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# Speed of Sound in the Liquid Phase of the R134a/152a Refrigerant Blend[1]

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The speed of sound in the liquid phase of the binary blend of R134a and R152a and its components has been studied. The speed of sound was measured by means of the impulse method at a frequency of 2.1 MHz. The temperature range was 230 to 350 K at pressures up to 16 MPa. The values of speed of sound were measured with a standard error of not more than 0.25%. The results obtained for both components of the blend are represented with expressions based on a physical model. The standard deviation (versus the model) of the measured data is 0.09%. On the basis of the results obtained, the Redlich–Kister correlation has been used over the entire ranges of composition, temperature, and pressure to determine the speed of sound in the liquid phase and at the bubble point of the blend investigated.

**KEY WORDS:** equation of state; experimental method; phase equilibrium parameters; refrigerant; speed of sound.

## 1. EXPERIMENTAL DATA

The speed of sound in the liquid phase was measured using an impulse method. The device consists of an acoustic cell placed inside a liquid bath filled with kerosene as a thermostatic liquid for temperature control. The lead–zirconate–titanate crystal with a basic frequency of 2.1 MHz was used to generate and receive the sound waves. The pressure and temperature in the acoustic cell were measured with a tensometric pressure transducer and platinum resistance thermometer, and errors do not exceed 0.1% and

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**Table I.** Experimental Values of Speed of Sound ($\omega$) in the Liquid Phase for R152a

| $P$ (MPa) | $\omega$ ($m \cdot s^{-1}$) | $P$ (MPa) | $\omega$ ($m \cdot s^{-1}$) | $P$ (MPa) | $\omega$ ($m \cdot s^{-1}$) | $P$ (MPa) | $\omega$ ($m \cdot s^{-1}$) | $P$ (MPa) | $\omega$ ($m \cdot s^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| $T = 302.97$ K | | $T = 271.16$ K | | $T = 256.73$ K | | $T = 248.53$ K | | $T = 233.28$ K | |
| 16.23 | 769.1 | 0.55 | 789.61 | 0.61 | 862.88 | 0.63 | 903.47 | 0.54 | 979.06 |
| $T = 303.27$ K | | 1 | 793.89 | 0.79 | 864.37 | 0.79 | 905.8 | 0.79 | 981.25 |
| | | 6 | 832.02 | 1 | 865.86 | 1 | 907.2 | 1 | 983.72 |
| 0.68 | 622.0 | 8 | 847.45 | 2 | 872.3 | 2 | 912.86 | 2 | 989.82 |
| 1 | 625.54 | 10 | 861.57 | 4 | 886.83 | 4 | 926.82 | 4 | 1001.7 |
| 2 | 636.38 | 12 | 875.3 | 6 | 900.23 | 6 | 938.21 | 6 | 1012.9 |
| 4 | 659.1 | 16 | 902.25 | 10 | 925.6 | 8 | 951.42 | 8 | 1024.2 |
| 6 | 680.62 | 18.16 | 913.98 | 12 | 938.7 | 10 | 963.42 | 10 | 1036.3 |
| 8.1 | 700.94 | | | 14 | 950.38 | 12 | 975.19 | 12 | 1046.8 |
| 10 | 718.26 | | | 16 | 961.3 | 14 | 986.14 | 14 | 1055.9 |
| 12 | 735.23 | | | | | 16 | 996.77 | 16 | 1067.1 |
| 14 | 751.59 | | | | | | | | |
| 16 | 767.03 | | | | | | | | |
| 16.4 | 769.72 | | | | | | | | |

0.02 K, respectively. This device has been described in detail in our previous publication [1]. The acoustic cell was examined and tested using water and toluene as the standard samples. The deviation of the test data around the standard values does not exceed 0.07%. The values of speed of sound in the liquid refrigerants are measured with a standard error of no more than 0.25%.

The samples of refrigerant binary solutions were prepared in the laboratory by weighing. The composition of each solution is determined with a standard error of about 0.001 mass fraction.

The present experimental data on the speed of sound in the liquid phase of refrigerant R152a and the R134a/152a mixture, at pressures ranging between saturation and up to 16 MPa and temperatures of 230 to 350 K, complete our previous study of refrigerants R134a and R152a [1–4]. The experimental data obtained are presented in Tables I and II.

## 2. RESULTS AND DISCUSSION

### 2.1. Speed of Sound

The data for the speed of sound in the liquid phase of refrigerants R134a and R152a are generalized over the investigated interval by the following polynomial expression:

$$\omega = (\omega'^3 + \Sigma)^{1/3}$$
$$\Sigma = 10^3 \sum_{i=0}^{2} \sum_{j=1}^{3} A_{ij} \tau^i (p - p_s)^j \tag{1}$$

where the temperature function for speed of sound along the boiling curve ($\omega'$) [5] is

$$\omega' = \sum_{i=0}^{4} A_i \tau^{n_i} \tag{2}$$

In Eqs. (1) and (2) $\tau = 1 - T/T_c$, and $p'$, $\omega'$, and $T_c$ are the saturated pressure, the speed of sound in the saturated liquid, and the critical temperature, respectively. The parameters of Eqs. (1) and (2), along with the standard deviation ($\sigma$), are given in Table III.

For representation of the data for the R152a/134a mixture, the model based on the Redlich–Kister correlation describing the deviation ($\Delta\omega$) of the speed of sound from the additive value is applied:

$$\Delta\omega = \omega_m - (x_1\omega_1 + x_2\omega_2) = x_1 x_2 \sum_i^k a_i (x_2 - x_1)^i \tag{3}$$

Hence, it follows that the speed of sound in the mixture along the boiling curve can be approximated by a polynomial expression:

$$\omega'_m = x_1\omega'_1 + x_2\omega'_2 + x_1 x_2 \sum_{i=0}^{2} \sum_{j=0}^{2} K_{ij} \tau_m^i (x_2 - x_1)^j \tag{4}$$

where $\tau_m = 1 - T/T_{cm}$ and $T_{cm}$ is the critical temperature of the given mixture, which can be defined by [6]

$$T_{cm} = 386.5 - 7.548x_1 - 4.722x_1^2 \tag{5}$$

Taking into account Eq. (3), the speed of sound in the liquid phase of the R152a/134a mixture is generalized with the following equation, similar to Eq. (1):

$$\omega_m = \left[ \omega'^3_m + x_1\Sigma_1 + x_2\Sigma_2 + x_1 x_2 (p - p'_m) \sum_{i=0}^{1} \sum_{j=0}^{1} B_{ij} \tau_m^i (x_2 - x_1)^j \right]^{1/3} \tag{6}$$

where $\Sigma_1$ and $\Sigma_2$ are corrections related to the pressure dependence on the speed of sound in pure components in Eq. (1).

**Table II.** Experimental Values of Speed of Sound ($\omega$) in the Liquid Phase for the R134a/152a Mixture

| $P$ (MPa) | $\omega$ ($m \cdot s^{-1}$) | $P$ (MPa) | $\omega$ ($m \cdot s^{-1}$) | $P$ (MPa) | $\omega$ ($m \cdot s^{-1}$) | $P$ (MPa) | $\omega$ ($m \cdot s^{-1}$) | $P$ (MPa) | $\omega$ ($m \cdot s^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| $x_{R134a} = 0.128$ mole fraction | | | | | | | | | |
| $T = 234.15$ K | | $T = 248.6$ K | | $T = 256.87$ K | | $T = 270.3$ K | | $T = 295.71$ K | |
| 0.499 | 939.3 | 0.503 | 869.1 | 0.609 | 828 | 0.698 | 763.9 | 0.759 | 637.5 |
| 0.762 | 940.8 | 0.762 | 869.5 | 0.762 | 829.1 | 0.762 | 764.4 | 1 | 640 |
| 1 | 942.3 | 1 | 872.1 | 1 | 830.7 | 1 | 766 | 2 | 650.1 |
| 2 | 948.5 | 2 | 878.4 | 2 | 838.4 | 2 | 774.5 | 4 | 670.3 |
| 4 | 960.1 | 4 | 891.8 | 4 | 852.4 | 4 | 790.3 | 6 | 689.4 |
| 6 | 971.8 | 6 | 904.9 | 6 | 866.5 | 6 | 805.9 | 8 | 707.2 |
| 8 | 982.4 | 8 | 916.7 | 8 | 878.9 | 8 | 820.4 | 10 | 724 |
| 10 | 993.3 | 10 | 928.3 | 10 | 891.6 | 10 | 833.4 | 12 | 740 |
| 12 | 1002.9 | 12 | 940.5 | 12 | 903.7 | 12 | 846.6 | 14 | 755.4 |
| | | 14 | 951.5 | 14 | 915.3 | 14 | 859.1 | 16 | 769 |
| | | 16 | 962.1 | 16 | 926.4 | 16 | 871.2 | | |
| $T = 306.27$ K | | $T = 315.92$ K | | $T = 327.58$ K | | $T = 336.19$ K | | $T = 350.37$ K | |
| 0.759 | 583.6 | 1.361 | 540 | 1.54 | 479.5 | 1.72 | 432.1 | 2.56 | 361.6 |
| 1 | 586.2 | 2 | 548.4 | 2 | 487.2 | 2 | 437.6 | 3.17 | 376.6 |
| 2 | 597.4 | 4 | 574.9 | 4 | 518.1 | 4 | 472.7 | 4 | 396.5 |
| 4 | 621.1 | 6 | 598.2 | 6 | 544.1 | 6 | 503.7 | 6 | 435.9 |
| 6 | 641.9 | 8 | 619.9 | 8 | 569.1 | 8 | 530.9 | 8.1 | 470.7 |
| 8 | 661.4 | 10 | 640.2 | 10 | 590.5 | 10 | 555.3 | 10 | 498.3 |
| 10 | 679.9 | 12 | 659.2 | 12 | 611 | 12 | 578.3 | 12 | 522.7 |
| 12 | 697 | 14 | 675.2 | 14 | 630.7 | 14 | 598.9 | 14 | 546.9 |
| 14 | 713.8 | 16 | 693 | 16 | 650.4 | 16 | 618 | | |
| 16 | 728.5 | | | | | | | | |
| $x_{R134a} = 0.315$ mole fraction | | | | | | | | | |
| $T = 287.01$ K | | $T = 233.92$ K | | $T = 248.53$ K | | $T = 256.86$ K | | $T = 271.39$ K | |
| 2.61 | 663.9 | 0.456 | 899.9 | 0.512 | 830.1 | 0.492 | 791.1 | 0.485 | 720.4 |
| 2.86 | 666.9 | 0.5 | 900.4 | 0.8 | 831.7 | 0.5 | 791.4 | 0.5 | 720.9 |
| 4 | 677.2 | 1 | 902.4 | 1 | 833.5 | 1 | 795.6 | 1 | 724.7 |
| 6 | 693.8 | 2 | 910.9 | 2 | 840.4 | 2 | 802.3 | 2 | 732.7 |
| 8 | 709.3 | 4 | 923.3 | 4 | 853.1 | 4 | 816.8 | 4 | 749.1 |
| 10 | 725.4 | 6 | 933.6 | 6 | 865.7 | 6 | 830.1 | 6 | 764.9 |
| 12 | 741 | 8 | 943.4 | 8 | 878.9 | 8 | 843.7 | 8 | 779.2 |
| 14 | 755.6 | 10 | 954.2 | 10 | 891.2 | 10 | 855 | 10 | 793.4 |
| 16 | 768.8 | 12 | 964.7 | 12 | 900.5 | 12 | 867.9 | 12 | 806.1 |
| 16.27 | 770.7 | 14 | 974 | 14 | 911.8 | 14 | 879.8 | 14 | 819.3 |
| | | 16 | 983.6 | 16 | 921.8 | 16 | 890.1 | 16 | 831.5 |
| | | 16.37 | 985.8 | 16.26 | 923 | 16.28 | 892.3 | 16.23 | 832.7 |

Table II. *(Continued)*

| $P$ (MPa) | $\omega$ (m·s$^{-1}$) | $P$ (MPa) | $\omega$ (m·s$^{-1}$) | $P$ (MPa) | $\omega$ (m·s$^{-1}$) | $P$ (MPa) | $\omega$ (m·s$^{-1}$) | $P$ (MPa) | $\omega$ (m·s$^{-1}$) | $P$ (MPa) | $\omega$ (m·s$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $x_{R134a} = 0.315$ mole fraction | | | | | | | | | | | |
| $T = 295.74$ K | | $T = 306.24$ K | | $T = 315.86$ K | | $T = 327.59$ K | | $T = 336.19$ K | | $T = 350.36$ K | |
| 0.589 | 598.2 | 0.878 | 549.7 | 1.027 | 501.6 | 1.415 | 443.6 | 2 | 404.7 | 2.28 | 321.6 |
| 0.795 | 600.6 | 1 | 550.9 | 1.208 | 504.1 | 1.62 | 447.7 | 4 | 441.5 | 2.65 | 332 |
| 1 | 603.3 | 2 | 563.2 | 2 | 515.2 | 1.83 | 451.2 | 6 | 473.3 | 4 | 366.3 |
| 4 | 634.5 | 4 | 586.3 | 4 | 541.6 | 2 | 453.9 | 8 | 499.5 | 6 | 407.4 |
| 8 | 671.5 | 6 | 607 | 6 | 565.6 | 4 | 484.1 | 10 | 525.3 | 8 | 440.5 |
| 10 | 688.1 | 8 | 627.4 | 8 | 586.9 | 6 | 511.7 | 12 | 547.6 | 10 | 469.7 |
| 12 | 703.5 | 10 | 645.8 | 10 | 607.3 | 8 | 536.6 | 14 | 568.6 | 12 | 495.2 |
| 16 | 733 | 12 | 663.1 | 16 | 659.9 | 10 | 559.5 | 16 | 587.6 | | |
| 16.11 | 733.7 | 14 | 679.4 | | | 12 | 580.5 | | | | |
| | | 16 | 693.9 | | | 14 | 599.4 | | | | |
| | | | | | | 16 | 617.8 | | | | |
| | | | | | | 16.15 | 618.9 | | | | |
| $x_{R134a} = 0.688$ mole fraction | | | | | | | | | | | |
| $T = 230.23$ K | | $T = 243.19$ K | | $T = 253.16$ K | | $T = 272.78$ K | | $T = 288.83$ K | | $T = 295.68$ K | |
| 0.687 | 865.92 | 0.646 | 803.11 | 0.568 | 755.04 | 0.799 | 664.56 | 0.772 | 588.6 | 0.794 | 552.78 |
| 0.799 | 866.34 | 0.799 | 804.03 | 0.634 | 755.69 | 1 | 666.33 | 0.882 | 589.49 | 0.877 | 553.73 |
| 1 | 867.63 | 1 | 805.32 | 1 | 758.62 | 2 | 674.76 | 1 | 590.87 | 1 | 555.11 |
| 2 | 873.24 | 2 | 811.27 | 2 | 765.06 | 4 | 690.12 | 2 | 600.45 | 2 | 565.82 |
| 4 | 884.45 | 4 | 822.67 | 4 | 778.97 | 6 | 705.48 | 4 | 618.93 | 4 | 585.22 |
| 6 | 892.32 | 6 | 835.98 | 6 | 791.6 | 8 | 720.07 | 4 | 616.21 | 6 | 604.25 |
| 8 | 903.11 | 8 | 847.47 | 8 | 803.36 | 10 | 734.05 | 6 | 633.48 | 8 | 621.93 |
| 10 | 913.45 | 10 | 859.28 | 10 | 815.48 | 12 | 747.31 | 8.39 | 653.3 | 10 | 637.8 |
| 12 | 923.54 | 12 | 869.71 | 12 | 826.6 | 14 | 760.06 | 10.21 | 666.31 | 12 | 653.9 |
| 14 | 932.62 | 14 | 880.17 | 14 | 838.23 | 16 | 771.91 | 12 | 680.88 | 13.83 | 667.93 |
| 16 | 941.36 | 16 | 889.76 | 16 | 848.56 | 16.34 | 773.61 | 13.83 | 693.66 | 16 | 682.58 |
| 16.27 | 942.9 | 16.08 | 890.2 | 16.5 | 851.2 | 16.49 | 774.1 | 16 | 708.2 | | |
| $T = 295.67$ K | | $T = 306.30$ K | | $T = 315.77$ K | | $T = 327.59$ K | | $T = 336.24$ K | | | |
| 0.607 | 552.01 | 1.7 | 512.03 | 1.62 | 463.5 | 1.416 | 398.31 | 2.17 | 363.66 | | |
| 1 | 556.16 | 1.84 | 513.58 | 2 | 468.82 | 1.62 | 401.96 | 2.45 | 368.83 | | |
| 1.21 | 558.17 | 2 | 515.3 | 4 | 493.78 | 2 | 408.24 | 2.86 | 377.13 | | |
| 2 | 566.27 | 4 | 538.34 | 6 | 517.07 | 8 | 492.48 | 4 | 398.43 | | |
| 4 | 586.67 | 6 | 559.46 | 8 | 539.29 | 10 | 515.42 | 6 | 429.8 | | |
| 6 | 605.59 | 8 | 578.99 | 10.3 | 562.55 | 13.28 | 547.85 | 8 | 457.87 | | |
| 8 | 623.13 | 10 | 596.7 | 12.2 | 579.03 | 16 | 571.74 | 10 | 482.49 | | |
| 10 | 640.1 | 12 | 613.61 | 14.23 | 596.34 | 16.05 | 571.74 | 12 | 504.19 | | |
| 12 | 655.83 | 13.83 | 628.83 | | | | | 13.83 | 522.81 | | |
| 14 | 670.96 | 16 | 645.17 | | | | | 16 | 542.69 | | |
| 16 | 684.55 | 16.42 | 648 | | | | | 16.03 | 543 | | |

**Table III.** Constants of Eqs. (1) and (2)

| $i$ | $n_i$ | $A_i$ | $A_{ij}$ $j=1$ | $j=2$ | $j=3$ |
|---|---|---|---|---|---|
| | | R152a: $T_c=386.41$ K, $\sigma=0.17\%$ | | | |
| 0 | 0.056 | 71.1291 | 9,375.02 | −37.74913 | — |
| 1 | 0.515 | 81.1976 | 21,354.38 | 58.6882 | — |
| 2 | 1.0 | 854.085 | 88.29415 | 0.861092 | — |
| 3 | 1.5 | 2,928.56 | — | — | — |
| 4 | 0.621 | 1,170.023 | — | — | — |
| 5 | 1.242 | −2737.83 | — | — | — |
| | | R134a: $T_c=374.27$ K, $\sigma=0.120\%$ | | | |
| 0 | 0.056 | 130.6534 | 5,412.091 | −3.421151 | 0.377037 |
| 1 | 0.515 | −344.8112 | 16,378.544 | 34.6088 | −2.47812 |
| 2 | 1.0 | 901.53 | −215.971 | −238.224 | — |
| 3 | 1.5 | 282.921 | — | — | — |
| 4 | 0.621 | 890.269 | — | — | — |

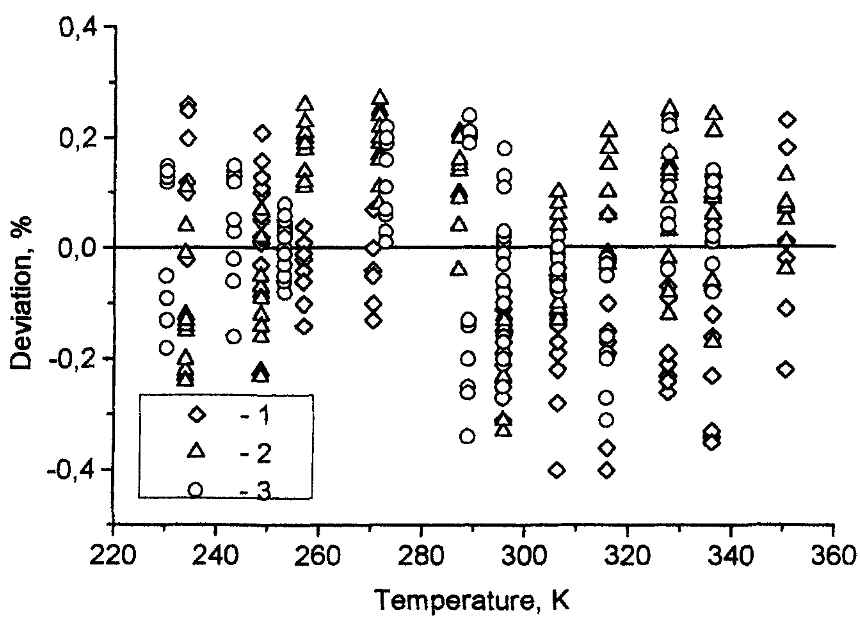


**Fig. 1.** Deviation of data on the speed of sound in the R134a/152a mixture from calculated values versus the mole fraction of R134a and temperature: 1, 2, and 3—$x_{R134a}=0.128$, 0.315, and 0.688 mole fractions of R134a, respectively.

**Table IV.** Coefficients $K_{ij}$ and $B_{ij}$

| | $K_{ij}$ | | | $B_{ij}$ | |
|---|---|---|---|---|---|
| | $j$ | | | $j$ | |
| $i$ | 0 | 1 | 2 | 0 | 1 |
| 0 | −51.13882 | −35.81273 | −6.371193 | −1,661,300 | −1,225,419 |
| 1 | −201.41905 | 192.075775 | 1,186.0470 | −5,534,388 | — |
| 2 | 387.942108 | −622.57489 | −3,519.406 | — | — |

The fitting coefficients of Eqs. (4) and (6) found by means of nonlinear regression are given in Table IV. The standard deviation of experimental data versus the model is 0.151% (see Fig. 1). The dependence of the value $\Delta\varpi(\tau)$ along the boiling curve is shown in Fig. 2.

## 2.2. Phase Equilibrium Parameters

One can assume that the above correlation requires the temperature function for the boiling curve of the investigated liquids. The experimental

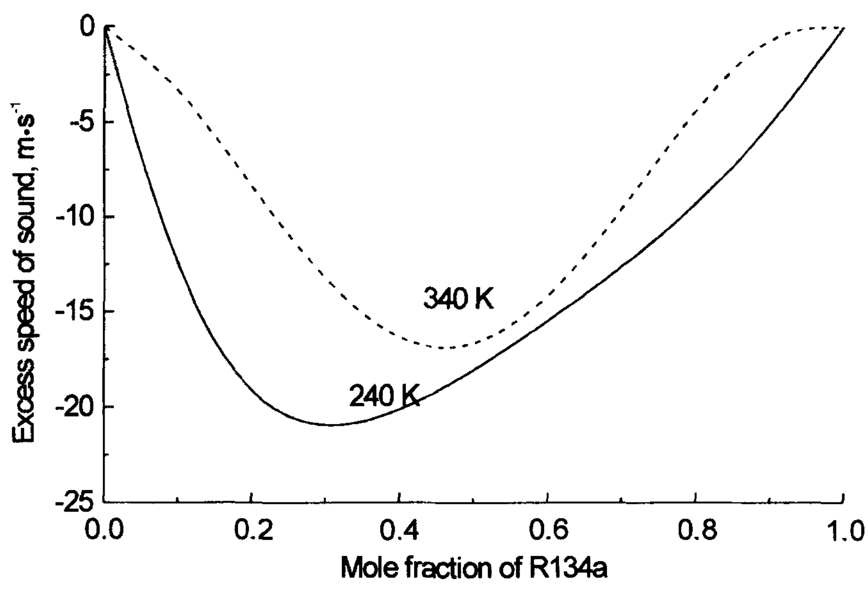


**Fig. 2.** Dependence of excess speed of sound for the R134a/152a mixture at bubble point on the mole fraction of R134a at 240 and 340 K.

data [7–9] for the parameters of the boiling curve were approximated with the use of a model from Ref. 10. For the phase equilibrium parameters of the basic component (R152a), the Wagner correlation [11] was applied. The vapor pressure of R134a is described with the use of additional coefficients $\varphi_i$ and $\theta_i$ incorporated into the same equation. As a result, the vapor pressure values of these refrigerants with a standard error of less than 3 kPa are defined by the following equation:

$$\ln(p_i/\varphi_i p_{ci}) = [1/(1-\tau_i)](A\tau_i^{\alpha} + B\tau_i^{\beta} + C\tau_i^{\gamma}) \tag{7}$$

where $\tau_i = 1 - T/\theta_i T_{ci}$, $\alpha = 1$, $\beta = 1.5$, $\gamma = 2.5$, $A = -7.469422$, $B = 1.907671$, and $C = -2.627579$.

The critical parameters of the components are $T_{c1} = 374.27$ K, $p_{c1} = 4.065$ MPa (for R134a) and $T_{c2} = 386.41$ K, $p_{c2} = 4.512$ MPa (for R152a). The correlation coefficients $\varphi_i$ and $\theta_i$ in accordance with Eq. (7) for R134a are $\varphi_1 = 1.33147$ and $\theta_1 = 1.04084$. For R152a these parameters are equal to 1.

According to the model [10], the value of the vapor pressure ($p_m$) along the boiling curve for a mixture is approximated with the following system of equations:

$$\begin{aligned} \ln(p_m/p_{cm}) &= [1/(1-\tau_m)](A\tau_m + B\tau_m^{1.5} + C\tau_m^3) \\ \tau_m &= 1 - T/T_{cm} \\ T_{cm} &= x_1\theta_1 T_{c1} + \theta_2 T_{c2} \\ p_{cm} &= x_1^2\varphi_1 p_{c1} + 2x_1x_2(1-k_{12})[\varphi_1 p_{c1}\varphi_2 p_{c2}]^{0.5} + x_2^2\varphi_2 p_{c2} \end{aligned} \tag{8}$$

where $x_1$ and $x_2$ are the mole fractions of the components R134a and R152a. The correlation of the $k_{12}$ coefficient versus temperature and composition is used in the form

$$k_{12} = k_{12}^0 + k_{12}^1(T - T_{12}^0) + m_{12}(x_1 - x_2) \tag{9}$$

Here $k_{12}^0$, $k_{12}^1$, $T_{12}^0$, and $m_{12}$ are fitting parameters defined by a nonlinear regression method on the basis of all data measured.

The standard deviation between the experimental vapor pressure data and the calculated results is 0.58%, and the parameters of Eq. (9) are $k_{12}^0 = -0.00270467$, $k_{12}^1 = 0.00007481$, $T_{12}^0 = 95.679$, and $m_{12} = 0.00093333$.

## 3. CONCLUSION

Since no other experimental data on the speed of sound for the investigated refrigerants are available, we could not test the consistency of the data among different sets. One can use the data presented in this paper to calculate the thermal coefficients and heat capacity of the fluids studied and examine the consistency with existing calorimetric and volumetric data.

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