

2n. Tensile Strength and Surface Tension of Liquids

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Symbols

| | |
|-----|----------------------------------|
| g | acceleration of gravity |
| h | rise of liquid in capillary tube |
| p | pressure |
| r | bore radius of capillary tube |

¹ P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* **61**, 57 (1926); "The Physics of High Pressure." G. Bell & Sons, Ltd., London, 1952.

² G. E. McDuffie, Jr., and M. V. Kelly, *J. Chem. Phys.* **41**(9), 2666 (1964).

³ J. D. Tauke, Viscosity of Glycerol at Constant Density, M.S. thesis, Catholic University, October, 1964.

| | |
|------------|------------------------------|
| R_1, R_2 | principal radii of curvature |
| V | volume of liquid drop |
| W | weight of liquid drop |
| γ | surface tension |
| θ | contact angle |
| λ | wavelength of ripple wave |
| ρ | density |

2n-1. Tensile Strength. Historical and General. The maximum negative pressure (tensile strength) that a liquid can withstand has been the object of numerous investigations. Experimental values are quite discordant among themselves and are generally much lower than the theoretical estimates. The tensile strength of a liquid, measured in a device known as a tonometer, is taken as that stress (negative pressure) under which the liquid ruptures. A point of concern has been the possibility that rupture occurs at the wall of the container rather than in the body of the liquid and that therefore the observed negative pressure is a measure of adhesive force rather than of the assumed cohesive force.

Methods of Measuring Tensile Strength. Brief descriptions of these methods are given below, arranged according to the means used to produce the stress in the liquid. Each method is given a code designation for identification in Table 2n-1.

A. STRESS PRODUCED BY COOLING AND THUS CONTRACTING THE LIQUID. In Berthelot's method (A-1) the liquid, sealed in a thick-walled capillary tube, is first warmed until it just fills the tube and is then cooled until the liquid "breaks." The maximum negative pressure is calculated from the known mechanical properties of the liquid, assuming its extensibility to be the same as its compressibility. In Meyer's method (A-2) a spiral glass capillary is part of the tonometer and indicates the pressure exerted by the liquid, which completely fills the vessel. Meyer calibrated his spiral manometers under both positive and reduced pressure. Worthington, in a single experiment (A-3), measured the tension by means of a mercury-in-glass dilatometer, the bulb of which was enclosed within the tonometer. The calibration curve of the dilatometer, obtained previously by applying positive pressure, was extrapolated into the negative region. Vincent used a viscosity tonometer (A-4) in which the liquid completely filled a glass bulb and a fine capillary tube attached to it. By controlled cooling of the bulb, a gradually increasing tension is exerted on the liquid, measured at any time by the rate of flow through the capillary. The maximum tension can be calculated from the observed rates of flow before and after the liquid ruptures.

B. STRESS PRODUCED BY EXPANDING THE VOLUME OF TONOMETER. Vincent has described a new method (B-1) which employs a metal bellows completely filled with the liquid. Extension of the bellows exerts a pull on the contained liquid. An early method (B-2) involved the use of a long (2-m) tube closed at one end with a semi-permeable membrane. After being filled with air-free water the tube is inverted and the open end is placed in a mercury trough. Evaporation of the water through the membrane causes the mercury to rise in the tube. The tension is estimated from the length of the column in excess of normal barometric height. Hulett (1903), in connection with an experiment of this type, observed a marked decrease in rate of evaporation as the mercury column rose and called attention to the analogy between negative pressure and osmotic pressure. This relationship forms the basis of a method for measuring the osmotic pressure of a solution. Budgett (B-3) measured the force required to pull apart flat steel surfaces wetted by a thin film of the liquid.

C. STRESS PRODUCED BY CENTRIFUGAL FORCE. Several experiments have been reported in which tension is developed by rotation of the tube containing the liquid. Reynolds (C-1) used U tubes sealed at both ends, with one arm longer than the other. One arm is filled completely with liquid; the other arm is only partially filled with

liquid under its own vapor pressure. The tube is rotated about an axis positioned somewhat above the open part of the U. Temperly used a similar method (C-2), except that the short arm was open to the atmosphere. Recently Briggs (C-3) employed a Z-shaped capillary tube, open at both ends, rotating in the Z plane about

TABLE 2n-1. TENSILE STRENGTH OF LIQUIDS BY VARIOUS METHODS

| Liquid and method | Max negative pressure, atm | Ref. | Liquid and method | Max negative pressure, atm | Ref. |
|-------------------|----------------------------|------|---------------------------|----------------------------|------|
| Water: | | | Ether: | | |
| A-1* | 50-150 | 1 | A-2 | 72 | 1 |
| A-1† | 157 | 2 | B-1 | 2.2 | 1 |
| A-1‡ | 17-56 | 3 | Mineral oil: | | |
| A-1 | 68 | 4 | A-1 | 119 | 2 |
| A-2 | 34 | 1 | A-1¶ | 24 | 2 |
| A-3 | 17 | 1 | A-4 | 7.8 | 7 |
| B-1 | 1.5 | 4 | B-1 | 2.9 | 1 |
| B-2 | 0.2-0.5 | 1 | Acetic acid, C-3 | 288 | 8 |
| B-3 | 4 | 1, 8 | Benzene, C-3 | 150 | 8 |
| C-1 | 4.8 | 1 | Aniline, C-3 | 300 | 8 |
| C-1 | 6.0 | 5 | Carbon tetrachloride, C-3 | 276 | 8 |
| C-2 | 5.6 | 5 | Chloroform, C-3 | 317 | 8 |
| C-3 | 277 | 6 | Mercury, C-3 | 425 | 9 |
| Alcohol: | | | | | |
| A-2 | 40 | 1 | | | |
| A-3 | 17 | 1 | | | |
| B-1 | 2.4 | 1 | | | |
| C-1 | 7.9 | 1 | | | |

* Values reported prior to 1941.

† Tubes boiled for 8 hr to expel air.

‡ Tubes filled by vacuum technique to eliminate air.

¶ Tube sealed by liquid frozen in capillary side arm.

References for Table 2n-1

1. Vincent, R. S.: *Proc. Phys. Soc.* **53**, 141 (1941).
2. Vincent, R. S., and G. H. Simmonds: *Proc. Phys. Soc.* **55**, 376 (1943).
3. Scott, A. F., D. P. Shoemaker, K. N. Tanner, and J. G. Wendel: *J. Chem. Phys.* **16**, 495 (1948).
4. Scott, A. F., and G. M. Pound: *J. Chem. Phys.* **9**, 726 (1941).
5. Temperly, H. N. V., and L. G. Chambers: *Proc. Phys. Soc.* **58**, 420 (1946).
6. Briggs, Lyman J.: *J. Appl. Phys.* **21**, 721 (1950).
7. Vincent, R. S.: *Proc. Phys. Soc.* **55**, 41 (1943).
8. Briggs, Lyman J.: *J. Chem. Phys.* **19**, 970 (1951).
9. Briggs, Lyman J.: *J. Appl. Phys.* **24**, 488 (1953).

an axis passing through the center of the Z and perpendicular to the plane. The liquid menisci are located in the bent-back short arms of the Z. The speed of rotation is increased gradually until the liquid in the capillary "breaks."

A fairly complete summary of the experimental measurements of the tensile strength of pure liquids is tabulated above. Information and references pertaining to work prior to 1941 are to be found in ref. 1 (Table 2n-1), a paper which describes method B-1.

Another experimental method which gives insight into liquid tension involves measuring the pressure-amplitude threshold for sonically generated cavitation. This threshold varies with conditions; values quoted in the literature vary over the same range as for the maximum negative pressures recorded in Table 2n-1. It is found the preexisting gaseous bubbles or cavitation *nuclei* are important; recently it has been shown that such nuclei may be provided by cosmic rays or neutrons passing through liquid.^{1,2}

2n-2. Surface Tension and Surface Energy of Liquids.³ *Definitions.* Owing to molecular attraction two fluids in contact adjust themselves so that the area of their interface is a minimum consistent with other requirements. The work required to extend the surface by unit area is called the "free surface energy." In solving problems it is convenient to replace the concept of free surface energy by that of a hypothetical tension, acting parallel to the surface. Named the surface tension and its value denoted by γ , this is defined as the normal tensile force per unit of length across any line traced on the surface. The free surface energy and the surface tension have the same dimensions (MT^{-2}) and are numerically equal; the units of γ may be given either as dynes/cm or as ergs/cm².

Formulas Involving Surface Tension. When the interfacial surface between two fluids is curved the pressure p_1 on the concave side exceeds that, p_2 , on the convex side by the amount

$$p_1 - p_2 = \gamma(R_1^{-1} + R_2^{-1}) \quad (2n-1)$$

where R_1, R_2 are the principal radii of curvature. The pressure p due to surface tension within a liquid drop or gas bubble of radius R surrounded by liquid is

$$p = \frac{2\gamma}{R} \quad (2n-2)$$

The velocity v of sinusoidal ripples on the surface of a liquid of great depth is given by⁴

$$v^2 = \frac{g\lambda}{2\pi} + \frac{2\pi\gamma}{\rho\lambda} \quad (2n-3)$$

where λ is the wavelength of the ripples, g is the acceleration due to gravity, and ρ is the density of the liquid (cf. Sec. 2a).

Methods of Measuring the Surface Tension of a Liquid Relative to a Gas Phase.

1. Capillary-height method. If a vertical capillary tube whose bore radius r is sufficiently small rests with its lower end below a liquid surface the liquid in it will rise to a height h given approximately by

$$h = \frac{2\gamma \cos \theta}{gr(\rho - \rho_v)} \quad (2n-4)$$

where ρ_v is the density of the gas above the liquid, and θ is the contact angle of the meniscus with the tube wall (θ is often zero). If the tube is not sufficiently small, corrections must be applied to the above formula.⁵

2. Maximum-bubble-pressure method. If a bubble is blown at the lower end of a tube of small bore dipping into a liquid the pressure in the bubble reaches a maximum value given by

$$p = \frac{2\gamma}{r} \quad (2n-5)$$

¹ H. G. Flynn, *Physics of Acoustic Cavitation in Liquids*, in "Physical Acoustics," vol. 1B, W. P. Mason, ed., Academic Press, Inc., New York, 1964.

² D. Sette and F. Wanderlingh, *Phys. Rev.* **125**, 409-417 (1962).

³ General references: Neil K. Adam, "The Physics and Chemistry of Surfaces," chap. IX, Oxford University Press, New York, 1941; H. S. Taylor and S. Glasstone, "A Treatise on Physical Chemistry," D. Van Nostrand Company, Inc., Princeton, N.J., 1952.

⁴ Rayleigh, *Phil. Mag.* **30**, 386 (1890).

⁵ Adam, *loc. cit.*

where r , as before, is the bore radius. If r is not sufficiently small, corrections must be applied to the above formula.¹

3. Drop-weight method. The weight W of a drop falling from the tip of a vertical tube is given by

$$W = \frac{r\gamma}{F} \quad (2n-6)$$

where F is an empirical function¹ of (V/r^3) , V being the drop volume. When (V/r^3) is 5,000, F is 0.172; as (V/r^3) decreases to 1.55, F increases steadily to 0.26; further decrease of (V/r^3) causes F to oscillate slightly around 0.25.

TABLE 2n-2. SURFACE TENSION OF WATER AGAINST AIR*

| Temp., °C | Surface tension, dynes/cm | Temp., °C | Surface tension, dynes/cm | Temp., °C | Surface tension, dynes/cm |
|--------------|---------------------------------|--------------|---------------------------------|--------------|---------------------------------|
| -8 | 77.0 | 15 | 73.49 | 40 | 69.56 |
| -5 | 76.4 | 18 | 73.05 | 50 | 67.91 |
| 0 | 75.6 | 20 | 72.75 | 60 | 66.18 |
| 5 | 74.9 | 25 | 71.97 | 70 | 64.4 |
| 10 | 74.22 | 30 | 71.18 | 80 | 62.6 |
| | | | | 100 | 58.9 |

* General reference: "Handbook of Chemistry and Physics," Chemical Rubber Publishing Company, Cleveland.

TABLE 2n-3. SURFACE TENSION OF VARIOUS LIQUIDS

| Name | Formula | In contact with | Temp., °C | Surface tension, dynes/cm | Ref.* |
|---------------------|--|-----------------------|--------------|---------------------------------|--|
| Acetic acid..... | C ₂ H ₄ O ₂ | Vapor | 10 | 28.8 | AC(22,23,25); |
| Acetic acid..... | C ₂ H ₄ O ₂ | Vapor | 50 | 24.8 | GC(1); JS(14); tPRS(1); ZC(1,6) |
| Acetone..... | C ₃ H ₆ O | Air or vapor | 0 | 26.21 | AC(20,24,25); AdC(1); BF(1); |
| Acetone..... | C ₃ H ₆ O | Air or vapor | 40 | 21.16 | JP(5); JS(4,14); ZC(6) |
| Ammonia..... | NH ₃ | Vapor | 11.1 | 23.4 | JP(7) |
| Ammonia..... | NH ₃ | Vapor | 34.1 | 18.1 | JP(7) |
| Argon..... | A | Vapor | -188 | 13.2 | JS(15) |
| Benzene..... | C ₆ H ₆ | Air | 10 | 30.22 | AC(3,5,31,32,34); |
| Benzene..... | C ₆ H ₆ | Air | 30 | 27.56 | BF(2); JP(5); JS(4,9,10,11,14); PRS(2); tRIA(1); tPRS(1); ZC(4,5) |
| Benzophenone..... | C ₁₃ H ₁₀ O | Air or vapor | 20 | 45.1 | AC(27); AS(1); ZC(5) |
| Bromine..... | Br ₂ | Air or vapor | 20 | 41.5 | AC(17); AdP(3); GC(1) |
| n-Butyric acid..... | C ₄ H ₈ O ₂ | Air | 20 | 26.8 | AC(27); GC(1); JS(4) |

¹ Adam, *loc. cit.*

TABLE 2n-3. SURFACE TENSION OF VARIOUS LIQUIDS (Continued)

| Name | Formula | In contact with | Temp., °C | Surface tension, dynes/cm | Ref.* |
|--------------------------|--|-----------------|-----------|---------------------------|--|
| Carbon bisulfide..... | CS ₂ | Vapor | 20 | 32.33 | AC(17,28); GC(1); BF(2); JS(14); PRS(2), ZC(6) |
| Carbon dioxide..... | CO ₂ | Vapor | 20 | 1.16 | VK(1,2) |
| Carbon dioxide..... | CO ₂ | Vapor | -25 | 9.13 | VK(1,2) |
| Carbon monoxide..... | CO | Vapor | -193 | 9.8 | JS(15) |
| Carbon tetrachloride.... | CCl ₄ | Vapor | 20 | 26.95 | AC(3,5,6,28,31); |
| Carbon tetrachloride.... | CCl ₄ | Vapor | 200 | 6.53 | PRS(1,2); ZC(5) |
| Chlorine..... | Cl ₂ | Vapor | 20 | 18.4 | AC(11); JP(3) |
| Chlorine..... | Cl ₂ | Vapor | -60 | 31.2 | AC(11); JP(3) |
| Chlorobenzene..... | C ₆ H ₅ Cl | Vapor | 20 | 33.56 | AC(6,20,28); JP(5); JS(11); PRS(2); tRIA(1); tPRS(1); ZC(5) |
| Chloroform..... | CHCl ₃ | Air | 20 | 27.14 | AC(6,28,31); AdC(1); PRS(2); tRIA(1); ZC(6) |
| Cyclohexane..... | C ₆ H ₁₂ | Air | 20 | 25.5 | PRS(1); ZA(1) |
| Ethyl acetate..... | C ₄ H ₈ O ₂ | Air | 0 | 26.5 | AC(26,33); |
| Ethyl acetate..... | C ₄ H ₈ O ₂ | Air | 50 | 20.2 | AdC(1); AS(2); JP(5); tPRS(1); ZC(6) |
| Ethyl alcohol..... | C ₂ H ₆ O | Air | 0 | 24.05 | AC(22,23,25,32); |
| Ethyl alcohol..... | C ₂ H ₆ O | Vapor | 30 | 21.89 | BF(2); JP(5); tRIA(1); tPRS(1) |
| Ethyl ether..... | C ₄ H ₁₀ O | Vapor | 20 | 17.01 | AC(4,15,28,31); |
| Ethyl ether..... | C ₄ H ₁₀ O | Vapor | 50 | 13.47 | AdC(1); tPRS(1) |
| Glycerol..... | C ₃ H ₈ O ₃ | Air | 20 | 63.4 | JR(1); MB(1); |
| Glycerol..... | C ₃ H ₈ O ₃ | Air | 150 | 51.9 | ZA(1); ZC(3) |
| Helium..... | He | Vapor | -269 | 0.12 | cUL(2); PRA(2) |
| Helium..... | He | Vapor | -271.5 | 0.353 | cUL(2); PRA(2) |
| n-Hexane..... | C ₆ H ₁₄ | Air | 20 | 18.43 | AC(5,6,16); AdC(1); AS(1) |
| Hydrogen..... | H ₂ | Vapor | -255 | 2.31 | cUL(1); PRA(1) |
| Hydrogen peroxide..... | H ₂ O ₂ | Vapor | 18.2 | 76.1 | AC(13) |
| Methyl alcohol..... | CH ₄ O | Air | 0 | 24.49 | AC(22,23,25,32); |
| Methyl alcohol..... | CH ₄ O | Vapor | 50 | 20.14 | tPRS(1) |
| Neon..... | Ne | Vapor | -248 | 5.50 | cUL(3); PRA(3) |
| Nitric acid (98.8%) | HNO ₃ | Air | 11.6 | 42.7 | JS(2) |
| Nitrogen..... | N ₂ | Vapor | -183 | 6.6 | JS(15) |
| Nitrogen..... | N ₂ | Vapor | -203 | 10.53 | JS(15) |
| Nitrogen tetra oxide.... | N ₂ O ₄ | Vapor | 19.8 | 27.5 | JS(4) |
| n-Octane..... | C ₈ H ₁₈ | Vapor | 20 | 21.80 | AC(4,5,34); JS(4) |
| n-Octyl alcohol..... | C ₈ H ₁₈ O | Air | 20 | 27.53 | AC(4,5) |
| Oxygen..... | O ₂ | Vapor | -183 | 13.2 | JS(15) |

TABLE 2n-3. SURFACE TENSION OF VARIOUS LIQUIDS (Continued)

| Name | Formula | In contact with | Temp., °C | Surface tension, dynes/cm | Ref.* |
|--------------------------|---------------------------------|-----------------|-----------|---------------------------|---------------------------------|
| Oxygen..... | O ₂ | Vapor | -203 | 18.3 | JS(15) |
| Phenol..... | C ₆ H ₆ O | Air or vapor | 20 | 40.9 | AC(18,19,25); JS(2,6,13); JP(4) |
| Phosphorus trichloride.. | PCl ₃ | Vapor | 20 | 29.1 | AC(17); GC(1); JP(2); JS(4) |
| n-Propylamine..... | C ₃ H ₇ N | Air | 20 | 22.4 | GC(1); JS(3) |
| Sulfuric acid (98.5%)... | H ₂ SO ₄ | Air or vapor | 20 | 55.1 | AC(17a); AdP(7); JS(2) |
| Toluene..... | C ₇ H ₈ | Vapor* | 10 | 27.7 | AC(4,17,20,31) |
| Toluene..... | C ₇ H ₈ | Vapor | 30 | 27.4 | JP(5); PRS(2); ZC(5,6) |

* General reference: "Handbook of Chemistry and Physics," Chemical Rubber Publishing Company, Cleveland. A reference key is at end of article.

TABLE 2n-4. SURFACE TENSION OF METALS

| Substance | | Gas | Temp., °C | Surface tension, dynes/cm | Ref.* |
|----------------|--------|-----------------|-----------|---------------------------|------------------------------|
| Name | Symbol | | | | |
| Aluminum..... | Al | Air | 700 | 840 | CR(1) |
| Antimony..... | Sb | H ₂ | 750 | 368 | ZA(4) |
| Antimony..... | Sb | H ₂ | 640 | 350 | PM(1) |
| Bismuth..... | Bi | H ₂ | 300 | 388 | PM(1) |
| Bismuth..... | Bi | H ₂ | 583 | 354 | ZA(4) |
| Bismuth..... | Bi | CO | 700-800 | 346 | AdP(2) |
| Cadmium..... | Cd | H ₂ | 320 | 630 | AC(10) |
| Copper..... | Cu | H ₂ | 1131 | 1,103 | ZA(4) |
| Gallium..... | Ga | CO ₂ | 30 | 358 | AC(30) |
| Gold..... | Au | H ₂ | 1070 | 580-1,000 | AdP(1); AdP(2); JI(1) |
| Lead..... | Pb | H ₂ | 350 | 453 | PM(1) |
| Lead..... | Pb | H ₂ | 750 | 423 | ZA(4) |
| Mercury..... | Hg | Vacuum | 0 | 480.3 | AC(7) |
| Mercury..... | Hg | Air | 15 | 487 | AC(9); AdP(5); AdP(6); CR(2) |
| Mercury..... | Hg | H ₂ | 19 | 470 | PM(1) |
| Mercury..... | Hg | Vacuum | 60 | 467.1 | AC(7) |
| Platinum..... | Pt | Air | 2000 | 1,819 | AdP(2) |
| Potassium..... | K | CO ₂ | 62 | 411 | AdP(3) |
| Silver..... | Ag | Air | 970 | 800 | AdP(2); AdP(4); JI(1) |
| Sodium..... | Na | CO ₂ | 90 | 294 | AdP(3) |
| Sodium..... | Na | Vacuum | 100 | 206.4 | PR(1) |
| Sodium..... | Na | Vacuum | 250 | 199.5 | PR(1) |
| Tin..... | Sn | H ₂ | 253 | 526 | PM(1) |
| Tin..... | Sn | H ₂ | 878 | 508 | ZA(4) |
| Zinc..... | Zn | H ₂ | 477 | 753 | AC(10) |
| Zinc..... | Zn | Air | 590 | 708 | JI(1) |

* General reference: "Handbook of Chemistry and Physics," Chemical Rubber Publishing Company, Cleveland.

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TABLE 2n-5. SURFACE TENSIONS OF AQUEOUS SOLUTIONS AGAINST
AIR—ORGANIC*

| Substance | °C | γ = surface tension for concentrations indicated | | | | | | | | |
|--------------------|----|---|-------|-------|-------|-------|-------|-------|-------|--------|
| | | % | | | | | | | | |
| Acetic acid..... | 30 | % | 1.000 | 2.475 | 5.001 | 10.01 | 30.09 | 49.96 | 69.91 | 100.00 |
| | | γ | 68.0 | 64.4 | 60.1 | 54.6 | 43.6 | 38.4 | 34.3 | 26.6 |
| Acetone..... | 25 | % | 5.00 | 10.0 | 20.00 | 25.00 | 50.00 | 75.0 | 95.0 | 100.00 |
| | | γ | 55.5 | 48.9 | 41.1 | 38.3 | 30.4 | 20.8 | 24.2 | 23.0 |
| Ethyl alcohol..... | 30 | % | 0.979 | 2.143 | 4.994 | 10.39 | 25.00 | 50.00 | 75.06 | 100.00 |
| | | γ | 66.1 | 61.6 | 54.2 | 45.9 | 34.1 | 27.5 | 24.7 | 21.5 |
| Sucrose..... | 25 | % | 10.0 | 20.0 | 30.0 | 40.0 | 55.0 | | | |
| | | γ | 72.5 | 73.0 | 73.4 | 74.1 | 75.7 | | | |

* General reference: "Handbook of Chemistry and Physics," Chemical Rubber Publishing Company, Cleveland.

TABLE 2n-6. SURFACE TENSION OF AQUEOUS SOLUTIONS AGAINST AIR—
 INORGANIC*

 (f = gram formula weights per 1,000 g of solvent)

 For these aqueous solutions the values of $\Delta\gamma$ are given. $\Delta\gamma$ is the difference between the surface tension of the solution and that of the solvent at the same temperature. Positive values of $\Delta\gamma$ mean that the surface tension of the solution is greater than that of the solvent; negative values the reverse. For convenience in computing the surface tension, the current accepted value for the surface tension of water at the stated temperature is given in the second column.

| Formula | °C (γ_{H_2O}) | $\Delta\gamma$ for concentrations indicated | | | | | | | | |
|---------------------------------------|---------------------------|---|-------|------|------|-------|-------|-------|-------|-------|
| | | f | 0.1 | 0.5 | 1.0 | 2.0 | 3.0 | 5.0 | 11.2 | |
| CaCl ₂ | 25 (71.97) | f | 0.1 | 0.5 | 1.0 | 2.0 | 3.0 | 5.0 | 11.2 | |
| | | $\Delta\gamma$ | 0.35 | 1.5 | 3.2 | 6.9 | 11.0 | 18.4 | 35 | |
| HCl..... | 20 (72.75) | f | ..... | 0.5 | 1.0 | 2.0 | 4.0 | 6.0 | 9.0 | 17.7 |
| | | $\Delta\gamma$ | ..... | -0.2 | -0.3 | -0.5 | -0.9 | -1.3 | -2.2 | -7 |
| NH ₄ OH..... | 18 (73.05) | f | ..... | 0.5 | 1.0 | 1.5 | 3.0 | 6.0 | 15.0 | 34.0 |
| | | $\Delta\gamma$ | ..... | -1.4 | -2.4 | -3.1 | -5.2 | -7.8 | -12.0 | -16.0 |
| HNO ₃ | 20 (72.75) | f | ..... | 0.7 | 1.5 | 2.8 | ..... | ..... | 8.5 | |
| | | $\Delta\gamma$ | ..... | -0.6 | -1.1 | -1.8 | ..... | ..... | -4 | |
| KCl..... | 20 (72.75) | f | 0.1 | 0.5 | 1.0 | 2.0 | 3.0 | 4.0 | 4.4 | |
| | | $\Delta\gamma$ | 0.16 | 0.70 | 1.4 | 2.8 | 4.2 | 5.5 | 6.0 | |
| KOH..... | 18 (73.05) | f | ..... | 0.5 | 1.0 | 2.0 | 3.8 | | | |
| | | $\Delta\gamma$ | ..... | 0.9 | 1.8 | 3.5 | 6.7 | | | |
| MgCl ₂ | 20 (72.75) | f | 0.1 | 0.5 | 1.0 | 2.0 | 3.0 | 3.65 | | |
| | | $\Delta\gamma$ | 0.32 | 1.52 | 3.0 | 6.4 | 10.2 | 13.0 | | |
| MgSO ₄ | 20 (72.75) | f | 0.1 | 0.5 | 1.0 | 2.0 | 2.7 | | | |
| | | $\Delta\gamma$ | 0.26 | 1.03 | 2.1 | 4.6 | 6.5 | | | |
| NaBr..... | 20 (72.75) | f | ..... | 0.5 | 1.0 | 1.5 | 2.9 | | | |
| | | $\Delta\gamma$ | ..... | 0.7 | 1.3 | 2.0 | 3.8 | | | |
| NaCl..... | 20 (72.75) | f | 0.1 | 0.5 | 1.0 | 2.0 | 3.0 | 5.0 | 6.0 | |
| | | $\Delta\gamma$ | 0.17 | 0.82 | 1.64 | 3.3 | 4.9 | 8.2 | 9.8 | |
| Na ₂ CO ₃ | 20 (72.75) | f | 0.25 | 0.5 | 1.0 | 1.5 | | | | |
| | | $\Delta\gamma$ | 0.7 | 1.3 | 2.7 | 4.0 | | | | |
| NaNO ₃ | 20 (72.75) | f | 0.1 | 0.5 | 1.0 | 2.0 | 3.0 | 5.0 | 7.0 | 12.2 |
| | | $\Delta\gamma$ | 0.12 | 0.60 | 1.2 | 2.4 | 3.5 | 5.6 | 7.5 | 11.3 |
| NaOH..... | 18 (73.05) | f | ..... | 0.7 | 1.5 | ..... | ..... | 5.0 | 11.0 | 14.0 |
| | | $\Delta\gamma$ | ..... | 1.3 | 2.8 | ..... | ..... | 10.0 | 23 | 28 |
| Na ₂ SO ₄ | 20 (72.75) | f | 0.2 | 0.5 | 1.0 | | | | | |
| | | $\Delta\gamma$ | 0.5 | 1.4 | 2.7 | | | | | |

* General reference: "Handbook of Chemistry and Physics," Chemical Rubber Publishing Company, Cleveland.

Reference Key to Surface-tension Data

- AC. *Journal of the American Chemical Society*. (1) Baker and Gilbert, **62**, 2479-2480 (1940). (2) H. Brown, **56**, 2564-2568 (1938). (3) Harkins and Brown, **41**, 449 (1919). (4) Harkins, Brown, and Davies, **39**, 354 (1917). (5) Harkins and Cheng, **43**, 35 (1921). (6) Harkins, Clark, and Roberts, **42**, 700 (1920). (7) Harkins and Ewing, **42**, 2539 (1920). (8) Harkins and Feldman, **44**, 2665 (1922). (9) Harkins and Grafton, **42**, 2534 (1920). (10) Hogness, **43**, 1621 (1921). (11) Johnson and McIntosh, **31**, 1139 (1909). (12) Maass and Boomer, **44**, 1709 (1922). (13) Maass and Hatcher, **42**, 2548 (1920). (14) Maass and McIntosh, **31**, 1139 (1909). (15) Maass and Wright, **43**, 1098 (1921). (16) Morgan and Chazel, **35**, 1821 (1913). (17) Morgan and Daghlian, **33**, 672 (1911). (17a) Morgan and Davis, **38**, 555 (1916). (18) Morgan and Egloff, **38**, 844 (1916). (19) Morgan and Evans, **39**, 2151 (1917). (20) Morgan and Griggs, **39**, 2261 (1917). (21) Morgan and Kramer, **35**, 1834 (1913). (22) Morgan and McAfee, **33**, 1275 (1911). (23) Morgan and Neidle, **35**, 1856 (1913). (24) Morgan and Owen, **33**, 1713 (1911). (25) Morgan and Scarlett, **39**, 2275 (1917). (26) Morgan and Schwartz, **33**, 1041 (1911). (27) Morgan and Stone, **35**, 1505 (1913). (28) Morgan and Thomssen, **33**, 657 (1911). (29) Morgan and Woodward, **35**, 1249 (1913). (30) Richards and Boyer, **43**, 274 (1921). (31) Richards and Carver, **43**, 827 (1921). (32) Richards and Coombs, **37**, 1656 (1915). (33) Richards and Matthews, **30**, 8 (1908). (34) Richards, Speyers, and Carver, **46**, 1196 (1924).
- AD. *Atti della reale accademia nazionale dei Lincei*. (1) Magini, **1911**, 184, 10.
- AdC. *Annalen der Chemie, Justus Liebig's*. (1) Schiff, **223**, (47) 84.
- AdP. *Annalen der Physik*. (1) Heydweiller, **62**, 694 (1897). (2) Quincke, **134**, 356 (1868). (3) Quincke, **135**, 621 (1868). (4) Gradenwitz, **67**, 467 (1899). (5) Meyer, **66**, 523 (1898). (6) Stöckle, **66**, 499 (1898). (7) Röntgen and Schneider, **29**, 165 (1886).*

- AS. *Archives des sciences physiques et naturelles*. (1) Dutoit and Friederich, **9**, 105 (1900). (2) Guye and Baud, **11**, 449 (1901). (3) Herzen, **14**, 232 (1902).
- BD. *Berichte der deutschen chemischen Gesellschaft*. (1) Lorenz and Kauffler, **41**, 3727 (1908). (2) Schenck and Ellenberger, **37**, 3443 (1904).
- BF. *Bulletin de la société chimique de France*. (1) Dutoit and Friederich, **19**, 321 (1898). (2) Santis Ann. Univ. Grenoble, **27**, 593 (1904).
- CR. *Comptes rendus*. (1) A. Portevin and P. Bastien, **202**, 1072-1074 (1936). (2) Popesco, **172**, 1474 (1921).
- cUL. *Communications from the Physical Laboratory at the University of Leiden*. (1) No. 142. (2) No. 179a. (3) No. 182b.
- GC. *Gazzetta chimica italiana*. (1) Schiff, **14**, 368 (1884). (2) A. Giacalone and D. DiMaggio, **3**, 198-206 (1939).
- JL. *Journal of the Institute of Metals*. (1) Smith, **12**, 168 (1914).
- JP. *Journal de chimie physique*. (1) Dutoit and Fath, **1**, 358 (1903). (2) Dutoit and Moiniu, **7**, 169 (1909). (3) Marchand, **11**, 573 (1913). (4) Bolle and Guye, **3**, 38 (1905). (5) Renard and Guye, **5**, 81 (1907). (6) Berthoud, **21**, 143 (1924). (7) Berthoud, **16**, 429 (1918). (8) Homfray and Guye, **1**, 505 (1903). (9) Przyluska, **7**, 511 (1909).
- JR. *Journal of the Russian Physical Chemical Society*. (1) Elisseev and Kurbatov, **41**, 1426 (1909).
- JS. *Journal of the Chemical Society (London)*. (1) Kellas, **113**, 903 (1918). (2) Aston and Ramsay, **65**, 167 (1894). (3) Turner and Merry, **97**, 2069 (1910). (4) Ramsay and Shields, **63**, 1089 (1893). (5) Sugden, Reed, and Wilkins, **127**, 1525 (1925). (6) Hewitt and Winmill, **91**, 441 (1907). (7) Smith, **105**, 1703 (1914). (8) Atkins, **99**, 10 (1911). (9) Sugden, **119**, 1483 (1921). (10) Sugden, **121**, 858 (1922). (11) Sugden, **125**, 32 (1924). (12) Sugden, **125**, 1167 (1924). (13) Worley, **105**, 260 (1914). (14) Worley, **105**, 273 (1914). (15) Baly and Donnan, **81**, 907 (1902).
- JSG. *Jahresberichte Schles. Ges. Vaterl. Kultur*. (1) Wilborn, **1912**, 56.
- MB. *Metron. Beil.* (1) Weinstein, no. 6, 89.
- MfC. *Monatshefte für Chemie und verwandte Teile anderer Wissenschaften*. (1) Kremann and Meingast, **35**, 1323 (1914).
- PM. *The London, Edinburgh & Dublin Philosophical Magazine and Journal of Science*. (1) Bircumshaw, **2**, 341 (1926); **3**, 1286 (1927). (2) R. C. Brown, **13**, 578-584 (1932). (3) A. E. Bate, **28**, 252-255 (1939).
- PR. *The Physical Review*. (1) Poindexter, **27**, 820 (1926).
- PRA. *Proceedings of the Royal Academy of Sciences of Amsterdam*. (1) Kamerlingh Onnes, and Kuypers, **17**, 528 (1914). (2) Van Urk, Keesom, and Onnes, **28**, 958, (1925). (3) Van Urk, Keesom, and Nijhoff, **29**, 914 (1926). (4) Jaeger and Kahn, **18**, 75 (1915).
- PRS. *Proceedings of the Royal Society (London)*. (1) Hardy, **88**, 303 (1913). (2) Ramsay and Aston, **56**, 162, 182 (1894).
- tPRS. *Philosophical Transactions of the Royal Society of London, Series A*. (1) Ramsay and Shields, **184**, 647 (1893).
- tRIA. *Royal Irish Academy Transactions*. (1) Ramsay and Aston, **32A**, 93 (1902).
- VK. *Verslag koninklijke Akademie van Wetenschappen te Amsterdam*. (1) Verschaffelt, no. 18, 74 (1895). (2) Verschaffelt, no. 28, 94 (1896).
- WN. *Wissenschaftliche Naturk., Tydschr.* (1) Verschaffelt, **2**, 231 (1925).
- ZA. *Zeitschrift für anorganische und allgemeine Chemie*. (1) Jaeger, **101**, 1 (1917). (2) Motylewski, **38**, 410 (1904). (3) Lorenz, Liebmann, and Hochberg, **94**, 301 (1916). (4) Sauerwald and Drath, **154**, 79 (1926).
- ZC. *Zeitschrift für physikalische Chemie*. (1) Bennett and Mitchell, **84**, 475 (1913). (2) Walden and Swinne, **82**, 271 (1913). (3) Drucker, **52**, 641 (1905). (4) Walden, **75**, 555 (1910). (5) Walden and Swinne, **79**, 700 (1912). (6) Whatmough, **39**, 129 (1902).
- ZE. *Zeitschrift für Elektrochemie und angewandte physikalische Chemie*. (1) Bredig and Tiechmann, **31**, 449 (1925).
- ZK. *Kolloid-Zeitschrift*. (1) N. Jermolanko, **48**, 14-146 (1929).