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Non-asymptotic approach to ultrasonic attenuation in nitroethane–isooctane critical mixture

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Abstract

The acoustic velocity and absorption have been measured in a nitroethane–isooctane mixture at critical composition in the frequency range 2–40 MHz and for temperatures of 31–43 °C. The experimental data have been analysed in terms of the Ferrell–Bhattacharjee dynamic scaling theory with the appropriate crossover corrections and recently developed Folk–Moser renormalization group theory. The shear viscosity of the studied mixture has been also measured to enable this analysis. A good agreement with theoretical predictions has been obtained.

1. Introduction

Sound propagation in binary mixtures provides important information about the dynamical behaviour near the critical point. When the mixture gradually approaches the critical point, the measured absorption coefficient grows rapidly and the rate of growth depends on the ultrasonic wave frequency. This behaviour can be explained in terms of the coupling of the acoustic field with the concentration fluctuations in critical mixtures. Due to the lagged response of the concentration fluctuations the energy of the acoustic wave is dissipated. Because of the absence of strain the fluids exhibit sharp phase transitions and therefore are excellent media for testing the theories of critical phenomena.

There are several theoretical models predicting the sound propagation in binary mixtures near the critical point of mixing [1–7]. In all of them sound attenuation per wavelength α_λ is expressed by the same general equation

$$\alpha_\lambda = \pi A(\epsilon) I(\omega^*), \quad (1)$$

or

$$\alpha_\lambda / \alpha_\lambda^c = I(\omega^*). \quad (2)$$

However, the models differ in the form of the critical amplitude $A(\epsilon)$ and the scaling function $I(\omega^*)$. The reduced temperature ϵ and reduced frequency ω^* are defined as follows:

$\epsilon = T - T_c/T_c$, $\omega^* = \omega/\omega_D$ where ω_D is a characteristic frequency of the concentration fluctuations that can be approximated by the Stokes–Einstein expression [8]:

$$\omega_D = 2D\xi^{-2} = \frac{k_B T}{3\pi\eta\xi^3} = \frac{k_B T}{3\pi\eta_0\xi_0^3} \epsilon^{(3+x_\eta)\nu}. \quad (3)$$

Here, D is the mass diffusion coefficient, ξ is the correlation length, η is the shear viscosity and k_B is the Boltzmann constant. In equation (3) the power laws $\xi = \xi_0\epsilon^{-\nu}$ and $\eta = \eta_0\epsilon^{-x_\eta}$ were used. As follows from equations (1) and (2) the absorption coefficient measured in different systems for different temperatures and frequencies, divided by $A(\epsilon)$ or its value at the critical point α_λ^c , should scale along a universal curve—the scaling function $I(\omega^*)$.

Kawasaki [1] and Mistura [2] developed the mode-coupling formalism which helped understand the physical mechanism underlying the critical anomaly of sound attenuation in binary mixtures and pure fluids, but their predictions did not agree with experimental results, especially for high values of the reduced frequency ($\omega^* > 10$) [9]. Shiwa and Kawaski [5] attempted to eliminate this discrepancy by taking into account higher order mode couplings. However, our experiments showed that their approach also leads to unsatisfactory results [10]. The most successful description turned out to be the dynamic scaling theory developed by Ferrell and Bhattacharjee [6, 7] whose particular merit is the ability to predict sound attenuation at the critical point. This theory seems to correctly describe experimental results in a broad range of reduced frequencies [8, 10, 11].

Unfortunately, all theories mentioned above are related to the asymptotic (near-critical) region in which the universal power laws describing various thermodynamical quantities are valid [12], and it is difficult to determine the temperature interval in which the theoretical predictions might apply. Ferrell and Bhattacharjee [13] proposed a simple correction procedure—based on the use of an effective reduced temperature—to clearly reveal the underlying universal scaling. Recently, Folk and Moser [14–17] have proposed a new model of sound propagation in pure fluids and critical mixtures. They analysed non-asymptotic transport coefficients (viscosity, mass diffusion and thermal diffusion) and sound propagation in the nonasymptotic limit using renormalization group theory.

In this paper the approach proposed by Ferrell and Bhattacharjee with appropriate crossover corrections, and the Folk–Moser theory, are compared with our ultrasonic attenuation measurements in the nitroethane–isooctane critical mixture.

2. Theory

2.1. The Ferrell–Bhattacharjee dynamic scaling theory

Bhattacharjee and Ferrell developed a theory for sound propagation in critical mixtures, which is based on the temperature fluctuations associated with propagation of the sound wave. The ultrasound attenuation is caused by a lagged response of the critical concentration fluctuations to the temperature variations in the sound wave. This effect is described by the adiabatic coupling constant g [18]:

$$g = \rho C_P [dT_c/dP - (\partial T/\partial P)_S], \quad (4)$$

where dT_c/dP is the change in the critical temperature, T_c , with pressure, P ; ρ is the density of the mixture, C_P is the heat capacity at constant pressure and S is the entropy. Equation (4) can be expressed in the following form, which is better suited to calculate the constant g [22]:

$$g = -T\alpha_{Pb} + \frac{T\alpha_{Pc}}{C_{Pc}} C_{Pb}. \quad (5)$$

Here, α_{Pc} and α_{Pb} stand for the critical and noncritical (background) part of the thermal expansion coefficient respectively, and C_{Pb} is the background part of the heat capacity at constant pressure. In the critical region, the heat capacity and the thermal expansion coefficient are given by the well known formulae:

$$C_P = C_{Pc}\epsilon^{-\bar{\alpha}} + C_{Pb}, \tag{6}$$

$$\alpha_P = \alpha_{Pc}\epsilon^{-\bar{\alpha}} + \alpha_{Pb}, \tag{7}$$

where $\bar{\alpha} = 0.11$ is the critical exponent. The Ferrell–Bhattacharjee theory predicts a linear relation between α/f^2 and $f^{-1.06}$ at the critical point:

$$\frac{\alpha(T_c)}{f^2} = \left[\frac{\pi^2 \bar{\alpha} g^2 u^2 C_{Pc}}{2z\nu T_c C_{Pb}^2} \left(\frac{\omega_0}{2\pi} \right)^{\frac{\bar{\alpha}}{z\nu}} \right] f^{-(1+\bar{\alpha}/z\nu)} + \frac{\alpha_b}{f^2} = S f^{-1.06} + b \tag{8}$$

where α_b/f^2 describes the classical absorption caused by the viscosity and the thermal conductivity, u stands for ultrasound velocity, ω_0 is the amplitude of a characteristic frequency $\omega_D = \omega_0 \epsilon^{z\nu}$ and $z\nu = 1.93$. Equation (8) can be used to determine the g constant from acoustic measurements.

The critical amplitude in the dynamic scaling theory takes the form

$$A(\epsilon) = \frac{\pi \bar{\alpha} g^2 u^2 C_{Pc}}{2z\nu T_c C_{Pb}^2} \epsilon^{-\bar{\alpha}} = A_0 \epsilon^{-\bar{\alpha}}, \tag{9}$$

while the approximate form of the scaling function $I_{FB}(\omega^*)$ is given by the equation

$$I_{FB}(\omega^*) = (\omega^*)^{-\bar{\alpha}/z\nu} F(\omega^*), \tag{10}$$

where

$$F(\omega^*) = \frac{3}{\pi} \int_0^\infty dx \frac{x}{(1+x)^2} \frac{\omega^* x (1+x)^{\frac{1}{2}}}{x^2 (1+x) + \omega^{*2}}. \tag{11}$$

Combining equations (8)–(10) one obtains for the scaling of the attenuation coefficient

$$\alpha_\lambda / \alpha_\lambda^c = F(\omega^*). \tag{12}$$

All the above equations were derived assuming that the temperature was close to T_c . However, the acoustic measurements are usually carried out in the so-called crossover temperature region, which lies between the truly critical and noncritical regimes. As a remedy to this problem Ferrell and Bhattacharjee [13] recently proposed a simple correction procedure, which introduces an effective reduced temperature ϵ_{eff} according to the equation

$$\epsilon_{\text{eff}} = \epsilon [1 + \bar{\beta}(\kappa/q_c)]^{1/2}, \tag{13}$$

where $\bar{\beta} = 1.18$, $\kappa = \xi^{-1} = \xi_0 \epsilon^{0.65}$, ξ is the correlation length and q_c is the characteristic noncritical crossover wavenumber.

2.2. The Folk–Moser renormalization group theory

Recently, an extensive analysis of sound propagation both in pure fluids and critical mixtures has been performed by Folk and Moser [14–17]. They studied non-asymptotic transport coefficient (viscosity, diffusion and thermal conductivity) and sound mode within the dynamical equations of model H' of the renormalization group theory [19]. The result of their analysis related to the sound attenuation can be written as

$$\frac{\alpha_\lambda}{\alpha_\lambda^c} = I_{FM}(\omega^*) = \frac{\text{Im}[F_+(v(\bar{\epsilon}), \bar{w}(\bar{\epsilon}))]}{\pi/16}, \tag{14}$$

where function F_+ takes the form

$$F_+(v, w) = -\frac{1}{4} \left[\frac{v^2}{v_+ v_-} \ln v + \frac{1}{v_+ - v_-} \left(\frac{v_-^2}{v_+} \ln v_- - \frac{v_+^2}{v_-} \ln v_+ \right) \right], \quad (15)$$

$$v_{\pm} = \frac{v}{2} \pm \sqrt{\frac{v^2}{2} + i\bar{w}}, \quad (16)$$

$$v(\epsilon, \bar{\epsilon}) = \frac{\xi^{-2}(\epsilon)}{\xi^{-2}(\bar{\epsilon})}, \quad (17)$$

$$\bar{w}(\bar{\epsilon}) = \frac{\omega}{2\Gamma_{\text{eff}}(\bar{\epsilon})\xi^{-4}(\bar{\epsilon})}, \quad (18)$$

$$\Gamma_{\text{eff}}(\bar{\epsilon}) = \Gamma(\bar{\epsilon})(1 - w_3^2(\bar{\epsilon})). \quad (19)$$

The effective reduced temperature $\bar{\epsilon}$ can be determined from the matching condition:

$$\epsilon^8 + \left(\frac{2\omega\xi_0^4}{\Gamma(\bar{\epsilon})(1 - w_3^2(\bar{\epsilon}))} \right)^2 = \bar{\epsilon}^8. \quad (20)$$

The Onsager coefficient Γ and parameter w_3 introducing an additional timescale appear in the equations for the coefficient of diffusion, derived by Folk and Moser [20]:

$$D(\epsilon) = (\xi_0^{-1}\epsilon^\nu)^2 \Gamma(\epsilon) \left(1 - \frac{f_t^2}{16} \right), \quad (21)$$

and the shear viscosity:

$$\eta(\epsilon) = \frac{k_B T \xi_0}{4\pi\epsilon^\nu \Gamma(\epsilon) F^2(\epsilon)} \left(1 - \frac{f_t^2(\epsilon)}{36(1 - w_3^2(\epsilon))} \right), \quad (22)$$

where f_t is the mode coupling parameter between the order parameter and transverse momentum density.

The temperature dependence of parameters Γ , w_3 and f_t can be obtained from the flow equations:

$$\epsilon \frac{d\Gamma}{d\epsilon} = -\frac{3\nu}{4} \Gamma(\epsilon) f_t^2(\epsilon), \quad (23)$$

$$\epsilon \frac{dw_3}{d\epsilon} = \frac{3\nu}{8} w_3(\epsilon) f_t^2(\epsilon), \quad (24)$$

$$\epsilon \frac{df_t}{d\epsilon} = -\frac{\nu}{3} f_t(\epsilon) \left(1 - \frac{3}{4} f_t^2(\epsilon) - \frac{f_t^2(\epsilon)}{24(1 - w_3^2(\epsilon))} \right). \quad (25)$$

The main advantage of the Folk–Moser theory is due to the fact that equations (21) and (22) are non-asymptotic which means that the theory is valid both in the asymptotic (near-critical) and non-asymptotic regions.

3. Experiment

A mixture of nitroethane and isooctane is a system with the upper critical temperature of mixing $T_c = 30.05^\circ\text{C}$ and the critical concentration $x_c = 0.4306$ mole fraction of isooctane [21]. The chemicals (Aldrich 99.8%) were used without further purification. The sample was prepared by weight with a precision $\Delta x = 0.001$ mole fraction of isooctane.

The ultrasound velocity was measured in the temperature range $32\text{--}44^\circ\text{C}$ using the echo-overlap method developed by Papadakis [23]. The experimental error was about $\Delta u = 0.2 \text{ m s}^{-1}$. The absorption coefficient was determined for six frequencies: 2, 9.6,

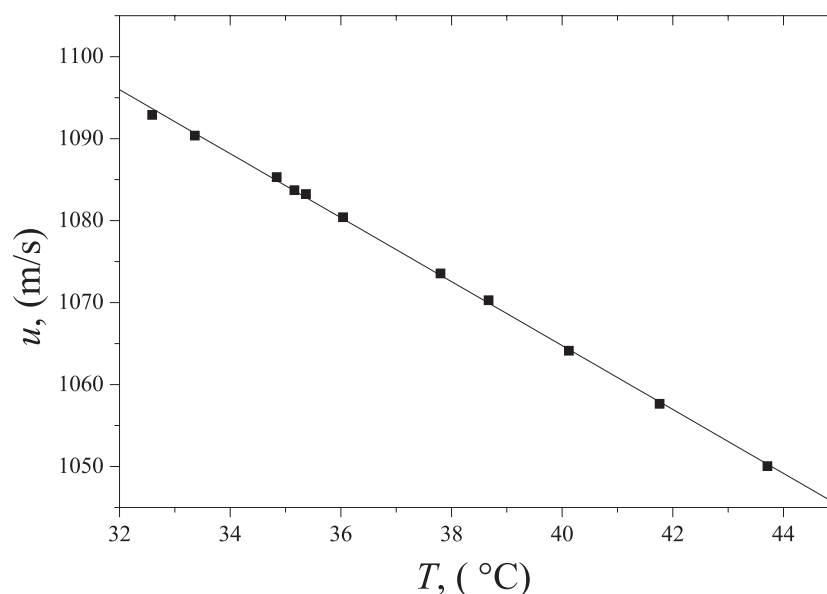


Figure 1. Temperature dependence of the velocity of the ultrasonic wave in the nitroethane–isooctane system. The solid curve represents a linear fit to experimental data.

13, 15.3, 19.1 and 38.4 MHz in the temperature range 31–42 °C using the pulse method by measuring the change in the amplitude of the received pulse as the receiving transducer was moved over a known distance. The relative error of absorption coefficient did not exceed 5%. The MATEC apparatus was used to perform these measurements. A detailed description of the experimental set-up can be found in [10]. All measurements were started at a temperature above T_c , and then the temperature was gradually decreased to a critical value. The measurements for 2 MHz and for the frequency range 9.6–38.4 MHz were carried out in different sample cells. However, in the first sample cell we were unable to obtain satisfactory signal when the transducer was driven on the first overtone (6 MHz). As a result there is a gap between 2 and 9.6 MHz in our frequency measurements.

It was found that the ultrasonic wave velocity decreases in a linear way with increasing temperature according to the relation $u = 1220.8 - 3.9 \times T$ (figure 1). No dispersion was observed in the nitroethane–isooctane mixture [26]. The lack of critical effects close to T_c was consistent with the theoretical predictions for high-frequency velocities in binary critical mixtures [24].

Figure 2 shows the temperature dependence of the absorption coefficient α_λ for six frequencies. This dependence appears typical for a critical mixture: absorption increases rapidly as the system approaches the critical point. The rate of growth depends on the frequency of the ultrasonic wave: the lower the frequency the quicker the growth of absorption.

The shear viscosity was measured using a Höppler viscometer in the temperature range 305–325 K. The flow times were measured with a precision of 0.1 s and the temperature was controlled with an accuracy up to 0.02 K. The viscosity η is characterized by the critical exponent x_η ,

$$\eta = \eta_0 \epsilon^{-x_\eta}, \quad (26)$$

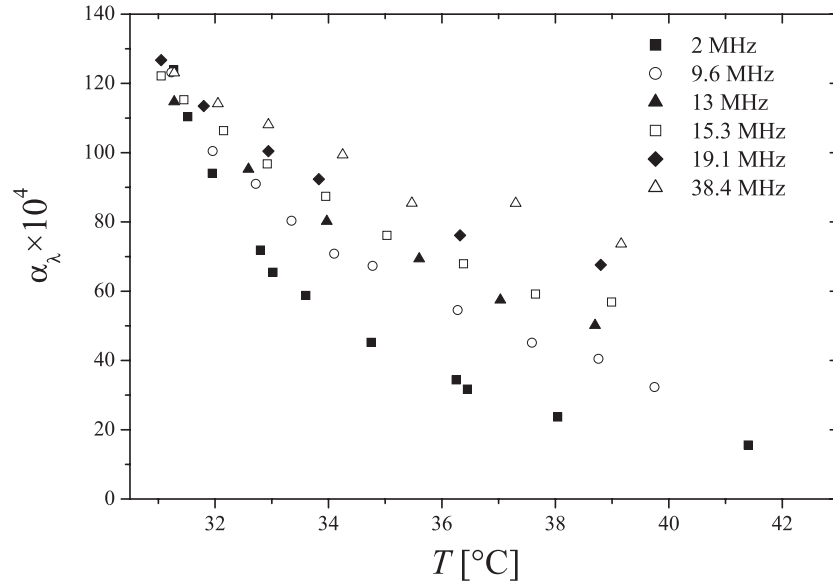


Figure 2. Temperature dependence of absorption coefficient α_λ in nitroethane–isooctane critical mixture.

where η_0 is the background viscosity described by an empirical Arrhenius equation:

$$\eta_0(T) = A_\eta \exp\left(\frac{B_\eta}{T}\right). \quad (27)$$

Substituting equation (27) into (26) and fitting the resulting equation to the viscosity data (figure 3), one obtains $A_\eta = (0.0198 \pm 0.0014)$ mPa s, $B_\eta = (996 \pm 27)$ K, and $x_\eta = 0.0426 \pm 0.0024$ which is very close to the theoretical value $x_\eta = 0.041$ predicted by the renormalization group theory. Using the above values one obtains from equation (27) $\eta_0 = (0.538 \pm 0.017)$ mPa s for the background viscosity in a nitroethane–isooctane mixture.

4. Analysis and discussion

4.1. Ferrell–Bhattacharjee dynamic scaling theory

The first step in analysing experimental data in the light of Ferrell–Bhattacharjee theory is to determine the background absorption from equation (8). Figure 4 shows the results of a linear fit of equation (8) to experimental data, which leads to the values of the slope $S = 2.8 \times 10^{-5} \text{ m s}^{-0.94}$ and the intercept $b = 44 \times 10^{-15} \text{ s}^2 \text{ m}^{-1}$. Since $\alpha_\lambda^b = bfu$, one obtains $\alpha_\lambda^b = 4.84 \times 10^{-11} f$. Using $\rho = 813 \text{ kg m}^{-3}$, $\alpha_{Pc} = 0.125 \times 10^{-4} \text{ K}^{-1}$, $\alpha_{Pb} = 12.7 \times 10^{-4} \text{ K}^{-1}$, $C_{Pc} = 181 \text{ J kg}^{-1} \text{ K}^{-1}$ and $C_{Pb} = 1750 \text{ J kg}^{-1} \text{ K}^{-1}$ [25] it is also possible to determine the value of g from slope S in equation (8),

$$g_{ac} = \sqrt{\frac{S2z\nu T_c C_{Pb}^2}{\pi^2 \bar{\alpha} u C_{Pc} \left(\frac{\omega_0}{2\pi}\right)^{\frac{\bar{\alpha}}{2\nu}}} = \pm(0.354 \pm 0.029), \quad (28)$$

and compare it with the theoretical value calculated from equation (5): $g_{th} = -0.348$.

The amplitude of the characteristic frequency $\omega_0 = 5.83 \times 10^{10} \text{ Hz}$ was determined from equation (3) taking $\xi_0 = 2.42 \times 10^{-10} \text{ m}$ [26].

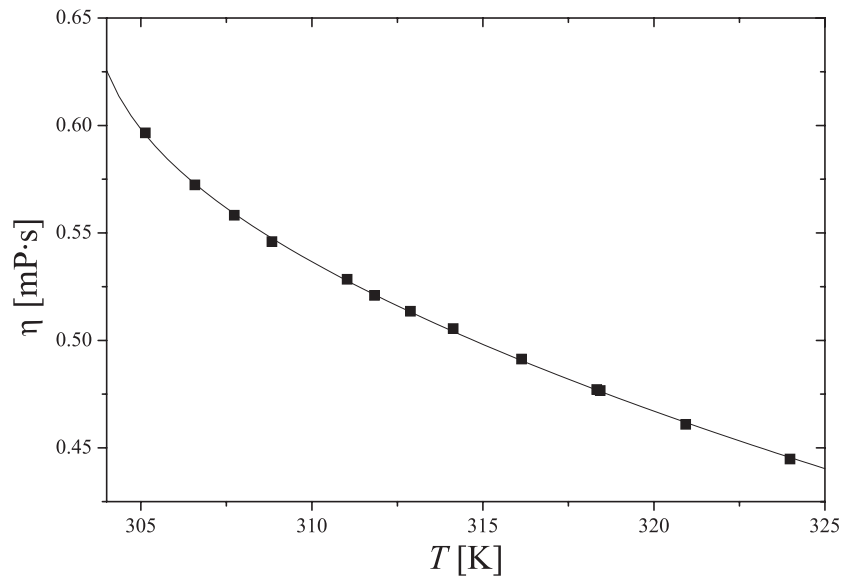


Figure 3. Temperature dependence of the shear viscosity in the nitroethane–isooctane system. The curve represents the fitting function given by equation (26) with the background viscosity described by an Arrhenius form (equation (27)).

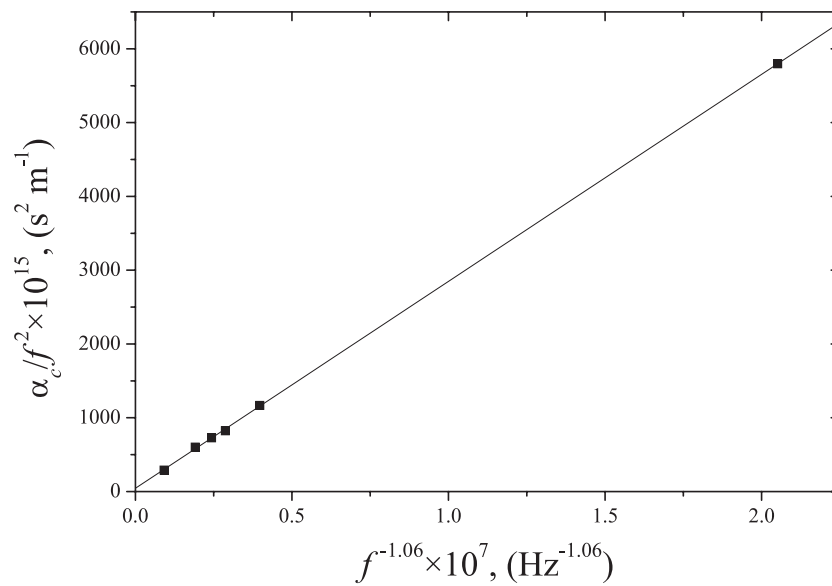


Figure 4. Dependence of α_c/f^2 on $f^{-1.06}$ in the critical mixture of nitroethane–isooctane. The solid line represents a linear fit of equation (8) to experimental points.

The absorption coefficient $\alpha_\lambda^{\text{exp}}$ measured is a sum of the critical part which enters equations (1) and (2) and the background part α_λ^b which was determined earlier. Thus we have

$$\alpha_\lambda = \alpha_\lambda^{\text{exp}} - \alpha_\lambda^b. \tag{29}$$

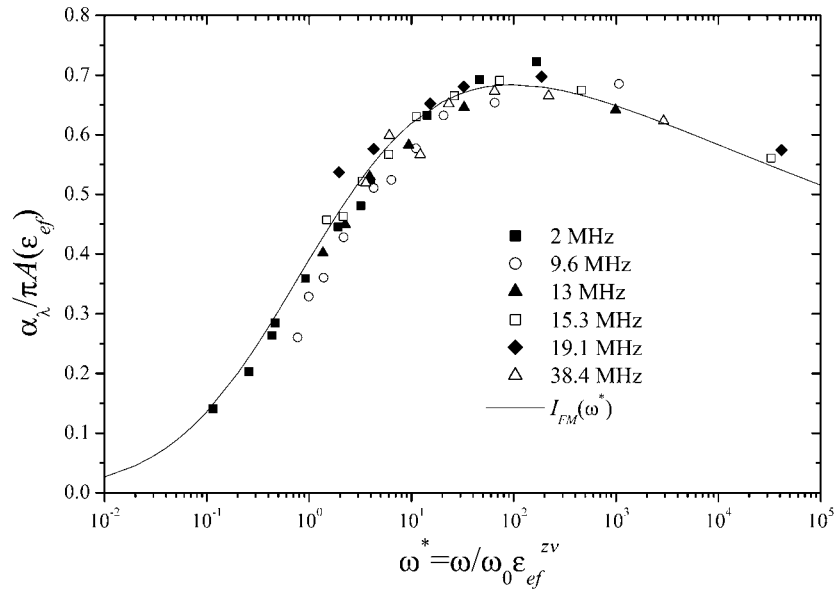


Figure 5. $\alpha_\lambda/\pi A(\epsilon_{\text{eff}})$ versus $\omega^* = \omega/\omega_0\epsilon_{\text{eff}}^{z\nu}$ in the nitroethane–isooctane system. The solid curve represents the scaling function $I_{FB}(\omega^*)$ given by equation (10).

All quantities needed to calculate the critical amplitude from equation (9) are known and lead to $A_0 = 2.49 \times 10^{-3}$.

The last step is to determine the effective temperature from equation (13). The value of q_c can be estimated from the dynamic light scattering results according to the relation [27]

$$Q_0^{-1} = \frac{1}{2}e^{4/3}(q_c^{-1} + q_D^{-1}), \quad (30)$$

where q_D is the Debye wavenumber. Inserting $Q_0 = 6.36 \times 10^8 \text{ m}^{-1}$ [28] and $q_D/q_c = 1.7$ [29] into equation (30) one obtains $q_c = 1.92 \times 10^9 \text{ m}^{-1}$. The difference between ϵ_{eff} and ϵ is negligible close to T_c but becomes noticeable far from the critical point. For example for $T - T_c = 30.42 \text{ }^\circ\text{C}$, $\epsilon_{\text{eff}} = 0.1205$ in comparison with $\epsilon = 0.1$.

Figure 5 shows the plots of $\alpha_\lambda/\pi A(\epsilon_{\text{eff}})$ versus reduced frequency $\omega^* = \omega/\omega_0\epsilon_{\text{eff}}^{z\nu}$. The solid curve represents the scaling function given by equation (10). Figure 5 illustrates a good agreement between the experimental data and the Ferrell–Bhattacharjee theoretical scaling function over the whole reduced frequency range. This confirms the correctness of the expression for the critical amplitude (equation (9)) as well as the value of ω_0 determined from viscosity measurements.

4.2. The Folk–Moser renormalization group theory

The theory of Folk and Moser predicts the attenuation data to scale according to equation (2). In order to confirm their predictions it is necessary to calculate the scaling function from equations (15)–(20). As the first step one has to find the initial values of $\Gamma(\epsilon_0)$, $w_3(\epsilon_0)$ and $f_i(\epsilon_0)$ by fitting equations (21) and (22) to the experimental data of shear viscosity. As the temperature dependence of the background part of viscosity is not described within the renormalization group theory, one has to correct the experimental data using the following expression [16]:

$$\eta^{\text{corr}}(\epsilon) = \eta^{\text{exp}}(\epsilon) - \eta_0(\epsilon) + \eta_0(0). \quad (31)$$

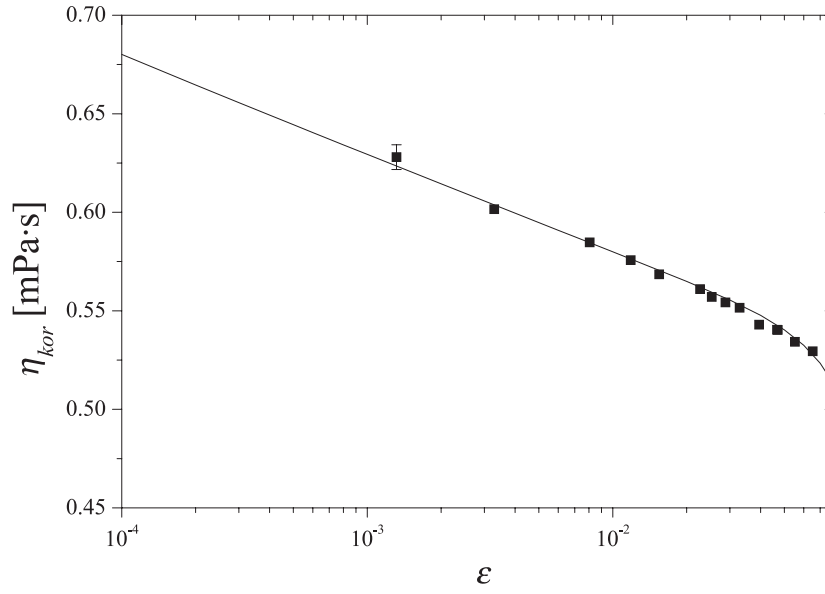


Figure 6. Temperature dependence of shear viscosity in the nitroethane–isooctane mixture. The solid curve represents equation (22) with initial values $\Gamma(\epsilon_0) = 6.2085 \times 10^{-28} \text{ m}^4 \text{ s}^{-1}$, $f_t(\epsilon_0) = 1.15431$ and $w_3(\epsilon_0) = 0.755$.

By choosing $\epsilon_0 = 0.068641$ far away from the critical point, where $\eta(\epsilon_0) = 0.547 \text{ mPa s}$ according to equation (27), one obtains from equation (22) the relationship between $\eta(\epsilon_0)$, and the initial values of the parameters $\Gamma(\epsilon_0)$, $f_t(\epsilon_0)$ and $w_3(\epsilon_0)$:

$$\eta(\epsilon_0) = \frac{k_B T \xi_0}{4\pi \epsilon_0^v \Gamma(\epsilon_0) f_t^2(\epsilon_0)} \left(1 - \frac{f_t^2(\epsilon_0)}{36(1 - w_3^2(\epsilon_0))} \right). \quad (32)$$

The value of mass diffusion coefficient can be determined from

$$D(\epsilon_0) = \frac{1}{2} \omega_0 \xi_0^2 \epsilon_0^{v(z-2)}, \quad (33)$$

which leads to $D(\epsilon_0) = 2.9 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$. By inserting this value into equation (21) one obtains the relationship between $D(\epsilon_0)$ and the initial values of the parameters $\Gamma(\epsilon_0)$, $f_t(\epsilon_0)$ and $w_3(\epsilon_0)$:

$$D(\epsilon_0) = (\xi_0^{-1} \epsilon_0^v)^2 \Gamma(\epsilon_0) \left(1 - \frac{f_t^2(\epsilon_0)}{16} \right). \quad (34)$$

Then it is possible to determine the initial values of $\Gamma(\epsilon_0)$, $f_t(\epsilon_0)$ and $w_3(\epsilon_0)$ by fitting the set of equations (32) and (34) to the experimental data.

Figure 6 shows the dependence of shear viscosity on reduced temperature in the nitroethane–isooctane mixture. The experimental data were corrected according to equation (31). The solid curve represents the Folk–Moser theoretical function given by equation (22) with initial values $\Gamma(\epsilon_0) = 6.2085 \times 10^{-28} \text{ m}^4 \text{ s}^{-1}$, $f_t(\epsilon_0) = 1.15431$ and $w_3(\epsilon_0) = 0.755$. The temperature evolution of parameters $\Gamma(\epsilon_0)$, $f_t(\epsilon_0)$ and $w_3(\epsilon_0)$ was obtained from the flow equations (equations (23)–(25)).

All quantities needed to determine the scaling function from equations (15)–(20) are known. Figure 7 shows the dependence of $\alpha_\lambda/\alpha_\lambda^c$ on the reduced frequency in the nitroethane–isooctane critical mixture. The solid curve represents the Folk–Moser scaling function

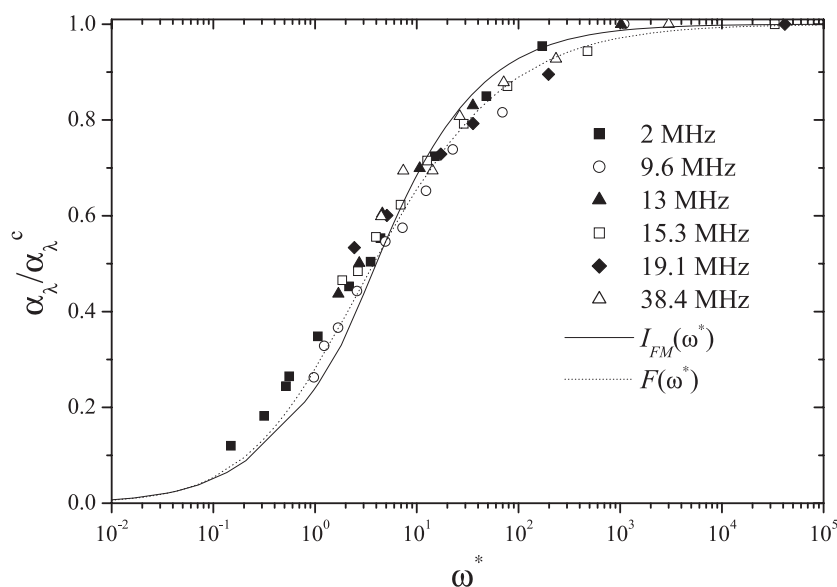


Figure 7. Dependence of $\alpha_\lambda/\alpha_\lambda^c$ on the reduced frequency in the nitroethane–isooctane mixture. The solid curve represents the Folk–Moser scaling function calculated from equation (14) and equations (15)–(20), the dotted curve the Ferrell–Bhattacharjee scaling function given by equation (11).

calculated from equation (14) and equations (15)–(20). Figure 7 also shows the scaling function obtained from the theory of Ferrell and Bhattacharjee given by equation (11) and plotted as a dotted curve. The differences between these two functions are small and rather difficult to detect experimentally.

A good agreement between the experimental data and the scaling functions of Folk–Moser theory (solid curve) and Ferrell–Bhattacharjee theory (dotted curve) was obtained in the whole frequency range. However, for small reduced frequencies our experimental data systematically exceed both theoretical scaling functions. These data correspond to attenuation values measured away from the critical temperature where the critical absorption is comparable with the background contribution. Thus, they are subjected to a greater experimental error. Similar deviations were detected by other authors for a different system [11].

4.3. Conclusions

Using the experimental results of the absorption coefficient and velocity of an ultrasonic wave in the nitroethane–isooctane critical mixture, as well as the data for the shear viscosity in the same system, the theoretical predictions of the ultrasound propagation in binary critical mixtures were analysed. Because the measurements were carried out in a wide temperature range, it was necessary to take into account the so-called crossover corrections. This was done using the effective reduced temperature approach proposed by Bhattacharjee and Ferrell and the non-asymptotic theory of ultrasound propagation in binary mixtures developed by Folk and Moser.

A good agreement between theoretical predictions and experimental results was obtained in both cases in the whole range of reduced frequencies. Thus, the present results do not permit us to decide in favour of one or the other theory, except that the analysis in terms of

the Bhattacharjee–Ferrell approach seems to be somewhat simpler. Additionally, the adiabatic coupling constant evaluated from the acoustic measurements agrees with the value obtained from thermodynamic data of the nitroethane–isooctane system.

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