An-Najah National University

Faculty of Graduate Studies

Critical Behavior of Refractive Index of Binary Mixture Cyclohexane - Phenol

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Dedication

For my parents with all love.

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الإقرار

أنا الموقعة أدناه مقدمة الرسالة التي تحمل عنوان

Critical Behavior of Refractive Index of Binary Mixture Cyclohexane – Phenol

اقر بان ما اشتملت عليه هذه الرسالة إنما هو نتاج جهدي الخاص، باستثناء ما تمت الإشارة اليه حيثما ورد، وان هذه الرسالة ككل من أو جزء منها لم يقدم من قبل لنيل أية درجة أو بحث علمي أو بحثي لدى أية مؤسسة تعليمية أو بحثية أخرى.

Deceleration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

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Date: 26/3/2015 **التاريخ:**

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List of Symbols and Abbreviations

R^2	Coefficient of determination
W_1 , W_2	Weight fraction
c_{pc}	Critical amplitude of the isobaric specific heat
K_B	Boltzmann's constant
R_ξ	Universal quantity
c_p	The specific heat at constant pressure
c_{pb}	Background isobaric specific heat
n_{0D}	Noncritical part of the measured refractive index
n_D	The refractive index for the medium at wavelength 589.29 nm
η_0	Noncritical part of the measured dynamic shear viscosity
η_{20}	Dynamic shear viscosity of water at 20 °C
η_T	Dynamic shear viscosity of water as a function of temperature
ξ_0	Noncritical correlation length
ρ_c	The liquid mass density at critical temperature and critical concentration
χ_nν	Critical exponent for refractive index
χ_ην	Critical exponent for dynamic shear viscosity
$\frac{\partial y}{\partial x}$	Rate of deformation or velocity gradient
cP	Centipoises
cSt	Centistokes
gm	Gram
J	Joule`s constant
K	Kelvin degree

MHz	Mega Hertz
MPa	Mega Pascal
N	Newton
S	Seconds
STP	Standard temperature and pressure
T	Temperature
ţ	Shear stress
T_c	Critical temperature
ΔT	Temperature difference
ρ	Mass density of liquid
χ_c	Critical concentration
ν	kinematic viscosity
H	Quantity of heat
I	Current
V	Volume
V'	Voltage
W	Work
c	The speed of sound in vacuum
t	Reduced temperature
t'	Time
v	The speed of light in medium
α	Critical exponent
η	Dynamic shear viscosity
ν	Critical exponent
ξ	Correlation length
kg	Kilogram
R	Universal gas constant
E_η	Temperature coefficient of viscosity
q_D	The Debye momentum cutoff
α_{pc}	Critical amplitude of the thermal expansion at constant Pressure
T'_c	Pressure derivation of the critical temperature along the critical line

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Abstract

The dynamic shear viscosity of binary mixture of cyclohexane - phenol was measured over the temperatures range (14.0 °C – 21.0 °C) and at concentration range (0.00% – 39.70%) by weight of phenol. The results above the critical temperature and critical concentration were analyzed by the mode coupling theory of one phase. The anomaly of the dynamic shear viscosity was detected as a function of temperature and concentration. Dynamic shear viscosity anomaly was clearly observed near the critical temperature T_c = 17.0 ℃ and the critical concentration χ_c = 2.70% by weight of phenol. The behavior of refractive index of cyclohexane - phenol obeys power law universality above the phase transition. The value of noncritical part of refractive index was found to be n_{0D} = 1.4276. The

universal critical exponent for refractive index χ_n is also calculated to be 0.00156. The critical isobaric specific heat for the critical binary mixture c_{pc} was found to be 106.6 $J/Kg.K$ using two scale factor universality. Joule`s constant for cyclohexane - phenol binary mixture was found to be 4.15 $Calorie/J$.

Chapter One

Introduction

1.1 Binary liquid mixtures:

Liquid systems exist in two forms, namely the pure form and the mixed form. The pure form is constituted of only one liquid substance such as olive oil, benzene, methanol or cyclohexane. The mixed form contains two or more substances existing in the liquid state (Santhi *et al*, 2012). A binary liquid is a system that contains two liquids/systems that are heterogeneously mixed together with no homogenous composition. The two liquids have solubility to each other at a certain temperature called *critical temperature* (T_c) and a certain concentration called *critical concentration* (χ_c). A phase separation occurs at temperatures below the critical point. However, at temperatures higher than critical temperature there is a homogenous phase and the two systems form a single liquid (Wheeler, 1975).

Examples for binary liquid mixtures include benzene – coconut oil, phenol– cyclohexane, benzene – tetrachloride and pentanol – nitromethane. A ternary mixture is composed of three liquids mixed together such as water, ethanol and *k*-ethyleneglycol. This type is composed of three different liquids that dissolve into each other at certain concentrations and certain temperatures (Iwanowski, 2007).

1.1.1 The critical point:

A critical point is the term called when both temperature and concentration are stabilized at their critical values. The two liquids behave as one liquid

with new physical characteristics. The temperature and concentration at which the two liquids become completely miscible at all proportions are called critical temperature T_c and critical concentration χ_c. A pure liquid has a critical point at the end of the vapor-liquid coexistence curve.

Many properties for different binary mixtures have been studied near their critical points, including the dynamic shear viscosity, bulk viscosity, thermal expansion coefficient, heat capacity at constant pressure and constant volume, ultrasonic propagation, sound attenuation, ultrasonic velocity, refractive index and other physical properties (Fixman, 1962; Repin *et al*, 1988).

1.2 Refractive index:

Refractive index of a given medium is a physical property for that medium. It is a dimensionless value which describes how light or any radiations can propagate through the medium.

Refractive index determines how much light is refracted. It can be defined as the ratio between the speed of light in vacuum and the speed of light in medium as expressed in equation (1.1):

$$n_D = \frac{c}{v} \tag{1.1}$$

Where n_D is the refractive index of the medium at wavelength 589.29 nm (The Fraunhofer D line), c is the speed of light in vacuum, and v is the speed of light in medium.

Refractive index is affected by factors such as density and temperature of the medium. The speed of electromagnetic waves (light) decreases for

medium with high density causing an increase in the refractive index (Beysens and Wesfreid, 1978). The refractive index is inversely proportional to the temperature (Kouissi and Bouanz, 2010). In addition, it depends on the wavelength of the incident light (Khodier, 2002).

The refractive index is one of the most important physical properties of a transparent solid, liquid and gas. Accurate knowledge of refractive index is correlated to the concentration, temperature, wavelength and pressure for transparent fluids. It can be used for the identification and characterization of pure materials. Concentrations of multi-component mixtures can be measured using values of refractive indices (Rahman *et al*, 2013).

1.3 Literature review:

Khodier measured the refractive indices for eight standard oils with an accuracy of $\pm 1\times10^{-4}$ using an Abbe Refractometer. The measurements were performed at temperature 20°C in the spectral range 400 –700 nm (Khodier, 2002).

Mónica and her group measured the refractive indices for six binary systems formed by three pyridinium-based ionic liquids: 1-butylpyridinium tetrafluoroborate, 1-butyl-3-methylpyridinium tetrafluoroborate or 1-butyl-4-methylpyridinium tetrafluoroborate and two alkanols: methanol or ethanol at four temperatures, T = 293.15, 303.15, 313.15 and 323.15 K. Excess refractive indices were calculated and fitted. The excess refractive indices of the mixtures were related to their corresponding excess volumes (Mónica *et al*,2013).

Rahman and his group measured the refractive indices for five binary mixtures, namely: decane ($C_{10}H_{22}$) / iso-butylbenzene (IBB), decane ($C_{10}H_{22}$) / 1,2,3,4-tetrahydronaphthalene (THN), dodecane ($C_{12}H_{26}$) / iso-butylbenzene (IBB), dodecane ($C_{12}H_{26}$) / 1,2,3,4-tetrahydronaphthalene (THN) and iso-butylbenzene (IBB) / 1,2,3,4-tetrahydronaphthalene (THN) using both Mach–Zehnder interferometer and a multi-wavelength Abbemat refractometer. The wavelength ranged from 436 nm to 657 nm (Rahman *et al*, 2013).

Dragoescu and his group measured the refractive indices for eight binary liquid mixtures of nitromethane with: 1,1,2,2-tetrachloroethane, 1,1,1-trichloroethane, trichloromethane, 1,2-dichloroethane, 1,3-dichloropropane, 1,4-dichlorobutane, 1-chlorobutane and 1-chloropentane, at temperatures range of 298.15–318.15 K under atmospheric pressure. The isentropic compressibilities and the excess isentropic compressibilities were calculated. The deviation in refractive indices and the molar refractions were also calculated. The ability of different theoretical values of (n, ρ) to predict the refractive indices were evaluated using mixing rules (Lorentz-Lorenz, Gladstone-Dale, Arago-Biot, Edwards and Eykman) (Dragoescu *et al*, 2014).

Andjela and her group measured the values of mass density ρ and refractive index n_D for the six binary mixtures of dimethylphthalate and dimethyladipate with 1-butanol, 2-butanol and 2-butanone. All measurements of ρ and n_D have been performed simultaneously at eight

temperatures (288.15, 293.15, 298.15, 303.15, 308.15, 313.15, 318.15 and 323.15) K under atmospheric pressure (Andjela *et al*, 2012).

Ali and her group measured the mass density ρ and refractive indices, n_D of binary mixtures of dimethylsulphoxide (DMSO) with poly(ethylene glycol) 200 (PEG200), poly(ethylene glycol) 300 (PEG300) and poly(ethylene glycol) 400 (PEG400) over the entire composition range at temperatures (298.15, 303.15, 308.15, and 313.15 K) and under atmospheric pressure. The refractive indices of these binary mixtures were calculated theoretically from the refractive index data of pure components and densities of the mixtures using various empirical and semi-empirical relations. Results were found to be similar to the experimental findings (Ali *et al*, 2013).

Losada-Pérez and her group predicted the nature of the critical behavior in the refractive index n_D. A comparison was made with the critical behavior of n_D as derived from the Lorentz-Lorenz equation (Losada-Pérez *et al*, 2012).

Miguel and his group measured the dynamic shear viscosities of pure cyclohexane, cyclohexane + tetradecane, and cyclohexane + benzene systems at four different compositions. The viscosities were measured using rolling ball viscometer at temperature range 313.2 - 393.2 K and under pressures up to 60 MPa with an estimated experimental uncertainty of 2% (Miguel *et al*, 2009).

Dynamic shear viscosity was measured as a function of temperature near critical temperature and critical concentration for the binary system of

nitrobenzene and n-heptane by Abdelraziq and his group. The anomaly of viscosity was detected as function of temperature and concentration (Abdelraziq *et al*,1997).

Abdelraziq *et al* (1990) measured the ultrasonic velocity and absorption as a function of temperature, concentration and frequency (5-25 MHz) of the binary mixture nitrobenzene/n-hexane in the homogeneous phase above critical temperature (Abdelraziq *et al*, 1990).

Abdelraziq measured the dynamic shear viscosity coefficient of nitroethane and 3-methylpentane using digital viscometer. The measured values were over the entire concentration range above the critical temperature (299.590 K). The anomaly was detected as function of temperature and concentration (Abdelraziq, 2002).

The dynamic shear viscosity in binary mixtures was studied and a theory was given for the sharp viscosity rise in mixtures in the critical mixing region. Marshall Fixman found good agreement with the experimental dependence of the dynamic shear viscosity on the composition and the temperature (Fixman, 1962; Qasem, 2014; Hussien, 2015).

Dynamic shear viscosity coefficients of benzene and coconut oil binary mixture were measured by Abdo using a digital viscometer. The measured values were taken over the entire concentration range above the critical temperature. The results above the critical temperature were analyzed by the mode coupling theory. The anomaly of dynamic shear viscosity was detected as a function of temperature and concentration (Abdo, 2014).

Taja and Rice measured dynamic shear viscosities of binary liquid mixtures of n-hexane/benzene, toluene/ethylbenzene at 298.15, 308.15 and 323.15K using Cannon Fenske viscometers (Teja and Rice, 1981).

The existence of dynamic shear viscosity anomaly was experimentally observed in some binary liquid systems near the critical temperature and concentration (Senger, 1972; Yamada and Kawasaki, 1975; Ohta and Kawasaki, 1976; Abdelraziq *et al,* 1992; Abdelraziq, 1996; Abdelraziq, 2000; Abdelraziq, 2001; Omar, 2014).

Kittany measured the dynamic shear viscosity coefficients of the binary liquid mixture carbon tetrachloride and coconut oil for different temperatures and concentrations using a digital viscometer with UL adapter (Kittany, 2014).

Kouissi and Bouanz measured the mass density ρ and refractive index n_D for the ternary critical mixture of 1,4-dioxane (1) + water (2) + saturated KCl(3) as a function of temperature for nine critical mixtures along the coexistence curve below the temperature of phase-transition (Kouissi and Bouanz, 2010).

Taib and her group measured the refractive indices of a ternary system of bis(2-hydroxyethyl) ammonium acetate (bheaa). The study was made using ([bheaa]) + monoethanolamine + water at temperatures in the range 303.15 to 353.15 K. The measured refractive index data were correlated as a function of concentration and temperature (Taib *et al*, 2013).

1.4 Objectives of thesis:

The main goals of this study are:

1. To measure the dynamic shear viscosity of cyclohexane - phenol binary mixture as a function of temperature over the entire possible concentration range.
2. To determine the critical temperature and critical concentration of cyclohexane -phenol binary mixture.
3. To set up the power law for refractive index and to calculate the critical exponent χ_n of the critical binary mixture.
4. To calculate the critical isobaric heat capacity for critical cyclohexane - phenol binary mixture.
5. To determine Joule`s constant of cyclohexane - phenol binary mixture.

1.4.1 Hypothesis

- At the critical point, there will be sharp changes in thermodynamic properties.
- Cyclohexane - phenol binary mixture exhibits anomaly at certain concentration (critical concentration). The power law can set up of the binary mixture at the critical concentration and above the critical temperature.

1.5 Novelty of this Work

- Measuring the dynamic shear viscosity for cyclohexane - phenol binary mixture has been conducted here for the first time.
- In this work, the power law of refractive index has been established for the first time. No other people managed to set up the power law for any binary mixture. This work is the first to do for cyclohexane – phenol.

1.5.1 Thesis lay out:

Chapter one of this thesis included the introduction which presents the definition of binary liquid mixture and its properties. The critical point is also explained in this Chapter.

Chapter two discussed the theories concerned with binary mixtures including the two scale factor universality, the mode-coupling theory for Fixman and power law.

The methodology of work is presented in Chapter three. Chapter four contained the results, their analysis and their discussions. In Chapter five, the conclusion of this work and suggestions for future works is displayed.

Chapter Two

Theory

2.1 Viscosity:

Viscosity measures the resistance of a fluid to gradual deformation by shear stress or tensile stress. For liquids, it corresponds to the informal notion of "thickness". Viscosity is due to friction between neighboring particles of the fluid that are moving at different velocities (Symon and Keith, 1971).

The shear viscosity of a fluid can be expressed in two distinct forms:

1- The dynamic or absolute shear viscosity:

The dynamic shear viscosity is defined as the ratio of shear stress (force over cross section area) to the rate of shear deformation or shear velocity.

$$\eta = \frac{ţ}{\frac{\partial y}{\partial x}} \tag{2.1}$$

Where η is dynamic shear viscosity in (Pa.s), ţ is shear stress in (N/m^2) and $\frac{\partial y}{\partial x}$ is rate of deformation (shear rate) in (s^{-1}) (Dutt *et al*, 2007).

The dynamic shear viscosity unit is the centipoise (cP).

2- Kinematic viscosity:

The kinematic viscosity is the dynamic viscosity η divided by the mass density of the fluid ρ.

$$\mathrm{v} = \frac{\eta}{\rho} \tag{2.2}$$

Where, v is kinematic viscosity in centistokes (cSt), and ρ is mass density (Dutt *et al*, 2007).

2.2 Dynamic shear viscosity of pure liquids:

The viscosity of a pure liquid is affected by temperature, pressure, density and surface tension of that liquid. The dynamic shear viscosity of liquids decreases with increasing temperature and decreasing pressure (Dutt *et al,* 2007).

Liquids have complex nature; therefore, several theories were proposed to describe the viscosity. Such as, the molecular dynamic approaches semi-empirical and empirical methods. The relationship that explains the relation between the dynamic viscosity and the temperature is in the form of an Arrhenius-type equation (Clements *et al,*1992).

$$\eta = \eta_0 e^{\frac{E_\eta}{R\,T}} \tag{2.3}$$

Where η is the measured dynamic shear viscosity in (cP), η_0 is the dynamic shear viscosity at some reference temperature, E_η is activation energy in (J/mol), R is the universal gas constant (J/mol.K) and T is the absolute temperature (K).

The logarithm of liquid viscosity varies linearly with the reciprocal of the absolute temperature T below the normal boiling point which is described by the empirical model.

$$Ln\,(\eta) = \text{Ă} + \frac{B}{T} \tag{2.4}$$

Where Ă and B are constants determined empirically.

At temperatures above the normal boiling point, the $Ln\,(\eta)$ versus $\frac{1}{T}$ relationship becomes nonlinear and is described by a number of semi empirical methods.

2.3 Dynamic shear viscosity of mixtures:

Viscosity is studied by several methods for solutions (homogeneous products of dissolution of solids or gases in liquids) and for liquid mixtures (homogeneous mixtures resulting from mixing of two or more liquids). Some of the methods are developed using excess Gibbs free energy models include Wilson, non-random two-liquid (NRTL) and universal quasi chemical (UNIQUAC) (Dutt *et al*, 2007).

Far from the critical point (under or above) of a binary liquid mixture, the behavior of the dynamic shear viscosity is like pure liquids, but around the critical point the situation becomes more complicated.

The mode coupling theory is used to study the critical anomaly of the dynamic shear viscosity and the coefficients.

2.3.1 The mode coupling theory:

The "mode" refers to eigenmodes of an idealized, "unperturbed", linear system. The superposition principle indicates that eigenmodes of linear systems are independent of each other. In most real systems, there are at least some perturbations that cause energy transfer between different modes. This perturbation is interpreted as an interaction between the modes. Therefore, the term "mode coupling" is coined to describe this theory (Horst, 2012).

Mode coupling theory is applied when the modes of one fluid are perturbed by the modes of the other fluid. Such perturbations lead to coupling and exchange of energy (Little and Huang, 1995), which indicates the start of the interaction between the fluids layers. It started originally by Fixman who proposed mechanisms by which the relaxation time and the kinetic coefficients, such as viscosity and density, could diverge at a critical point (Fixman, 1962). These ideas were more fully developed by Kawasaki, Kadanoff and Swift (Kawasaki, 1970; Kadanoff and Swift, 1968).

Reichman and Charbonneau derived the mode-coupling equations for the description of density fluctuations from microscopic considerations. In addition, they derived schematic mode-coupling equations of a similar form from a field-theoretical perspective. They reviewed the successes and failures of mode-coupling theory, and discussed recent advances in the applications of the theory (Reichman and Charbonneau, 2005).

The theories that describe the critical absorption of the binary mixture are based on the mode-coupling theories which consider the effect of two mode states. These theories are based on understanding fluctuations that occur in those binary mixtures rather than focusing on microscopic aspects (Botchand and Fixman, 1965). The available theories can thus give important information about how binary mixtures act at their critical points (Fuchs *et al,*1998).

2.3.2 Dynamic shear viscosity near the critical point:

The critical anomaly of the dynamic shear viscosity coefficient by Kawasaki and Perl and Ferrell is given according to the equation (2.5) (Perl and Ferrell, 1972):

$$\frac{\eta-\eta_0}{\eta} = \frac{\Delta\eta}{\eta} = A\ Ln\ (\xi) + A\ Ln\ (q_D) \qquad (2.5)$$

Where η_0 is the noncritical part of the measured dynamic shear viscosity, A is the mode coupling theory universal constant predicted to have the theoretical value $\frac{8}{15\pi^2}$ = 0.054 (D'Arrigo *et al*, 1977), ξ is the correlation length and q_D is the Debye momentum cutoff.

Mode coupling theory predicts a divergence of the kinetic coefficients near the critical point. One of the kinetic transport coefficients is the dynamic shear viscosity η. The divergence of η can be described near the critical point. However, two contributions must be considered: the critical part; which is dominant near the critical point, and the regular part; which is dominant far away from critical point. The dynamic shear viscosity η is temperature dependent at the critical concentration which is given by the power law equation (2.6):

$$\eta = \eta_0 t^{-\chi_\eta \mathrm{v}} \qquad (2.6)$$

Where t is the reduced temperature, η_0 is the noncritical part of the dynamic shear viscosity in cP, and $\chi_\eta \mathrm{v}$ is the critical exponent for the dynamic shear viscosity anomaly which equals 0.04 (Klein and Woermann, 1978; Abdelraziq, 2002).

The correlation length is the average distance between two molecules at temperatures near the critical temperature. The correlation length expression is given by equation (2.7):

$$\xi = \xi_0 \, t^{-\nu} \tag{2.7}$$

This is related to the reduced temperature t near the critical temperature T_c and critical concentration χ_c.

Van der Waals intermolecular forces act between stable molecules or between functional groups of macromolecules. The intermolecular force range is the reciprocal of the correlation length ξ at $\eta = \eta_0$ (Buchingham, 1937).

The mode coupling theory has important applications such as fiber optics, lasers, and condensed-matter physics, to describe the slowing down of the critical behavior.

2.4 Refractive index of a binary mixture:

The refractive index n_D of any mixture can be calculated from the knowledge of the refractive index and the mass density of pure components. n_D can be measured in all ranges of existing temperatures and can also be deduced theoretically (Rilo *et al*, 2012). The Lorentz and Lorenz mixing rule in the form reported has been verified for the system under investigation (Tasic *et al*, 1992). This rule was used to calculate the refractive index theoretically. The rule is given by equation (2.8):

$$n_D = \sqrt{\frac{(2\,A+1)}{(1-A)}} \tag{2.8}$$

Where A is given by equation (2.9):

$$A = \left\{\left[\left(\frac{n_{1D}^2-1}{n_{2D}^2+2}\right)\frac{1}{\rho_c}\right] - \left[\left(\frac{n_{1D}^2-1}{n_{2D}^2+2}\right)\frac{W_1}{\rho_1}\right] + \left[\left(\frac{n_{2D}^2-1}{n_{2D}^2+2}\right)\frac{W_2}{\rho_2}\right]\rho_c\right\} \quad (2.9)$$

Where n_{1D} and n_{2D} are the pure components refractive indices, $W_1$and W_2 are the weight fractions, ρ_c is the mixture mass density at critical temperature and critical concentration, $\rho_1$and ρ_2 are the pure components mass densities (Maurizio and Giovanni, 1999).

2.5 Power law of refractive index:

Specific heat, thermal expansion coefficient and thermal conductivity and other thermodynamic properties, diverge as the critical temperature T_c is approached with the divergence obeying a power-law in $|T - T_c|$. The exponents that go with these power laws are called critical exponents (Qasim and Darwish, 2013).

The refractive index is expected to be temperature dependent, as viscosity and density of binary mixture, as given by the power law shown in equation (2.10):

$$n_D = n_{0D}t^{-\chi_n \nu} \quad (2.10)$$

Where t is reduced temperature, which is given by$\frac{T-T_c}{T_c}$, χ_n is the critical exponent for the refractive index, and ν is critical exponent which equals to 0.64 (D'Arrigo *et al*, 1977; Klein and Woermann, 1978).

2.6 Two – scale – factor universality:

The two – scale – factor universality has been used in some theories to explain the critical phenomena of binary liquid mixtures by prediction of R_ξ (Hohenberg *et al*, 1976). This quantity is defined in equation (2.11):

$$R_{\xi} = \xi_0 (\frac{\alpha\, T_c \alpha_{pc}}{K_B T'_c})^{\frac{1}{d}} = \xi_0 (\frac{\alpha\, \rho_c c_{pc}}{K_B})^{\frac{1}{d}} \quad (2.11)$$

Where R_{ξ} is the universal quantity that equals 0.270 (Bervillier, 1976), α is the critical exponent that equals 0.11, ρ_c is the mass density at the critical temperature, c_{pc} is the critical amplitude of the isobaric specific heat, K_B is the Boltzmann's constant, $\alpha_{pc}$is the critical amplitude of the thermal expansion and T'_c is the pressure derivation of the critical temperature along the critical line (Abdelraziq, 2003; Hohenberg *et al*, 1976).

The specific heat at constant pressure c_p is given by equation (2.12):

$$c_p = c_{pc} t^{-\alpha} + c_{pb} \quad (2.12)$$

Where c_{pc} is the critical amplitude of the isobaric specific heat that is calculated from equation (2.11) and c_{pb} is the background isobaric specific heat.

Chapter Three

Methodology

High-purity samples of cyclohexane and phenol are used in this work. The dynamic shear viscosities at temperatures ranging from 14.0 to 21.0 ºC are measured for cyclohexane - phenol binary mixtures (above 21.0 °C cyclohexane start to vibrate then the concentration of samples will be changed), at concentrations range (0.00% - 39.70%) by weight of phenol. The dependence of the dynamic shear viscosity on the concentration and temperature is determined. Refractive indices are measured at temperatures in the range 14.0 to 21.0 ºC of different concentrations of cyclohexane - phenol binary mixture.

3.1 The characteristics of the binary mixture components.

1- Cyclohexane:

Cyclohexane is a colorless organic solvent produced by reacting benzene with hydrogen. Cyclohexane is fractionated from petroleum and exists as a liquid at standard temperature and pressure (STP). It causes central nervous system depression as a result of acute exposures and may additionally cause irreversible damage to the liver and kidneys over prolonged exposures (Gad, 2014). Cyclohexane with purity (99.5%) was used in this work. The molecular structure of cyclohexane is shown in Figure (3.1).

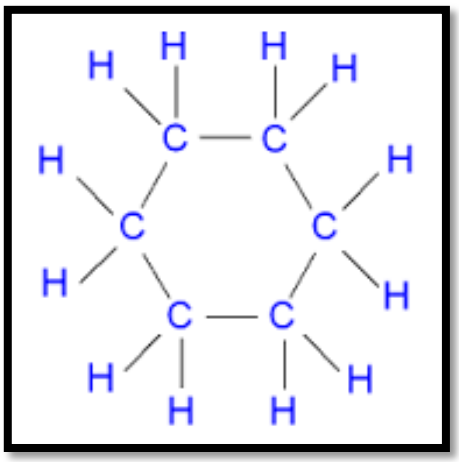

Figure (3.1) The molecular structure of cyclohexane

2-Phenol:

The organic compound phenol is known as carbolic acid and phenic acid. It is a colorless white crystalline solid at room temperature and naturally available. Besides its uses in chemical laboratories, phenol is used in manufacturing plastics, fertilizers, paints, rubber, adhesives, and paper. Phenol and its vapors are corrosive and toxic to the eyes, the skin and the respiratory tract. It is very toxic to neurons and if injected into the blood stream it can lead to instant death by blocking the neural transmission system (Abdullahi *et al*, 2014). Phenol with purity (99.9%) was used in this work. The molecular structure of phenol is shown in Figure (3.2).

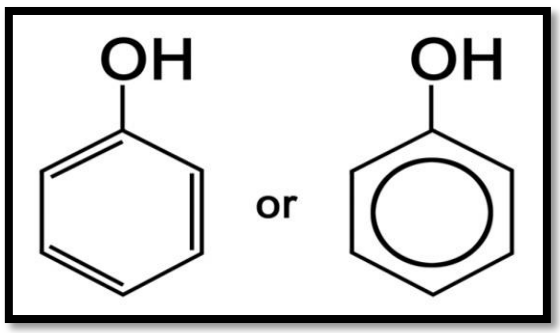

Figure (3.2) The molecular structure of phenol

Some physical and chemical properties for pure cyclohexane and pure phenol are given in Table (3.1).

Table (3.1) Physical and chemical properties of cyclohexane and phenol

Property	**Phenol (Lide, 1993)**	**Cyclohexane (Colette *et al*, 2003)**
Molecular formula	C_6H_6O	C_6H_{12}
Molecular mass (gm/mol)	94.11	84.16
Boiling temperature (℃)	181.7	80.7
Melting temperature (℃)	43.0	6.5
Appearance	Transparent crystalline solid	Colorless liquid
Refractive index n_D (at 20℃)	1.5425	1.4266
Density at (20℃)(gm/cm^3)	1.0576	0.7792

3.2 Experimental apparatus:

3.2.1 Viscosity apparatus:

A Glass capillary U-tube viscometer is used for viscosity measurement. It consists of a U-shaped glass tube held vertically in a controlled temperature bath. One of the U-tube arms is vertically oriented with a narrow bore that consists of two bulbs. The other arm has a large bulb lower down the two bulbs on the first arm Figure (3.3).

Figure (3.3) Glass capillary viscometer

3.2.2 Temperature controller:

Julabo F25-MV Refrigerated and Heating Circulator with temperature range (-28 to 200 °C) of error ±0.5%, Figure (3.4),is used to control the temperature of the sample in the glass capillary viscometer.

Figure (3.4) Julabo F25-MV refrigerated and heating circulator

3.2.3 Digital thermometer:

A digital thermometer of error ±0.5% is used to measure the temperature of the water path for the samples, Figure (3.5).

Figure (3.5) Digital thermometer

3.2.4 Refractive index apparatus:

Digital abbe refractometer, Figure (3.6), is used to measure the refractive indices (n_D) of the samples with error ±0.00005% at the entire range of temperatures. Incident light with visible wavelength of D line wavelength (589.29 nm) is used.

Figure (3.6) Digital abbe refractometer

3.2.5 Calorimeter:

The specific heat of cyclohexane - phenol sample is measured using the calorimeter shown Figure (3.7).

Figure (3.7) Calorimeter

The calorimeter used is manufactured in this laboratory. It is made of insulated glass to achieve our purpose (to avoid the effect of phenol on the metal).

Glass capillary viscometer, calorimeter cup and pycnometer are cleaned twice using ethanol alcohol (99.9%) and dried completely.

3.3 Samples preparation:

3.3.1 Density measurements:

A volume of 10.0 ml is measured by a 10.0 ml pycnometer, and weighed using an HR-200 analytical balance with accuracy of ±0.00005%, Figures (3.8) and (3.9).

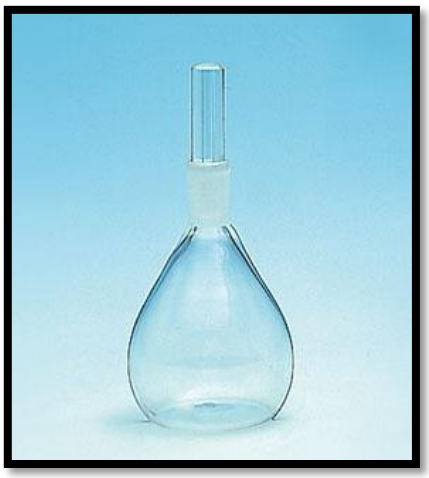

Figure (3.8) 10 ml pycnomete **Figure (3.9)**HR-200 analytical balance

The mass density (ρ) is calculated using equation (3.1).

$$\rho\left(\frac{gm}{cm^3}\right) = \frac{mass\ of\ the\ sample}{20\ ml} \qquad (3.1)$$

The mass density of binary mixture changes with temperature. Therefore, the samples of each binary mixture with fixed concentrations are prepared at same temperature at which the density is measured.

The average measured densities of pure cyclohexane and pure phenol at room temperature (T = 23.0 °C) are 0.7647 gm/cm^3 and1.0476 gm/cm^3, respectively.

3.3.2 Concentration of samples:

Samples of different concentrations are prepared in the range 0.00% to 39.70% by weight of phenol. The binary mixture samples of cyclohexane – phenol will be in solid state for concentrations above the concentration 39.70% by weight of phenol at the temperature range (14.0 °C – 21.0 °C). The concentration of phenol in a given sample of cyclohexane and phenol in a given volume V can be calculated from equation (3.2):

$$\chi_{phenol} = \frac{mass\ of\ phenol}{total\ mass\ of\ the\ binary\ mixture} = \frac{(\rho\ V)_{phenol}}{(\rho\ V)_{phenol}+(\rho\ V)_{cyclohexan}} \quad (3.2)$$

The volume of phenol is changed to enable its addition to the sample. One component volume is fixed to find the volume of the other component for a specific concentration.

3.3.3 Dynamic shear viscosity measurements:

The sample of cyclohexane - phenol mixture is put into the upper bulb by suction. It is then allowed to flow down through the capillary into the lower bulb. Two marks (one above and one below the upper bulb) indicate a known volume. The time taken for the level of the liquid to pass between these marks is proportional to the dynamic shear viscosity. The time required for the test liquid to flow through a capillary of a known diameter of a certain factor between two marked points is measured. The experiment is performed three times for each concentration.

Viscosity of binary mixture can be calculated using equation (3.3):

$$\eta_{mix} = \frac{\eta_{water}\, t'_{mix}\, \rho_{mix}}{t'_{water}\, \rho_{water}} \quad (3.3)$$

Where η_{mix} is the dynamic shear viscosity of binary mixture; $t'_{mix}$is the time flow of binary mixture and ρ_{mix} is the mass density of binary mixture at certain temperature and concentration; η_{water} is the dynamic shear viscosity of water, t'_{water} is the time flow of water and ρ_{water} is the mass density of water at certain temperature.

Water viscosity η_{water} at temperature range (0.0 °C – 20.0 °C) can be calculated using equation (3.4.1) (David, 1985):

$$\log(\eta_T) = \frac{1301}{998.333+8.1855(T-20)+0.00583(T-20)^2} - 1.30233 \quad (3.4.1)$$

Water viscosity η_{water} at temperature range (20.0 °C – 100.0 °C) can be calculated using equation (3.4.2) (David, 1985):

$$\log\left(\frac{\eta_T}{\eta_{20}}\right) = \frac{1.3272\ (20-T) - 0.001053\ (T-20)^2}{T+105} \qquad (3.4.2)$$

3.3.4 Refractive index measurements:

A sample of 20.0 ml of cyclohexane - phenol is incubated in a water bath until its temperature is equilibrated with the water bath. The temperature of the abbe refractometer prism is controlled using a thermostated bath. Two drops of the sample are taken to measure n_D at certain temperature. Refractive indices are measured at temperature rang (14.0 – 21.0 °C).

3.3.5 Isobaric specific heat measurement:

The calorimeter is connected with the power supply, digital ammeter, and digital voltmeter. The 150.0 ml of critical binary mixture is weighted before being placed inside the calorimeter. The applied voltage is changed from power supply until the temperature 25.0 °C is reached for the binary mixture. The power supply is then cut off from the set and temperature started decreasing. The time needed to reach the certain temperature is measured using stopwatch.

The work done on the binary mixture is calculated using equation (3.5):

$$\text{Work} = \text{current} \times \text{volt} \times \text{time}$$

$$W = I \times V' \times t' \qquad (3.5)$$

Joule`s constant (J) is calculated for cyclohexane - phenol mixture using equation (3.6):

$$\text{J} = \frac{H}{W} \qquad (3.6)$$

Where H is the quantity of heat in calorie.

Heat quantity (H) can be calculated using equation (3.7):

$$H = (m_0 c_0 + m_s c_s + m_h c_h + m_{mix} c_p)\ \Delta T \qquad (3.7)$$

Where: m_0 is the mass of calorimeter cup (pyrex beaker), m_s is the mass of stirring rod, m_h is the mass of heater, m_{mix} is the mass of the binary mixture, $c_0$is the specific heat of calorimeter cup, $c_s$is the specific heat of stirring rod, $c_h$is the specific heat of heater and $c_p$is the specific heat of the binary mixture at critical concentration, and ΔT is temperature difference.

3.4 Statistical analysis:

The statistical program (Microsoft Office Excel) is used to tabulate, analyze, and plot data for viscosity and refractive indices for cyclohexane - phenol binary mixture. The coefficient of determination R^2, which represents the percent of the data that is the closest to the line of best fit was calculated. Error bars are also plotted on the curves.

Chapter Four

Results and Discussion

4.1 Viscosity measurements:

This section has been done in collaboration with other group members to investigate the x_c and T_c. The main objective of this work starts with section 4.2.

The dynamic shear viscosity values for cyclohexane - phenol mixture are measured for a concentration range (0.00% – 39.70%) by weight of phenol at temperature range (14.0 °C – 21.0 °C). The data of dynamic shear viscosity values for the entire composition range of temperatures and concentrations are given in Table (4.1).

Table (4.1) The dynamic shear viscosity values of cyclohexane - phenol samples of different concentrations (0.00% - 39.70%) by weight of phenol of temperature range (14.0 ºC – 21.0 ºC)

T (°C)	η (cP) 0.00%	η (cP) 2.00%	η (cP) 2.70%	η (cP) 3.40%	η (cP) 6.70%	η (cP) 9.90%	η (cP) 13.20%	η (cP) 16.00%	η (cP) 17.90%	η (cP) 19.46%	η (cP) 22.50%	η (cP) 25.50%	η (cP) 31.00%	η (cP) 34.00%	η (cP) 37.00%	η (cP) 39.70%
14.0	1.0243	0.9615	0.9850	1.0007	1.0366	1.0671	1.1177	1.3232	1.2687	1.3549	1.4157	1.5976	1.7471	1.7750	2.1044	2.1533
15.0	1.0150	0.9395	0.9771	0.9826	1.0061	1.0575	1.1166	1.2987	1.2650	1.3454	1.3831	1.5258	1.7122	1.7894	2.0454	2.1000
16.0	0.9948	0.9196	0.9566	0.9591	0.9928	1.0384	1.0793	1.2822	1.2568	1.2800	1.3295	1.4738	1.6671	1.7483	1.9456	2.0062
17.0	0.9819	0.9040	0.9672	0.9550	0.9885	1.0289	1.0815	1.2677	1.2383	1.2241	1.3105	1.4221	1.6433	1.7351	1.9366	1.9665
17.5	0.9757	0.8986	0.9416	0.9461	0.9791	1.0284	1.0800	1.2611	1.2304	1.2224	1.2984	1.4050	1.6293	1.7464	1.9408	1.9491
18.0	0.9668	0.8877	0.9232	0.9362	0.9689	1.0160	1.0632	1.2435	1.1894	1.2103	1.2753	1.4041	1.6091	1.7284	1.9297	1.9098
18.5	0.9613	0.8796	0.9225	0.9293	0.9657	1.0129	1.0552	1.2282	1.1802	1.2098	1.2650	1.3933	1.5819	1.7061	1.8430	1.8905
19.0	0.9532	0.8709	0.9047	0.9193	0.9520	1.0042	1.0425	1.2073	1.1718	1.1817	1.2498	1.3775	1.5595	1.6901	1.8222	1.8545
19.5	0.9436	0.8633	0.8895	0.9054	0.9442	0.9828	1.0250	1.1899	1.1557	1.1554	1.2221	1.3818	1.5205	1.6340	1.8010	1.8183
20.0	0.9359	0.8525	0.8885	0.9050	0.9301	0.9802	1.0217	1.1799	1.1309	1.1463	1.2105	1.3652	1.5150	1.5751	1.8075	1.8138
20.5	0.9247	0.8354	0.8784	0.8910	0.9163	0.9665	1.0076	1.1743	1.1133	1.1331	1.1972	1.3489	1.4878	1.5597	1.7326	1.7689
21.0	0.9236	0.8240	0.8768	0.8908	0.9172	0.9670	1.0059	1.1624	1.1102	1.1218	1.1835	1.3194	1.4825	1.5607	1.7205	1.7656

The dynamic shear viscosity of cyclohexane - phenol binary mixture depends on temperature. A positive relationship is found between the dynamic shear viscosity and the concentration of phenol in the sample. This is due to the high viscosity of phenol in the mixture.

The dynamic shear viscosity of cyclohexane - phenol of different concentrations (0.00% - 39.70%) by weight of phenol is plotted as a function of temperature, as shown in Figures (4.1) – (4.4).

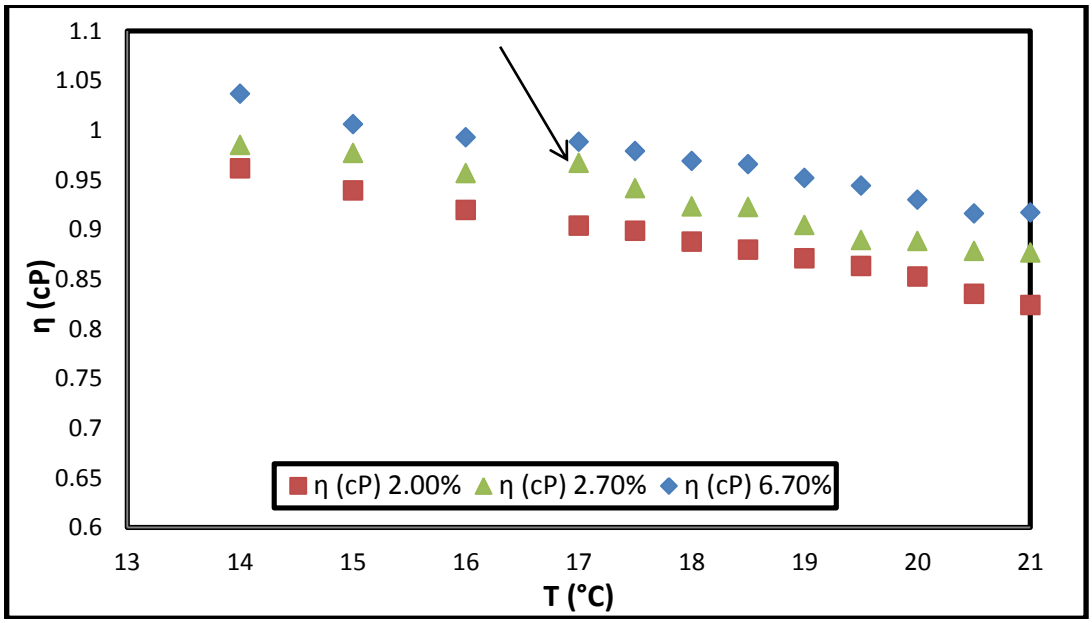

Figure (4.1) The dynamic shear viscosity of cyclohexane - phenol as a function of temperature of concentrations (2.00% - 6.70%) by weight of phenol

Figure (4.1) shows that the dynamic shear viscosity behaves anomalously near the concentration 2.70% by weight of phenol and at the temperature 17.0 °C. This gives an indication that this is the critical point (T_c = 17.0 °C, χ_c= 2.70% by weight of phenol) for the binary mixture cyclohexane - phenol.

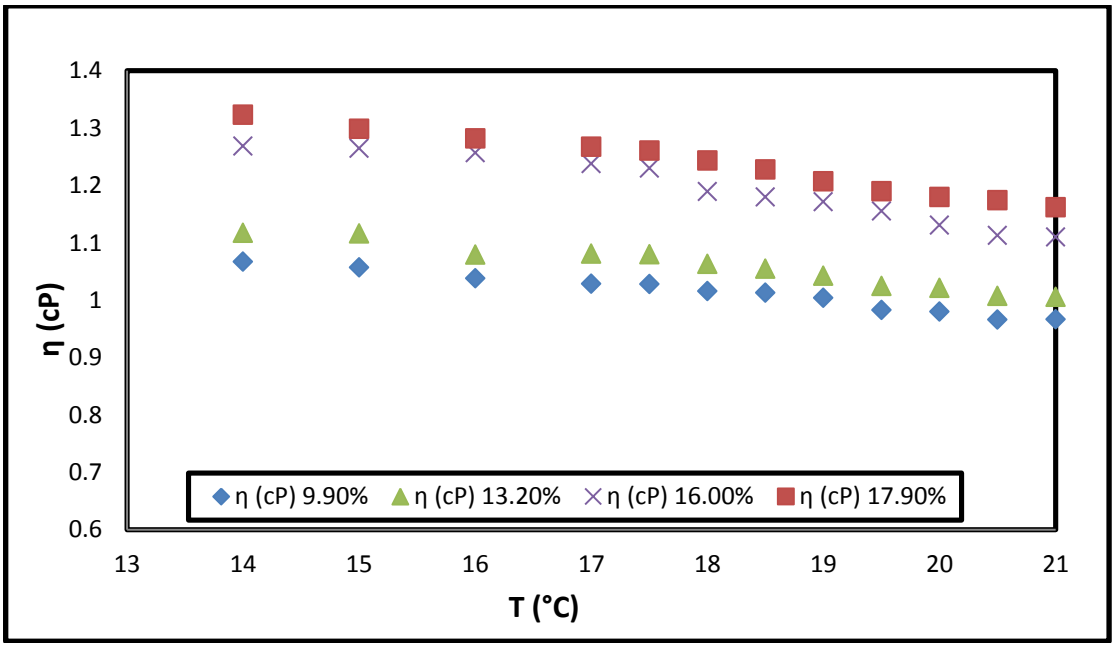

Figure (4.2) The dynamic shear viscosity of cyclohexane - phenol as a function of temperature of concentrations (9.90% - 17.90%) by weight of phenol

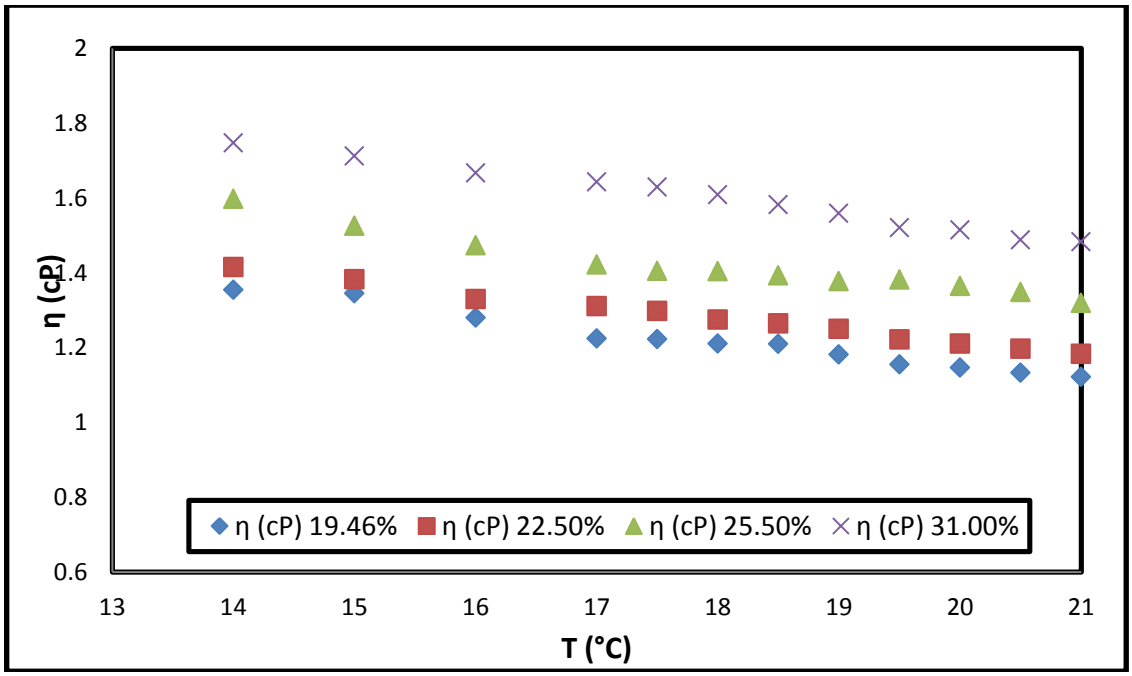

Figure (4.3) The dynamic shear viscosity of cyclohexane - phenol as a function of temperature of concentrations (19.46% - 31.00%) by weight of phenol

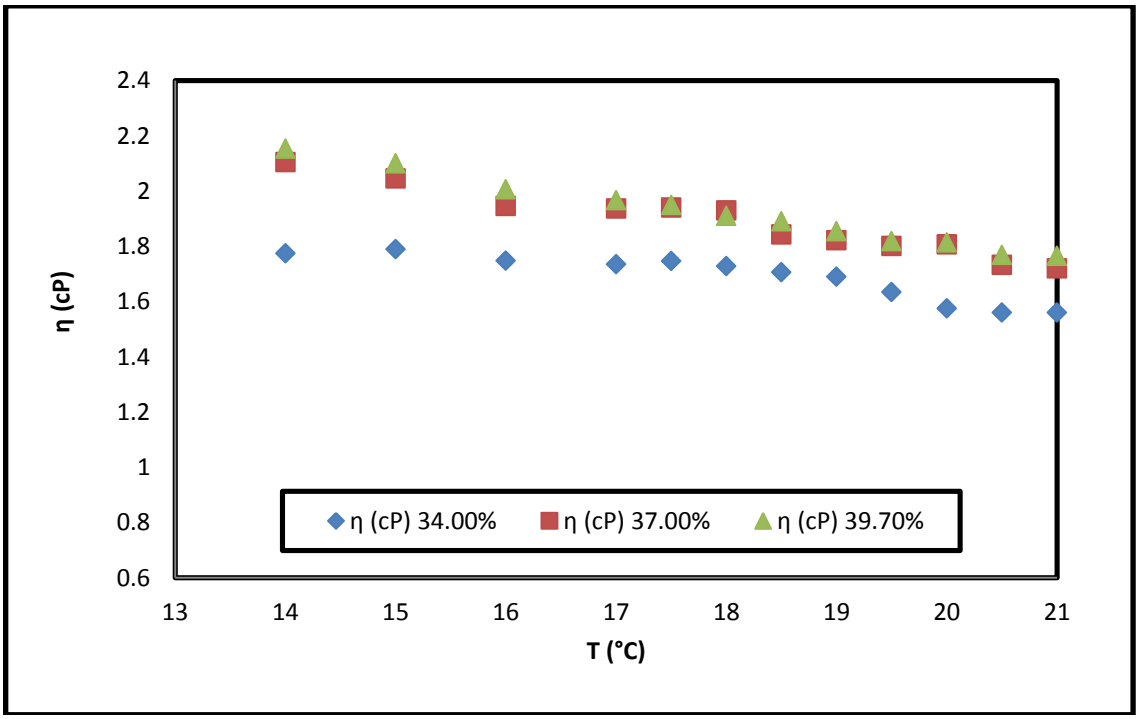

Figure (4.4) The dynamic shear viscosity of cyclohexane - phenol as a function of temperature of concentrations (34.00% - 39.70%) by weight of phenol

Figures (4.2) - (4.4) show that at each concentration of phenol the dynamic shear viscosity continuously decreases as the temperature increases. This is normal, because when temperature is applied to liquids the molecules their average kinetic energy increases. The molecules can then slide over each other more easily. The liquid thus becomes less viscous. Moreover, for each temperature the dynamic shear viscosity increases as the concentration of phenol increases because phenol substance is more viscous than cyclohexane. The viscosity dependence on the temperature at the critical concentration is different from the other concentrations; there are no anomalous behaviors for these concentrations.

The anomaly can be clearly noticed by plotting the dynamic shear viscosity versus temperature for the concentrations 2.00%, 2.70% and 6.70% by weight of phenol, as shown in Figure (4.5).

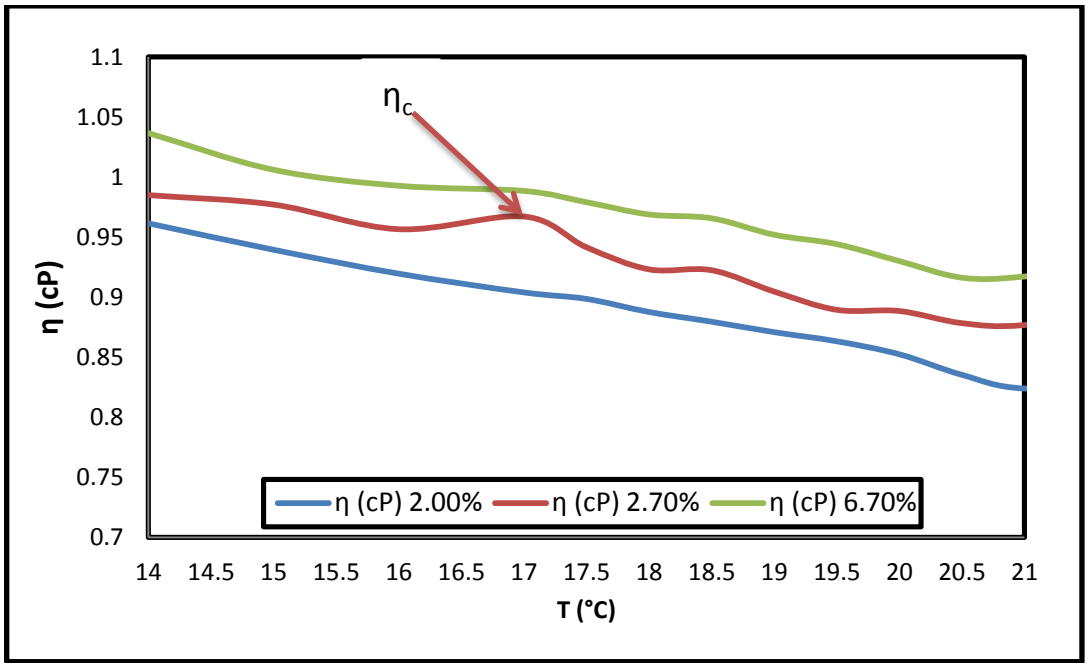

Figure (4.5) Dynamic shear viscosity of cyclohexane - phenol measured as function of temperature of 2.00%, 2.70% and 6.70% by weight of phenol

Figures (4.1) and (4.5) show a cusp at concentration χ_c = 2.70% by weight of phenol and temperature T_c = 17.0 ºC. This point is considered to be a critical point where the two liquids become one phase. Mode coupling theory of dynamic shear viscosity is used to fit the data near the critical point. These figures describe the divergence of η near the critical temperature 17.0 ºC (the curve has singular point at critical temperature which is equal to η_c = 0.9672). This limit occurs once when $|T - T_c|$ goes to zero. At the critical point phase boundaries vanish, cyclohexane and phenol cannot be distinguished from each other; it is the point at which the mixture has homogenous composition

4.2 The noncritical part of refractive index (n_{0D}):

The Lorentz and Lorenz mixing rule can be used to verify the refractive index values for different binary mixtures, but in this work it is difficult to use because of the nature of phenol that it found in solid state at room temperature so its refractive index can't be measured using the available refractometers.

The power law of the refractive index n_D is used to determine the noncritical part of refractive index n_{0D}. The refractive index is temperature dependent which is given by the power law. The data of refractive indices are fitted using the power law $n_D = n_{0D} t^{-\chi_n \nu}$, where n_{0D} is the noncritical part of refractive index, χ_n and ν are critical exponents, and t is the reduced temperature $\frac{T-T_c}{T_c}$.

The measured data of refractive indices n_D of the critical concentration above the critical temperature are given in Table (4.2).

Table (4.2) The measured refractive index values of critical binary mixture above critical temperature

T (°C)	$T - T_c$	$t = \frac{T-T_c}{T_c}$	n_D	$Ln(n_D)$	$Ln(t)$
17.3	0.3	0.0176	1.431	0.3583	-4.0372
17.5	0.5	0.0294	1.4306	0.3580	-3.5264
18.0	1.0	0.0588	1.4304	0.3579	-2.8332
18.5	1.5	0.0882	1.4299	0.3576	-2.4277
19.0	2.0	0.1176	1.4297	0.3574	-2.1401
19.5	2.5	0.1470	1.4296	0.3573	-1.9169
20.0	3.0	0.1764	1.4295	0.3573	-1.7346
20.5	3.5	0.2058	1.4294	0.3572	-1.5805
21.0	4.0	0.2352	1.4292	0.3571	-1.4469

Equation (4.1) gives relation between refractive index (n_D)and reduced temperature (t).

$$n_D = n_{0D} t^{-\chi_n \nu} \tag{4.1}$$

Equation (4.1) can be re-written as shown in equation (4.2).

$$Ln(n_D) = Ln(n_{0D}) - \chi_n \nu \, Ln(t) \tag{4.2}$$

Figure (4.6) shows the relation between $Ln(n_D)$ and $Ln(t)$ to find the value of the critical exponent χ_n and the noncritical part of refractive index n_{0D}.

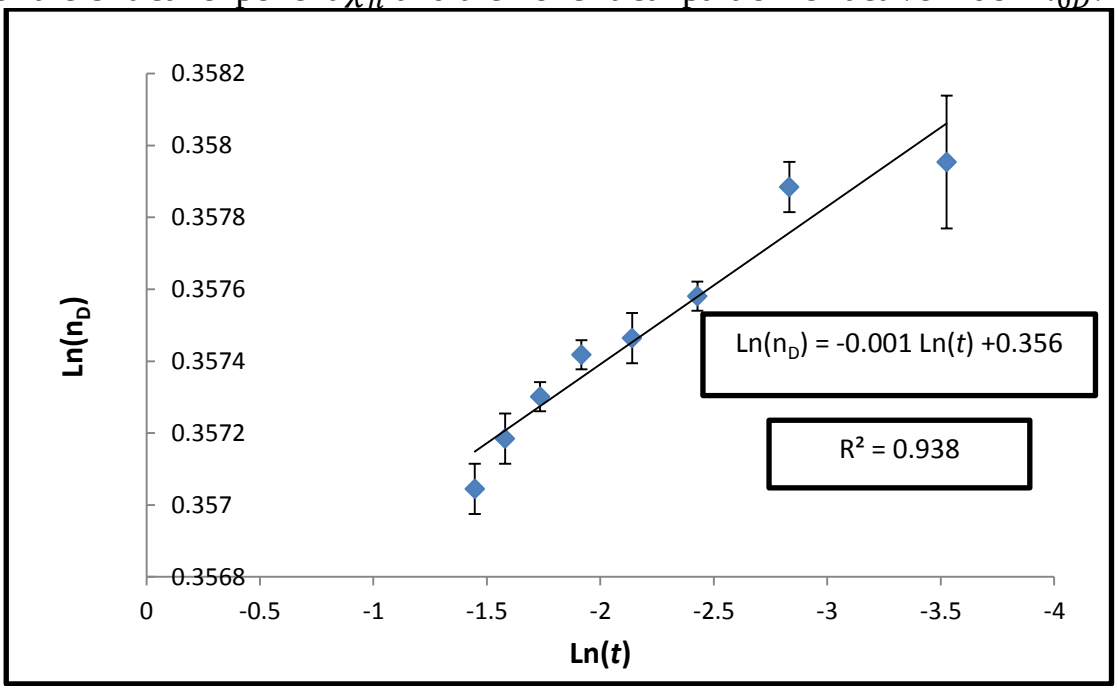

Figure (4.6) $Ln(n_D)$ versus $Ln(t)$

Figure (4.6) shows a linear relation between $Ln(n_D)$ and $Ln(t)$ which can be noticed from equation (4.2). The values for the slope equals to $\chi_n \nu$ = 0.001, but as $\nu = 0.64$, the universal constant for refractive index χ_n = 0.00156. The intercept value $Ln(n_{0D})$ = 0.356 is also needed to calculate the background refractive index n_{0D} = 1.4276. A least square fit gives the best value for χ_n.

Refractive index typically exhibit power law behavior in the asymptotic region which is very close to a critical point like other thermodynamic

properties. Refractive index power law universal critical exponent, the value of critical exponent depending only on very general properties, such as dimensionality and the range of microscopic interactions in the system.

4.3 Calculation of specific heat:

The specific heat under constant pressure at the critical temperature is calculated using the two scale factor universality.

The universal constant R_ξ is given by equation (4.3):

$$R_\xi = \xi_0 \left(\frac{\alpha T_c \alpha_{pc}}{K_B T'_c}\right)^{\frac{1}{d}} = \xi_0 \left(\frac{\alpha \rho_c c_{pc}}{K_B}\right)^{\frac{1}{d}} = 0.270 \qquad (4.3)$$

Where the critical exponent α = 0.11, dimension d = 3, the mass density of binary mixture cyclohexane - phenol at the critical temperature ρ_c= 0.7627 gm/cm^3 that is found in this work, Boltzmann's constant is given by K_B = 1.38 × 10^{-23} J/k, $\xi_0$is the noncritical part of correlation length for critical binary mixture and it is equal to 3.12 Å (Abdelraziq, unpublished). The value for c_{pc}can be calculated to be 106.6 $J/Kg.K$.

The isobaric specific heat of cyclohexane - phenol binary mixture can be calculated using equation (4.4).

$$c_p = c_{pc} t^{-0.11} + c_{pb} \qquad (4.4)$$

The isobaric specific heat c_p values can be calculated at different temperatures close to the critical temperature (17.0 °C) are given in Table (4.3).

Table (4.3) Isobaric specific heat data

T (°C)	$t = \frac{T-T_c}{T_c}$	$t^{-0.11}$	c_p $(J/Kg.K)$
18.5	0.088	1.306	139.2
19.0	0.117	1.265	134.8
19.5	0.147	1.234	131.6

The average value for c_p is 135.2 $J/kg.K$ for cyclohexane - phenol binary mixture.

4.4 Joule`s constant for cyclohexane - phenol binary mixture:

The specific heat at constant pressure c_p of the critical cyclohexane - phenol binary mixture is calculated to be 135.2 $J/Kg.K$.

Joule`s constant J for cyclohexane - phenol binary mixture can be calculated from equation (3.6):

$$\mathrm{J} = \frac{H}{W}$$

Where H is heat quantity and it can be calculated from equation (3.7):

$$H = (m_0 c_0 + m_s c_s + m_h c_h + m_{mix} c_p)\ \Delta\mathrm{T}$$

W is the work done on the binary mixture, it can be calculated from equation (3.5):

$$W = I \times V' \times t'$$

The values of different masses and different specific heats are given in Table (4.4):

Table (4.4) The value of different parameters in equation (3.7)

m_0 (gm)	m_s (gm)	m_h (gm)	m_{mix} (gm)	c_0 $(calorie/gm.K)$	c_s $(calorie/gm.K)$	c_h $(calorie/gm.K)$
81.2519	0.8800	15.0390	149.1400	0.75	0.45	0.84

Joule`s constant values for different temperature ranges are given in Table (4.5).

Table (4.5) Joule`s constant of different quantities of cyclohexane - phenol

T (°C)	ΔT = 25-T (°C)	Time (sec)	I (Amp)	V (volt)	W (J)	c_p $(J/Kg.K)$	H (Calorie)	J (Calorie/J)
18.5	6.5	4219	0.94	10.22	42260	139.2	135423	3.20
19.0	6.0	2978	0.94	10.22	28609	134.8	121068	4.23
19.5	5.5	2252	0.94	10.22	21635	131.6	108354	5.01

The average Joule`s constant value is 4.15 Calorie/J. The average value for Joule`s constant for cyclohexane - phenol binary mixture is less than the Joule`s constant for water (4.1860 Calorie/J). This small deviation between the two values is due to the change in temperature ranges at which Joule`s constants are calculated.

Chapter Five

Conclusion and Future Work

The mode coupling theory of the anomalous dynamic shear viscosity near the critical point has been studied for cyclohexane - phenol binary liquid mixture.

The critical temperature T_c and critical concentration χ_c values have been measured of cyclohexane - phenol binary mixture.

The dynamic shear viscosity coefficients and some thermodynamic properties about the binary mixtures are important for the scientists working on the improvement of molecular theories.

The behavior of refractive index of cyclohexane - phenol obeys the power law universality above the phase transition. The noncritical part of refractive index n_{0D} has been obtained. The universal critical exponent for refractive index χ_n has also been calculated.

The isobaric specific heat for the critical binary mixture c_{pc} has been calculated using two scale factor universality. The value of Joule`s constant J of cyclohexane - phenol binary mixture was determined.

To our knowledge, the experimental values T_c, χ_c, n_{0D}, χ_n, c_{pc} and Joule`s constant of binary mixture cyclohexane - phenol were calculated in this work for the first time. Such values give further characteristic properties to be employed in the identification of a highly industrially used and yet a seriously bio-hazardous for mixture.

The results of the different properties that have been calculated and measured of the binary liquid mixture cyclohexane - phenol are summarized in Table (5.1).

Table (5.1) Summary of values of constants measured or calculated in this work

Constant measured or calculated	Value
T_c	17.0 ℃
χ_c	2.70% by weight of phenol
χ_n v	0.001
n_{0D}	1.4276
χ_n	0.00156
η_c	0.9672
c_{pc}	106.6 $J/Kg.K$
J	4.15 $Calorie/J$

For future works, many other binary mixtures can be studied using the mode coupling approach to determine the unknown physical parameters. Other kinetic coefficients, including heat capacity, susceptibility and thermal expansion coefficient, can also be identified for the cyclohexane - phenol binary mixture and other binary mixtures near their critical points**.**

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جامعة النجاح الوطنية

كلية الدراسات العليا

السلوك الحرج لمعامل الانكسار للخليط الثنائي سايكلوهكسان – فينول

إعداد

هبة يوسف بشارات

إشراف

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د. محمد أبو جعفر

قدمت هذه الأطروحة استكمالا لمتطلبات الحصول على درجة الماجستير في الفيزياء في كلية الدراسات العليا في جامعة النجاح الوطنية في نابلس – فلسطين.

2015

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الملخص

تم قياس معامل اللزوجة للخليط الثنائي سايكوهكسان – فينول باستخدام مقياس اللزوجة الزجاجي الشعريglass capillary viscometer ، حيث تم القياس للتراكيز (0.00% - 39.70%) من وزن الفينول وعلى درجات الحرارة. (14.0 °C – 21.0 °C) تم تحليل النتائج فوق درجة الحرارة الحرجة باستخدام نظرية الازدواج. وقد ظهر الشذوذ في اللزوجة كاقتران مع درجة الحرارة والتركيز. وتم تحديد درجة الحرارة الحرجة عند T_c= 17.0 °C والتركيز الحرج عند χ_c = 2.7%من وزن الفينول. وقد تم اثبات ان سلوك معامل الانكسار للخليط الثنائي سيكلوهكسان – فينول يخضع للقانون الاسي فوق درجة الحرارة الحرجة. وقد وجد الجزء غير الحرج لمعامل الانكسار ليكون $n_{0D} = 1.4276$. وقد تم حساب قيمة الاس الحرج لمعامل الانكسار χ_n ليكون 0.00156. و تم ايجاد السعة الحرارية النوعية الحرجة عند ثبوت الضغط وعند التركيز الحرج باستخدام قانون المقياس العالمي للمخاليط الثنائية ليكون $c_{pc} = 106.6\ J/kg.K$. وقد تم إيجاد ثابت جول للمحلول سايكلوهكسان – فينول ليكون $Calorie/J$ 4.15 = J.