0701	-6.6004	-2.8187	-3.7784
318.15	2.9865	-5.1051	5.4909	-6.8301	-2.5643	-3.6116

4.6 Viscometric Properties

Having enormous medicinal and biological applications of NAC in human body, its viscometric investigation in versatile solvent water and in common organic solvent CH_3COOH as well as in H_2O–CH_3COOH mixed solvents might be interesting. CH_3COOH–H_2O mixtures are very important systems exhibiting properties that are of great interest in physics, chemistry and biology. Due to this reason viscometric behavior of NAC in CH_3COOH, water and H_2O–CH_3COOH mixture system is also fascinating and has been discussed.

4.6.1 Viscosity of Pure Solvent

The viscosity at different temperatures of the pure solvents; CH_3COOH and water have been tabulated in Table 4.11 with the literature values [61, 54] for possible comparison. The larger viscosity values of CH_3COOH indicate that CH_3COOH is more viscous than water at all investigated temperatures. From viscosity values of CH_3COOH and water it is seen that viscosities of water are higher at all temperatures than those of CH_3COOH which correlate the density results of the solvents in Table 4.1. From the table it is also seen that viscosities of the solvents decreased with the increasing temperature as expected and provide almost similar results as mentioned in the cited literatures. It indicates that the solvents being used in the experiments were pure and analytical grade as declared by suppliers.

Table 4.11: Viscosity, η values of CH₃COOH and Water at 298.15 to 318.15 K at 5 K interval

Temperature (K)	Viscosity (mPa.s) of CH₃COOH		Viscosity (mPa.s) of Water	
	Literature Value	Experimental Value	Literature Value	Experimental Value
298.15	1.1610 [61]	1.1578	0.8926 [54]	0.8939
303.15	1.0768 [61]	1.0752	0.8007 [54]	0.8135
308.15	1.0025 [61]	0.9919	0.7234 [54]	0.7265
313.15	0.9258 [61]	0.9263	0.6579 [54]	0.6663
318.15	0.8653 [61]	0.8682	0.6017 [54]	0.6097

4.6.2 Viscosity of CH₃COOH–H₂O Binary System

The viscosities of CH_3COOH–H_2O binary mixture has been shown here in Table 4.12. The values increase with the amount of CH_3COOH increases in [H_2O–CH_3COOH]. It shows maximum value for [3:2] [H_2O–CH_3COOH] mixture solution in lower temperature (298.15 K, 303.15 K and 308.15 K).

Table 4.12: Experimental viscosity values, η of [9:1], [4:1], [7:3] and [3:2] [H₂O–CH₃COOH] systems at 298.15 to 318.15 K at 5 K interval

Name of the system	Experimental Value, η (mPa.s)				
	298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
[9:1] [H₂O–CH₃COOH]	0.9796	0.8791	0.7733	0.6573	0.5649
[4:1] [H₂O–CH₃COOH]	1.2693	1.1492	1.0240	0.9007	0.8089
[7:3] [H₂O–CH₃COOH]	1.5446	1.4488	1.3268	1.2448	1.1256
[3:2] [H₂O–CH₃COOH]	1.9732	1.8300	1.7061	1.5925	1.4875

4.6.3 Viscosity of NAC−H₂O and NAC−CH₃COOH Binary Systems

The viscosities, η of binary system NAC−H$_2$O and NAC−CH$_3$COOH have been studied at 298.15, 303.15, 308.15, 313.15, and 318.15 K temperature over a concentration range of (~0.10 to ~1.00) M of NAC. The experimented results are tabulated in Table 4.13. The viscosity values in NAC–H$_2$Oand NAC–CH$_3$COOH systems increased with the increase of concentration as expected and the graphical presentation has been shown here in Figure 4.13 and 4.14. The values of the binary systems are also greater than the values of the pure solvents which have been shown in Table 4.11. The increase of η values of NAC with concentration can be attributed to the increase in solute−solvent, solvent−solvent and solute−solute interactions in solution. The wide range of dissolution of NAC in water and CH$_3$COOH might have intriguing aspects which may be the consequence of the great ability of both water and CH$_3$COOH to make dipole-dipole, ion-dipole and hydrogen bonds with NAC. It is also seen that the viscosity of NAC– CH$_3$COOH systems are higher at all temperatures and at all concentrations of NAC than those of NAC−H$_2$O systems. This is may be due the presence of hydrophobic nature in NAC and CH$_3$COOH in addition to the above mentioned interactions. At the same time it is seen that the viscosity values decrease considerably with the rise in temperature at a constant molarity. In both cases with the increase of temperature in binary systems the internal energy of the system increased and as because of this the solute-solute or solute-solvent interaction may be depleted. The graphical presentation of the fact has been viewed in Figure 4.13 and 4.14.

So in the measurement of viscous property in binary systems both NAC−H$_2$O and NAC– CH$_3$COOH systems show the same character but in different amount and the order of the viscosity maxima is as follows:

$$NAC–CH_3COOH > NAC–H_2O$$

Table 4.13: Viscosities, η of N-Acetylcysteine in water and CH$_3$COOH system at 298.15 to 318.15 K at 5 K interval

| Name of the system	Conc. (mol.L^{-1})	Viscosity, η (mPa.s)				
		298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
NAC–H$_2$O	0.1004	0.9393	0.8504	0.7447	0.6785	0.6213
	0.3005	0.9860	0.898	0.8180	0.7291	0.6677
	0.5004	1.0469	0.9435	0.8603	0.7917	0.7280
	0.7020	1.2115	1.0701	0.9616	0.8850	0.8172
	1.0008	1.341	1.1610	1.0380	0.9462	0.8381
NAC–CH$_3$COOH	0.1006	1.4692	1.3500	1.2327	1.1377	1.0465
	0.3004	1.7005	1.5875	1.4228	1.277	1.1703
	0.5007	1.9313	1.7501	1.6326	1.4896	1.3770
	0.7011	2.2177	1.9548	1.7711	1.6123	1.4764
	1.0010	3.0552	2.5900	2.4099	2.1373	1.9029
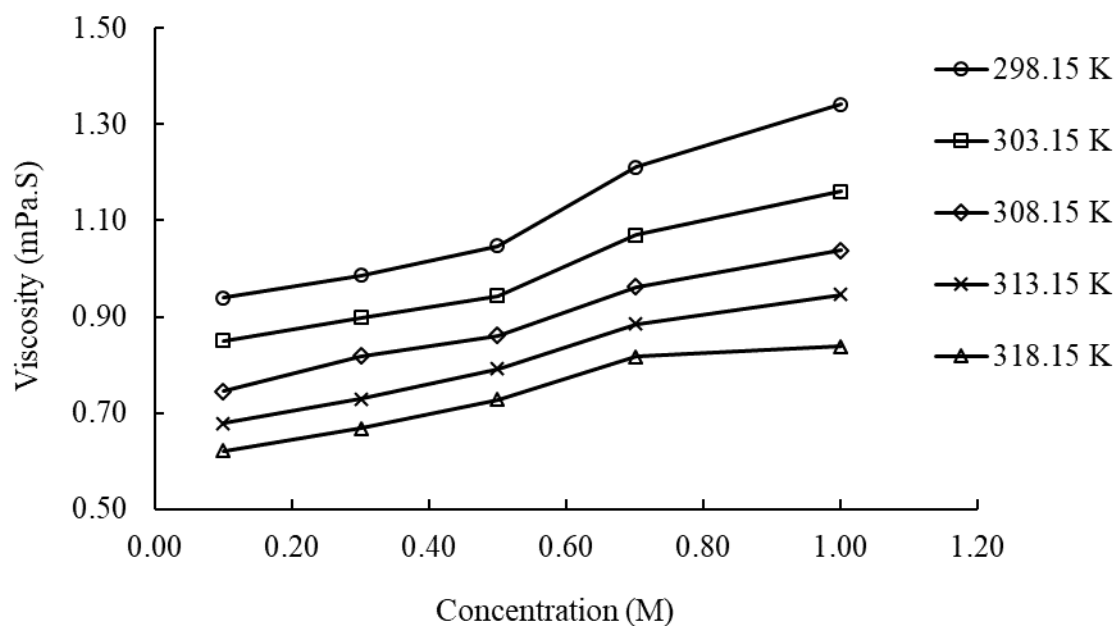
Figure 4.13: Viscosities, η vs concentration (M) of N-Acetylcysteine in water system at 298.15 to 318.15 K at 5 K interval
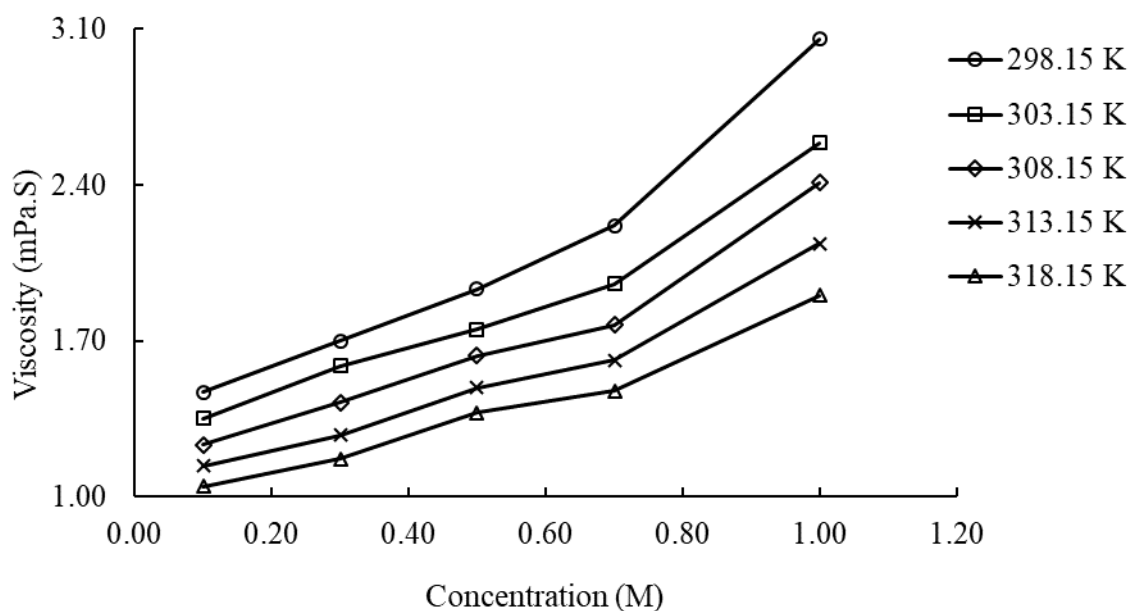

Figure 4.14: Viscosities, η vs concentration (M) of N-Acetylcysteine in CH₃COOH system at 298.15 to 318.15 K at 5 K interval

4.6.4 Viscosity of NAC–CH$_3$COOH–H$_2$O Ternary Systems

The viscosities, η of NAC in [9:1], [4:1], [7:3] and [3:2] [H$_2$O–CH$_3$COOH] systems have been described at 298.15, 303.15, 308.15, 313.15, and 318.15 K temperature over a concentration range of (~0.10 to ~1.00) M. The values of the viscosity of ternary systems have been tabulated in Table 4.14. The results are also presented graphically in Figure 4.15, 4.16, 4.17 and 4.18. From the table we can see that the viscosity values are positive in all ternary systems and are lower than NAC–CH$_3$COOH binary systems as shown in Table 4.13 and even those of the solvents (Table 4.11). So there may be solute-solute or solute-solvent interactions in the ternary systems than the others. Viscosity values increased significantly with the increase in concentration of NAC. At the same time it is seen that the viscosity values decreased considerably with temperature at a constant molarity as expected. The reason is been discussed earlier in the section 4.7.3. The reason of more interactions in ternary systems may be due to the fact that CH$_3$COOH, water and H$_2$O–CH$_3$COOH systems can be stabilized by hydrogen-bonded structure. Also each CH$_3$COOH consists of two methyl group which provide hydrophobic interaction with NAC. Thus the solubility of ternary solution is therefore become facile or make available more of the interactions and offer more organized structures. At the same time the polar groups of NAC get easily mixed with the polar solvent H$_2$O. It dissolves in water in any amount. On the other hand NAC contains two polar groups; –COOH and CONH–. It also contains almost nonpolar –SH group. Using this NAC make strong interactions in NAC–H$_2$O or NAC–CH$_3$COOH binary and NAC–CH$_3$COOH–H$_2$O ternary systems. In case of ternary, binary and solvent systems the viscosity maxima follow the order:

NAC–CH$_3$COOH > NAC in [3:2] [H$_2$O–CH$_3$COOH] > NAC in [7:3] [H$_2$O–CH$_3$COOH] > NAC in [4:1] [H$_2$O–CH$_3$COOH] > NAC in [9:1] [H$_2$O–CH$_3$COOH] > NAC–H$_2$O

Table 4.14: Viscosities, η of NAC in [9:1], [4:1], [7:3] and [3:2] [H₂O–CH₃COOH] system at 298.15 to 318.15 K at 5 K interval

Name of the system		Conc. (mol.L^{-1})	Viscosity, η (mPa.s)				
			298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
NAC in [9:1]	[H₂O–CH₃COOH]	0.1005	1.1151	1.0189	0.9231	0.8310	0.7422
		0.3005	1.1853	1.0913	0.9776	0.8889	0.8179
		0.5019	1.3352	1.2131	1.0983	0.9898	0.9174
		0.7026	1.6086	1.4551	1.3344	1.2158	1.1075
		1.0003	1.7071	1.6217	1.5039	1.3790	1.2579
NAC in [4:1]	[H₂O–CH₃COOH]	0.1018	1.2424	1.1414	1.0133	0.9239	0.8309
		0.3009	1.3141	1.2089	1.1003	0.9887	0.8607
		0.5019	1.509	1.4090	1.2769	1.2098	1.1195
		0.7027	1.6791	1.5528	1.4312	1.3105	1.2217
		1.0020	1.7267	1.5813	1.4452	1.3577	1.2737
NAC in [7:3]	[H₂O–CH₃COOH]	0.1001	1.3886	1.2983	1.2112	1.1075	1.0183
		0.3012	1.5137	1.3947	1.3043	1.1959	1.1186
		0.5012	1.6240	1.4985	1.3725	1.2626	1.1721
		0.7009	1.7672	1.6433	1.5444	1.4514	1.2875
		1.0002	1.9111	1.7055	1.5821	1.4787	1.3289
NAC in [3:2]	[H₂O–CH₃COOH]	0.1008	1.4797	1.3770	1.3290	1.1983	1.0841
		0.3017	1.5570	1.4274	1.3502	1.2426	1.1502
		0.5003	1.6692	1.5437	1.4221	1.3244	1.2234
		0.7026	1.8656	1.7497	1.6029	1.5152	1.3534
		1.0020	1.9901	1.7610	1.6364	1.5467	1.3765

Figure 4.15: Viscosities, η vs concentration (M) of N-Acetylcysteine in [9:1] [H$_2$O–CH$_3$COOH] system at 298.15 to 318.15 K at 5 K interval

Figure 4.16: Viscosities, η vs concentration (M) of N-Acetylcysteine in [4:1] [H$_2$O–CH$_3$COOH] system at 298.15 to 318.15 K at 5 K interval
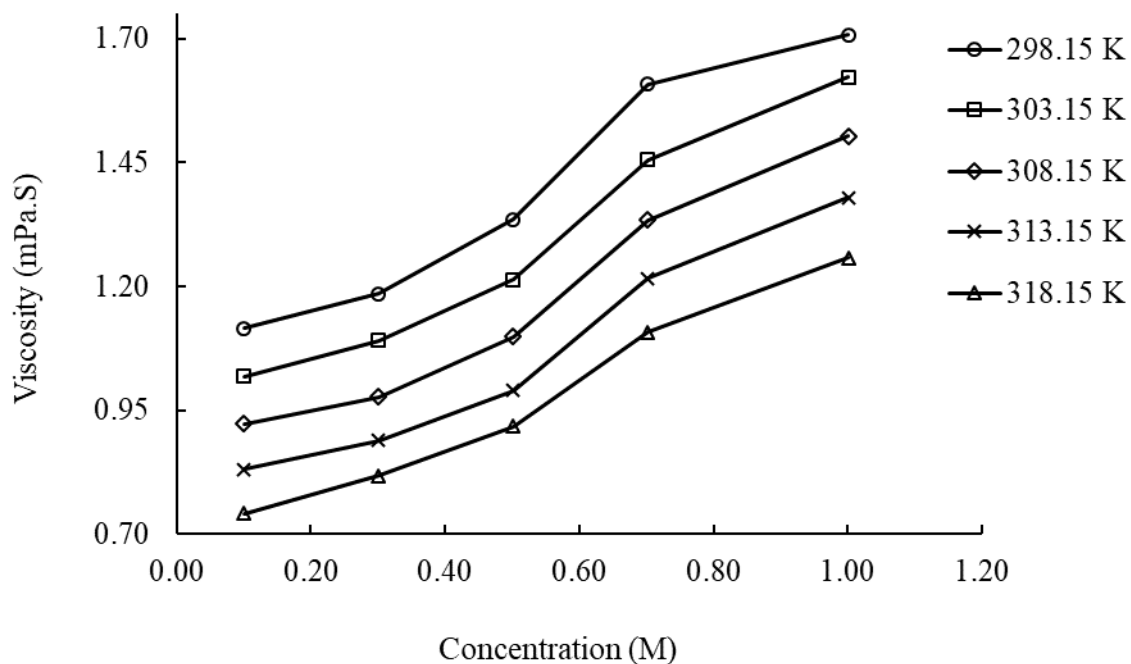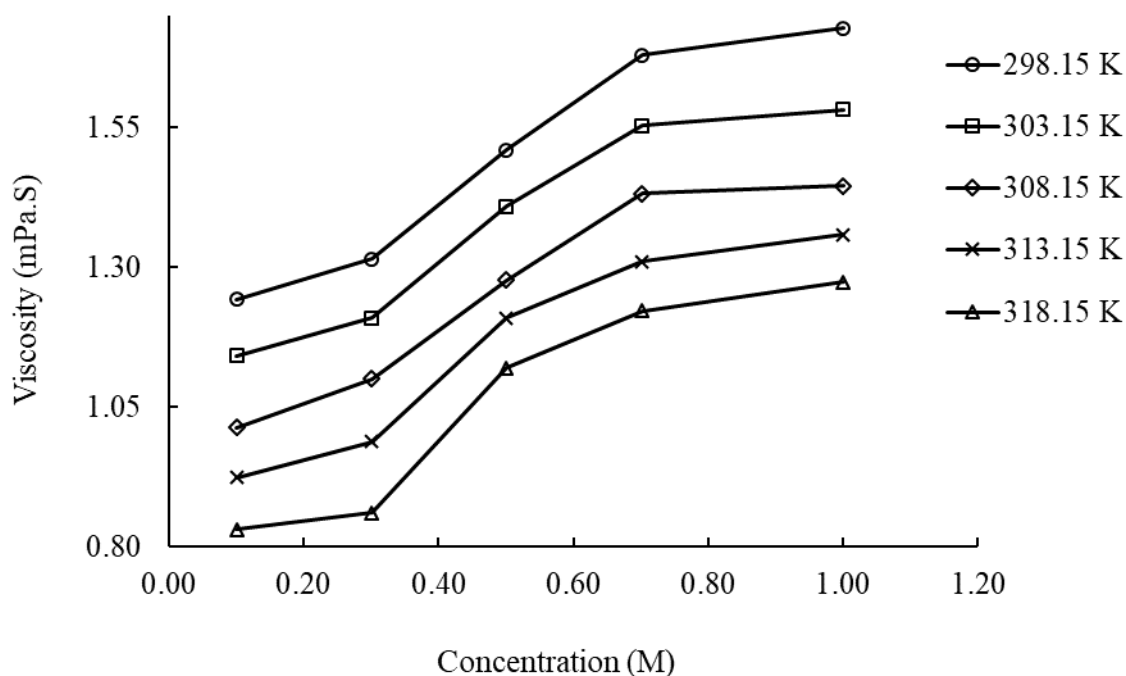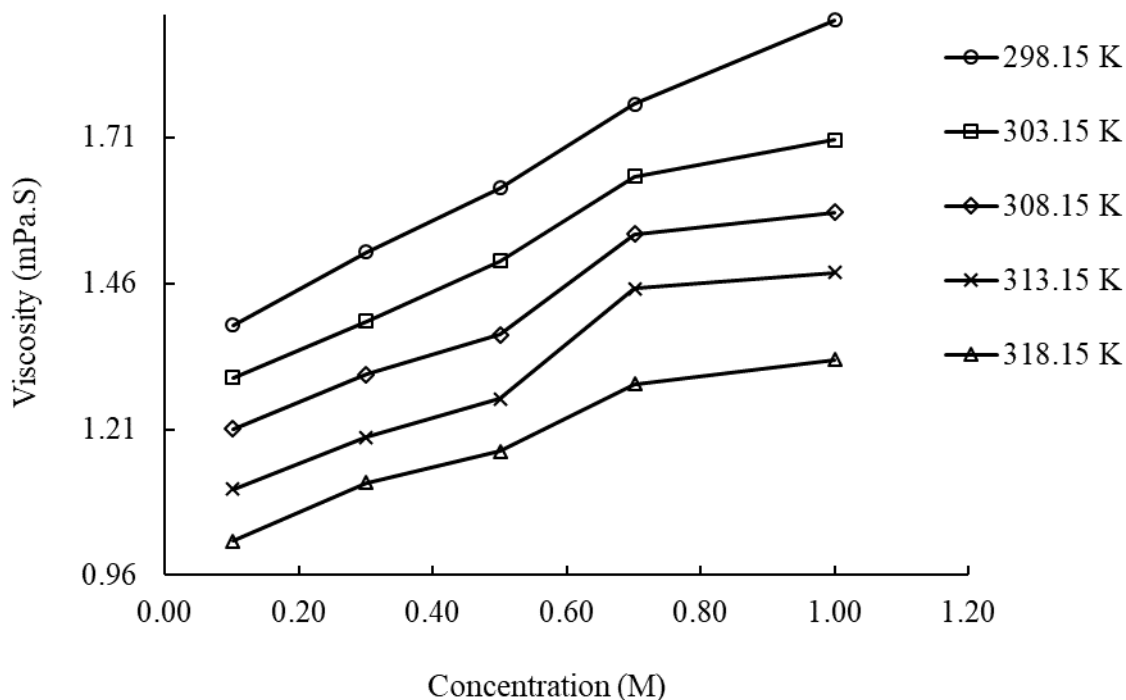
Figure 4.17: Viscosities, η vs concentration (M) of N-Acetylcysteine in [7:3] [H$_2$O–CH$_3$COOH] system at 298.15 to 318.15 K at 5 K interval
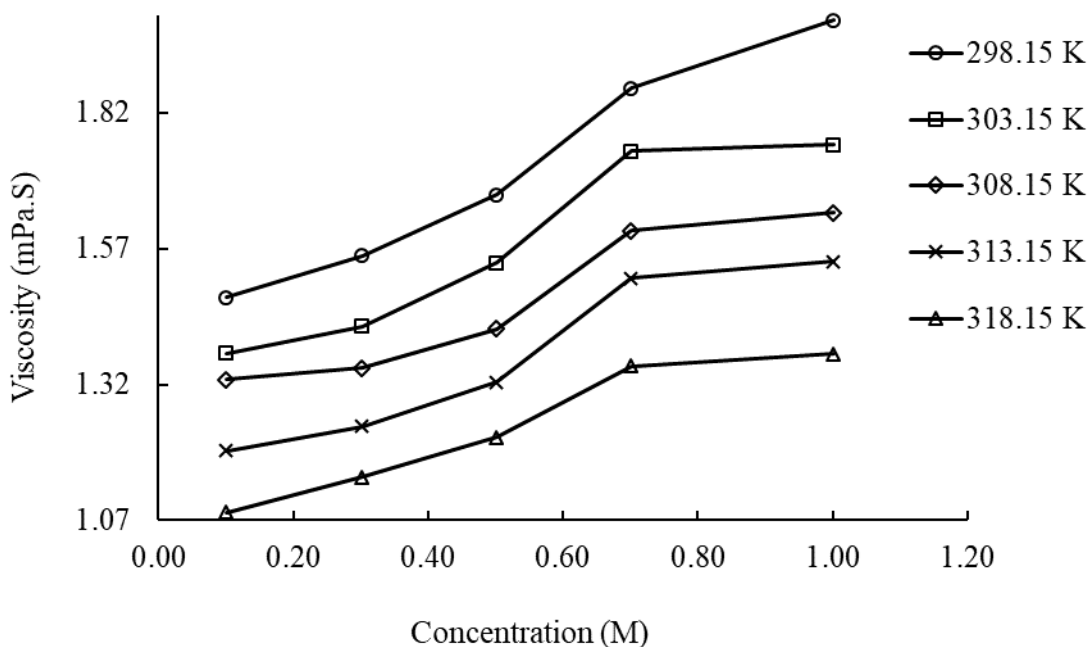
Figure 4.18: Viscosities, η vs concentration (M) of N-Acetylcysteine in [3:2] [H$_2$O–CH$_3$COOH] system at 298.15 to 318.15 K at 5 K interval

4.7 Jones-Dole co-efficient

The Jones-Dole co-efficient, A, reflects the effect of solute-solute interaction and B, is a measure of structural modifications induced by the solute-solvent interaction. The viscosity co-efficient A and B were obtained from the intercept and slope of the plots $(\eta_{rel} -1)/C^{1/2}$ against $C^{1/2}$. The values of A and B are listed in Table 4.15-4.17 shows that the values of A co-efficient are negative whereas those of B co-efficient are positive [62]. Values of A co-efficient are negative for all systems at all the investigated temperatures except NAC–CH₃COOH and NAC in [9:1] [H₂O–CH₃COOH] solution. These results indicate the presence of weak solute-solute interactions. The positive values of B co-efficient point out the existence of strong ion-solvent interaction in the investigated systems at the all specific temperatures. The values of B co-efficient for most of the solutions are lower at higher temperature that proves the decrease of ion-solvent interaction at higher temperature.

Table 4.15: Jones-Dole co-efficient for NAC–H$_2$O and NAC–CH$_3$COOH

Temperature (K)	NAC–H$_2$O		NAC–CH$_3$COOH	
	A co-efficient	B co-efficient	A co-efficient	B co-efficient
298.15	-0.0603	0.5326	0.3595	1.0498
303.15	-0.0287	0.4415	0.4681	0.7642
308.15	-0.0758	0.5169	0.3815	0.8590
313.15	-0.1253	0.5667	0.3512	0.7929
318.15	-0.0969	0.5198	0.3140	0.7527

Table 4.16: Jones-Dole co-efficient for NAC in [9:1] and [4:1] [H_2O–CH_3COOH]]

Temperature (K)	NAC in [9:1] [H_2O–CH_3COOH]		NAC in [4:1] [H_2O–CH_3COOH]	
	A co-efficient	B co-efficient	A co-efficient	B co-efficient
298.15	0.1800	0.5686	-0.2836	0.7108
303.15	0.2229	0.5831	-0.2260	0.6785
308.15	0.2997	0.5855	-0.2437	0.7481
313.15	0.5293	0.4849	-0.1462	0.7391
318.15	0.7172	0.4318	-0.2176	0.8827

Table 4.17: Jones-Dole co-efficient for NAC in [7:3] and [3:2] [H_2O–CH_3COOH]

Temperature (K)	NAC in [7:3] [H_2O–CH_3COOH]		NAC in [3:2] [H_2O–CH_3COOH]	
	A co-efficient	B co-efficient	A co-efficient	B co-efficient
298.15	-0.5293	0.8132	-1.0929	1.1778
303.15	-0.5224	0.7628	-1.0687	1.1289
308.15	-0.4599	0.7126	-0.9624	0.9927
313.15	-0.5635	0.8221	-1.0748	1.1341
318.15	-0.4657	0.7114	-1.1298	1.1572

4.8 Thermodynamics Properties

The change in viscosity of NAC in different solvents can make a significant contribution to thermodynamic properties of the solution, such as enthalpy, entropy, and other properties in solution. So in this section different thermodynamic parameters such as, change of free energy, ΔG^*, change of enthalpy, ΔH^*, change of entropy, ΔS^* for viscous flow for NAC in different solvent systems have been discussed.

NAC–CH_3COOH, NAC–H_2O and NAC–CH_3COOH–H_2O are considered to be very important systems exhibiting properties that are of great interest in many biological and medicinal applications. These include several thermodynamic properties such as, free energy, entropy, enthalpy, etc. Thermodynamic properties, change of free energy, ΔG^*, change of enthalpy, ΔH^*, change of entropy, ΔS^* for viscous flow have been calculated from viscometric data via Eyring equation. Gibbs free energy is a thermodynamic function and the energy of the system which is ready to work. The Gibbs free energy is used when considering processes that occur under constant pressure and temperature conditions. For a process that occurs at constant temperature and pressure, spontaneity can be determined using the change in Gibbs free energy, which is given by the sign, ΔG; depends on the changes in enthalpy (ΔH) and entropy (ΔS), as well as on the absolute temperature (T).

In cases where ΔG [63] is:

- Negative, the process is spontaneous and may proceed in the forward direction as written.
- Positive, the process is non-spontaneous as written, but it may be proceed spontaneously in the reverse direction.
- Zero, the process is at equilibrium, with no net change taking place over time.

The ΔG^*, values are positive for all the studied systems NAC–CH_3COOH, NAC–H_2O and NAC–CH_3COOH–H_2O indicate that studied systems are non-spontaneous for the flow process as shown in Table 4.18 and 4.19 and it is spontaneous in the reverse direction. The positive free energy change, ΔG^* for viscous flow may be interpreted by Furth model [64] which states that kinetic species involved in forming holes in the

investigated solution systems may be stated by the work is required in forming the holes against surface tension of the solution. Positive ΔG^* values also explain the interstitial incorporation, solute–solvent interaction that render the binary and ternary systems are more structured.

Enthalpy is the thermodynamic quantity equivalent to the total heat content of a system. It is defined as the sum of internal energy of a system and the product of the pressure and volume of the system or pressure-volume work. Internal energy is the sum of translational energy, rotational energy, vibrational energy and the kinetic energy of a matter. The change in enthalpy is the sum of the change in the internal energy and the work done. Entropy is a measure of disorder or randomness of a system. In other words, it's a measurement of the degree of randomness of energy in a system. An ordered system has low entropy. A disordered system has high entropy.

The set of rules can be used to determine four distinct cases by examining the signs of the ΔS and ΔH] [63].

➢ When $\Delta S > 0$ and $\Delta H < 0$, the process is always spontaneous as written.
➢ When $\Delta S < 0$ and $\Delta H > 0$, the process is never spontaneous, but the reverse process is always spontaneous.
➢ When $\Delta S > 0$ and $\Delta H > 0$, the process will be spontaneous at high temperatures and non-spontaneous at low temperatures.
➢ When $\Delta S < 0$ and $\Delta H < 0$, the process will be spontaneous at low temperatures and non-spontaneous at high temperatures.
➢ For the latter two cases, the temperature at which the spontaneity changes will be determined by the relative magnitudes of ΔS and ΔH.

The change enthalpy, ΔH^* values are positive for all the studied system as shown in Table 4.20-4.21. The positive ΔH values indicate that work has to be done for all the investigated systems. That is, the viscous flow is not thermodynamically favored for the systems studied. The change of entropy, ΔS^* of the investigated systems are shown in same Table 4.20-4.21. The ΔS^* values are negative for almost all the systems studied. This means that binary and ternary systems are random than those of the pure one. Here one point may be remarked that as $\Delta S < 0$ and $\Delta H > 0$, so the the processes are never

spontaneous, but the reverse process is always spontaneous. In case of my studied temperatures these systems were found to be non-spontaneous. The negative entropy of NAC–CH$_3$COOH mixtures arises due to the interplay between the relative strengths of the CH$_3$COOH–CH$_3$COOH, CH$_3$COOH–H$_2$O, H$_2$O–H$_2$O and hydrogen bonds. Thiol group of NAC molecule undergoes dipole-dipole interaction with CH$_3$COOH. The oxygen of carbonyl group pulls the electron towards itself and hold negative charge. Lone pair electrons of nitrogen atom fill up the electron deficiency of carbonyl carbon. The structure established H-bond with water.

Table 4.18: Free energy, ΔG^* of N-Acetylcysteine in water and CH$_3$COOH system at 298.15 to 318.15 K at 5 K interval

Name of the system	Conc. (mol.L^{-1})	Free energy, ΔG^* KJ.mol^{-1}				
		298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
NAC– H$_2$O	0.1004	14.7590	14.7595	14.6670	14.6674	14.6740
	0.3005	14.8794	14.8971	14.9077	14.8546	14.8644
	0.5004	15.0280	15.0212	15.0367	15.0691	15.0933
	0.7020	15.3898	15.3387	15.3218	15.3592	15.3990
	1.0010	15.6431	15.5442	15.5179	15.5334	15.4659
NAC– CH$_3$COOH	0.1006	15.7444	15.8086	15.8503	15.9128	15.9604
	0.3004	16.1067	16.2171	16.2178	16.2146	16.2561
	0.5007	16.4222	16.4627	16.5702	16.6144	16.6862
	0.7011	16.7651	16.7416	16.7788	16.8205	16.8706
	1.0010	17.5591	17.4508	17.5678	17.5544	17.5419

Table 4.19: Free energy, ΔG* of NAC in [9:1], [4:1], [7:3] and [3:2] [H$_2$O–CH$_3$COOH] system at 298.15 to 318.15 K at 5 K interval

Name of the system	Conc. (mol.L^{-1})	Free energy, ΔG* KJ.mol^{-1}				
		298.15 K	303.15 K	308.15 K	313.15 K	318.15 K
NAC in [9:1] [H$_2$O–CH$_3$COOH]	0.1005	15.1843	15.2150	15.2173	15.1953	15.1443
	0.3005	15.3357	15.3881	15.3641	15.3707	15.4014
	0.5019	15.6308	15.6547	15.6626	15.6505	15.7050
	0.7026	16.0926	16.1133	16.1612	16.1859	16.2029
	1.0003	16.2399	16.3864	16.4676	16.5139	16.5398
NAC in [4:1] [H$_2$O–CH$_3$COOH]	0.1018	15.4523	15.5012	15.4560	15.4712	15.4429
	0.3009	15.5914	15.6461	15.6670	15.6476	15.5362
	0.5019	15.9343	16.0320	16.0484	16.1730	16.2314
	0.7027	16.1988	16.2770	16.3406	16.3813	16.4625
	1.0020	16.2682	16.3228	16.3657	16.4733	16.5728
NAC in [7:3] [H$_2$O–CH$_3$COOH]	0.1001	15.7281	15.8258	15.9131	15.9432	15.9808
	0.3012	15.9419	16.0063	16.1030	16.1431	16.2293
	0.5012	16.1162	16.1873	16.2334	16.2844	16.3530
	0.7009	16.3256	16.4197	16.5358	16.6472	16.6013
	1.0002	16.5196	16.5134	16.5974	16.6957	16.6850
NAC in [3:2] [H$_2$O–CH$_3$COOH]	0.1008	15.8856	15.9741	16.1509	16.1483	16.1465
	0.3017	16.0118	16.0648	16.1915	16.2427	16.3029
	0.5003	16.1842	16.2621	16.3243	16.4088	16.4663
	0.7026	16.4599	16.5779	16.6309	16.7592	16.7334
	1.0020	16.6201	16.5941	16.6840	16.8126	16.7781

It is evident from Table 4.18, 4.19 in all cases of NAC–H$_2$O, NAC–CH$_3$COOH and NAC–CH$_3$COOH–H$_2$O system, positive value of ΔG increases with the increase in solute concentration and the rise of temperature. This behavior of ΔG [65] suggests that the work is required for viscous flow. Lower values of ΔG at higher temperatures may be due to weaken solute–solvent and solvent–solvent interactions for greater thermal agitation. The positive value of ΔH increases randomly with the increase of solute composition. This indicates that to overcome the energy barrier, some positive work has to be done. Thus the viscous flow is not favored for all the NAC molecules in solution systems. This might be due to the fact that the ground state of the binary and ternary systems is more organized than the transition states.

In fact, change of enthalpy, ΔH* and change of entropy, ΔS* are derived from viscosity and molar volume as secondary derived data. It can also be here mentioned that the instrumental limitations during the experiments. So some irregularities as well as some ambiguity may be present in change enthalpy, ΔH* and change entropy, ΔS* values.

Table 4.20: Change of Enthalpy, ΔH* and Entropy, ΔS* of N–Acetylcysteine in CH$_3$COOH and water system at 298.15 to 318.15 K at 5 K interval

Name of the system	Conc.(mol.L^{-1})	Change of Enthalpy, ΔH* J.K^{-1}mol^{-1}	Change of Entropy, ΔS* J.K^{-1}mol^{-1}
NAC–H$_2$O	0.1004	16341.1870	5.3085
	0.3005	15311.2110	1.3971
	0.5004	13964.7878	-3.5205
	0.7020	15170.2851	-0.6212
	1.0008	17812.9651	7.3733
NAC–CH$_3$COOH	0.1006	12548.0470	-10.7326
	0.3004	14347.1136	-6.0210
	0.5007	12362.5720	-13.5927
	0.7011	15038.8903	-5.6999
	1.0010	17122.2696	-1.3387

Table 4.21: Change of Enthalpy, ΔH* and Entropy, ΔS* of NAC in [9:1], [4:1], [7:3] and [3:2] [H_2O–CH_3COOH] systems at 298.15 to 318.15 K at 5 K interval

Name of the system		Conc.(mol.L^{-1})	Change of Enthalpy, ΔH* $J.K^{-1}mol^{-1}$	Change of Enthalpy, ΔS* $J.K^{-1}mol^{-1}$
NAC in [9:1]	[H_2O–CH_3COOH]	0.1005	15768.3222	1.8726
		0.3005	14666.7898	-2.2885
		0.5019	14780.2512	-2.8573
		0.7026	14338.0521	-5.8839
		1.0003	11891.1816	-14.7277
NAC in [4:1]	[H_2O–CH_3COOH]	0.1018	15746.8338	0.9155
		0.3009	16213.9831	1.9351
		0.5019	11558.0783	-14.6868
		0.7027	12435.3467	-12.6454
		1.0020	11749.2263	-15.0943
NAC in [7:3]	[H_2O–CH_3COOH]	0.1001	12004.1410	-12.5720
		0.3012	11695.5042	-14.2438
		0.5012	12717.3731	-11.4148
		0.7009	11650.3623	-15.7572
		1.0002	13442.7834	-10.2529
NAC in [3:2]	[H_2O–CH_3COOH]	0.1008	11700.6815	-14.1503
		0.3017	11465.7058	-15.2426
		0.5003	11945.7930	-14.2247
		0.7026	12102.7651	-14.6991
		1.0020	13408.5945	-10.6740

CHAPTER V

Conclusion

In order to determining the molecular interactions among NAC, CH_3COOH and H_2O volumetric and viscometric investigations have been carried out. Discussing all results and data the following decisions have been taken into account.

(i) Throughout the all investigated systems volumetric, viscometric and thermodynamic properties are depended upon the concentration of NAC as well as on the temperature. The order of density:

NAC in [3:2] [H_2O–CH_3COOH] > NAC–CH_3COOH > NAC in [7:3] [H_2O–CH_3COOH] > NAC in [4:1] [H_2O–CH_3COOH] > NAC–H_2O > NAC in [9:1] [H_2O–CH_3COOH]

(ii) Apparent Molar Volume decreased with increasing concentration of NAC for all other solutions except NAC–H_2O, NAC in [9:1] [H_2O–CH_3COOH] solvent systems i.e., solute-solute interactions predominant in NAC–H_2O, NAC in [9:1] [H_2O–CH_3COOH] solvent systems but in all other systems solute-solvent interactions are predominant.

(iii) Values of apparent molar volume at infinite dilution are positive which indicates solute-solvent interactions are present in the systems.

(iv) Positive values of S_v in NAC–H_2O and NAC in [9:1] [H_2O–CH_3COOH] solution predict that solute-solute interactions are predominant as compared to pair-pair interactions.

(v) The negative S_v values for NAC in CH_3COOH and [4:1], [7:3] and [3:2] [H_2O–CH_3COOH] solvent systems predict that ion–solvent interactions prevail as compared to ion–ion interactions.

(vi) In all binary and ternary systems viscosity increased with concentration of NAC but decreased with temperature.

(vii) The ΔG^* and ΔH^* values are positive for all solutions whereas ΔS^* values are negative; i.e., so the the process is never spontaneous, but the reverse process is always spontaneous.

(viii) A co-efficients are negative except NAC-CH_3COOH and [9:1] [H_2O–CH_3COOH] whereas those of B co-efficients are positive, suggesting weak solute-solute and strong solute-solvent interaction present in the binary and ternary solution.

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