

API[®] TECHNICAL DATA BOOK 10th Edition

INTRODUCTION

Tenth Edition (2016)

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API Forward to the Tenth Edition

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Generally, API standards are reviewed and revised, reaffirmed, or withdrawn at least every five years. A one-time extension of up to two years may be added to this review cycle. Status of the publication can be ascertained from the API Standards Department, telephone (202) 682-8000. A catalog of API publications and materials is published annually and updated quarterly by API, 1220 L Street, N.W., Washington, D.C. 20005.

Suggested revisions are invited and should be submitted to the Standards and Publications Department, API, 1220 L Street, NW, Washington, DC 20005, standards@api.org.

The project that resulted in the publication of the *Technical Data Book* was initiated as a result of a general recognition by the petroleum refining industry of the desirability of an authoritative publication setting forth a collection of correlations and methods for estimating physical properties that are used in process design.

Introduction

API, the API Technical Data Committee, and EPCON International are pleased to provide the publication of the 10th Edition of the essential API Tech Data Book. API has sponsored this important flagship project since the first edition of the API Tech Data Book was released in 1966. For 40 years, the project has been managed by the API Technical Data committee, whose members include the petroleum industry's leading experts in thermodynamics and chemical engineering. API member companies and EPCON International have worked on improving the API Technical Data Book into a full electronic software and printed reference manual product for the past 18 years for the benefit of engineers working in the petroleum industry. This is one of the many projects that API is pursuing to benefit its member companies.

Included is a property simulation software package with rigorous 3-phase flash capabilities that delivers over 130 API recommended methods. The Data Book Explorer software interface enables quick searching of any text or phase within a specific chapter of the Data Book with single click access for direct calculation of these API methods within the property simulation software.

The purpose of the API Technical Data Book is to provide a critically reviewed compilation of the physical and thermodynamic data and correlations that are of most interest to petroleum refiners for practical application to process evaluation and equipment design. Chapters on the following topics are provided in electronic, searchable software format along with software applications for implementation of recommended Data Book methods.

Introduction

Chapter 1 - General Data

Chapter 2 - Characterization of Hydrocarbons

Chapter 3 - Petroleum Fraction Distillation Interconversions

Chapter 4 - Critical Properties

Chapter 5 - Vapor Pressure

Chapter 6 – Density

Chapter 7 - Thermal Properties

Chapter 8 - Vapor-Liquid Equilibrium K-Values

Chapter 9 - Phase Equilibria in Systems Containing Water

Chapter 10 - Surface and Interfacial Tension

Chapter 11 - Viscosity

Chapter 12 - Thermal Conductivity

Chapter 13 - Diffusivity

Chapter 14 - Combustion

Chapter 15 - Adsorption Equilibria

Chapter 16 – Software Applications

The API Technical Data Book concentrates on hydrocarbons and their mixtures. Non-hydrocarbon gases and some oxygenated compounds important in petroleum processing are included where appropriate. Hydrocarbon systems are divided into three groups: those in the pure state, petroleum mixtures for which the compositions of all the species are known (defined mixtures), and mixtures whose composition is unknown (undefined mixtures). The undefined mixtures must usually be characterized by one or more measured physical properties, such as density, molecular weight, viscosity, and ASTM distillation, which reflect their constitution. Obviously the treatments for these three classifications differ; thus, separate methods are given for each. Predictions for defined mixtures can often be made using correlations for undefined

mixtures, but this procedure is rarely recommended.

Although some methods can be done with hand calculators, computer methods have been developed as the primary, recommended methods. Procedures are equation based, but many are also presented as figures to help illustrate these procedures and for use in educational forums. Computer methods are included for essentially all critical, volumetric, and thermodynamic properties discussed. The Data Book Explorer interface environment provides for quick searching and navigation of the API Technical Data Book in electronic PDF format with direct links to the computer methods that implement these procedures.

Data Book Organization

Each chapter is devoted to a single property or group of related properties. Within the chapters, further divisions in sections and subsections are made according to the property (when more than one is given in a chapter), the phase, and the state of the hydrocarbon (pure, defined mixture, or undefined mixture). Generally, non-hydrocarbons are covered in a section different from the one in which the corresponding treatment for hydrocarbons is given. Titles for the subdivisions are given in the table of contents of each chapter.

Chapter 1, "General Data," contains information on conversion factors and pure component properties.

In Chapters 2-15, for numbering purposes, the figures, tables, and procedures that are to be used to calculate values are not treated separately according to kind but are numbered serially in order of presentation, whether Figure, Table, or Procedure. In the designation "Figure 12B1.3," for example, "12" is the chapter number, "B" is the section designation, "1" is the subsection number, and "3" indicates the third exhibit from the subsection.

Comments are typically given for each figure or procedure and are normally located on the following pages. For groups of related figures, comments are given following the last figure only. Where tables and figures are used as part of a procedure, the procedure and comments for the entire unit are given first, followed by the supporting exhibits (which have no individual comments).

Included in the procedure and comments sections are some or all of the following sub-sections (shown as bold blue font in the Data Book):

- **Discussion**
- **Procedure**
- **Purpose**
- **Limitations**
- **Reliability**
- **Notation**
- **Special Comments**
- **Literatures Sources**
- **Examples**

To help avoid any errors or difficulties in using the Data Book correlations, it is recommended to review the Comments and Examples sections to understand their implementation and application. References to other chapters are usually no more specific than the chapter number.

Data Book Accuracy

Neither the availability of many correlations nor the endorsement of one or more of them in this book implies that any of them is totally satisfactory for all conditions of temperature, pressure, phase, composition, and hydrocarbon type. The selections were based on the available data, tempered by scientific judgment. There is no guarantee that any of the methods will be reliable for unusual compounds or conditions, and the user is cautioned against blind faith and particularly against being deceived by the rigorous appearance of a complicated correlation. The user is cautioned against using any of the methods outside the conditions stated in the limitations section. Many more experimental data are needed before our correlative knowledge can be described as satisfactory. In spite of these shortcomings, the selected correlations are believed to be the best compromise among accuracy, generality, internal consistency, and ease of use that can be obtained from the readily available methods and data.

Participation in the Development of API Standards

The ongoing work of the API Technical Data Committee relies on volunteer efforts by its committee members through the support of API member companies. Your company's participation is encouraged in the ongoing development and improvement of this important API standard. Though this joint, collaborative efforts, API is able to provide the best possible data and methods to further the profitability and safety of the refining industry.

For further information on how you can participate in the development of API Standards on behalf of your company, contact the American Petroleum Institute at 202-682-8000 (www.api.org).

For technical support and ordering information on the API Technical Data Book, 8th Edition, contact EPCON International at 800-367-3585, 281-398-9400 (www.epcon.com).

Development Summary

First Edition (1966)

The preparation of the first edition of the API Technical Data Book covered a period of more than four years from 1959 to 1964. During that time, the work of the Penn State staff, led by the late Dr. M. R. Fenske, Dr. W. G. Braun, and Mr. W. H. Thompson, was guided and coordinated by the API Subcommittee on Technical Data with assistance from the Contractors' Advisory Subcommittee, under the sponsorship of the API Refining Department. [For more details, see A. S. Lehmann, "API Technical Data Book Project," *Proc. AP144(III)* 278 (1964). The general pattern followed by Penn State in preparing each phase of each section of the book is outlined below:

The literature was searched for pertinent data and correlations. When there were many applicable correlations, some were eliminated from further consideration on the basis of such factors as complexity, lack of generality, failure to be internally consistent, and available of improved forms.

A set of data was assembled for comparison with the predictions of the correlations. The correlations were evaluated for accuracy, generality, ease of use and other characteristics. The evaluation results, conclusions and recommendations were reported to the subcommittees for review. Occasionally, reevaluations or further checking was performed, based on comments from the reviewers.

The recommended data and correlations, along with descriptive comments, were prepared in final form for subcommittee review. The draft chapters were modified to satisfy reviewers' criticisms and were submitted for publication. As implied, no attempt was made to develop new correlations for the first edition of the API Technical Data Book.

During the literature searches, approximately 10,000 articles were reviewed. Of these, 3000 were useful enough to include in reports, and approximately 750 are cited in the book. Four bibliographies of data were prepared and published as incidental by-products of this effort:

Fenske, M. R., Braun, W. G., Holmes, A. S., *Bibliography of Vapor-Liquid Equilibrium Data for Hydrocarbon Systems Bibliography No. 1*, Am Petrol. Inst., New York (1963).

Holmes, A. S., Braun, W. G., Fenske, M. R., *Bibliography of Vapor Pressure Data for Hydrocarbons, Bibliography No. 2*, Am. Petrol. Inst., New York (1964).

Jeter, L. T., Thompson, W. H., Braun, W. G., Fenske, M. R., *Bibliography of Volumetric and Thermodynamic Data for Pure Hydrocarbons and Their Mixtures, Bibliography No. 3*, Am. Petrol. Inst., New York (1964).

Wilson, R. F., Thompson, W. H., Braun, W. G., Fenske, M. R., *Bibliography of Vapor-Liquid Equilibrium Data for Hydrocarbon-Nonhydrocarbon Gas Systems, Bibliography No. 4*, Am Petrol. Inst., New York (1964).

These bibliographies, documentation reports (see below), and the tables of data issued by API Research Project 44 extended the usefulness of this book to unusual hydrocarbons and systems.

One of the most difficult tasks was narrowing the evaluations to reasonable sizes, consistent with the importance of the property under consideration and the available time and funds. It was neither possible nor justifiable, for example, to

examine in detail all of the more than 80 correlations that are available for the vapor pressure or the heat of vaporization of pure hydrocarbons. For many properties, extensive data bases have been assembled.

Selecting a single method for use with all hydrocarbons at all temperatures and pressures was often difficult because different correlations normally excelled in different areas. Furthermore, the results of error analyses were occasionally complicated, for example, when different correlations were applicable to different groups of data points and the difficulty of the non-common points varied. If only common data points were compared, the set was usually so small and restricted that the effects of temperature, pressure, system, and /or hydrocarbon type could not be studied. The intangible criteria of generality and ease of use were always considered, along with the more concrete error analysis results.

Although there were usually too many applicable correlations, occasionally none were available for technically important circumstances. Notable examples of this are correlations for mixtures containing hydrogen or high concentrations of unsaturated or aromatic hydrocarbons. Methods are given for these mixtures, but data were rarely available to confirm the methods' validity.

After the evaluations were completed, the results and recommendations were reported to the subcommittee members in 85 different documents, including 29 formal reports. Fourteen more formal reports were draft chapters, which contained draft copies of the figures in the *Technical Data Book*. Most figures had previously been redrawn from their original sources to unify style, to make them more convenient and useful for a quantitative application, and in some cases, to correct errors. Comments from the subcommittee members resulted in the elimination of many troublesome errors and obstacles for the inexperienced user.

After the publication of the *Technical Data Book*, the American Petroleum Institute made Documentation Report Nos. 2-66 through 14-66 to holders of the book. These reports are an organization of the evaluation reports and document the selection of the correlations in this data book on a chapter-by-chapter basis. In addition to providing answers to many questions about the selection of the contents of the data book, the information was useful in estimating the reliabilities of the various correlations in specific situations. These reports are now unavailable.

The extensive literature surveys, correlation evaluations and the review procedure outlined above make this data book the most complete and reliable work yet compiled specifically for general use in the evaluation of petroleum refining processing and related equipment.

The direct product of the work described above is, of course, the data book. The project also resulted in partial or total support for a number of undergraduate and graduate students and for a professional staff. Many of the students have completed their academic work and have since entered industry, and an unusually large proportion have entered the petroleum industry. All have an increased understanding of and sympathy for the problems of the petroleum industry.

Second Edition (1970)

Since the literature search for the first edition was completed, a large number of new correlations and an even larger amount of experimental data of potential use in the *Technical Data Book* have appeared in the open literature. This information prompted further studies, also supported by the American

Petroleum Institute as a vital part of its continuing program to provide the best current data and correlations for the practicing engineer, which ultimately resulted in publication of the second and third editions.

Revisions for the second edition, published in 1970, were made in Chapters 1, 7, 8, 9, and 11. In Chapter 1, the physical property tables of the C₁-C₁₀ hydrocarbons were extensively revised based on the changes in, or additions to, the tables of API Research Project 44. Also included were tables for the physical properties of biphenyls, diphenyls, tetrahydronaphthalenes, and decahydronaphthalenes. In Chapter 7, the tables of coefficients for the calculations of ideal gas enthalpies, the enthalpy-temperature diagrams, and the enthalpy-entropy diagrams for methane, ethane, propane, and ethene were revised. In Chapter 8, material was added on the solubility of gases in water and the water content of natural gases. Chapters 9 and 11 concerning water-hydrocarbon phase equilibria and viscosity, respectively, were completely revised.

The numerical solutions of all of the example problems in the book were changed to reflect the revisions of the properties that were made in Chapter 1. Inadvertent errors in chapters, which were listed in Revision Sheet 1 (July 1, 1967) and Revision Sheet 2 (December 1, 1969), were corrected.

Third Edition (1976)

For the third edition, published in 1976, Chapters 4, 6, and 7 were completely revised, and necessary changes were made in Chapters 1 and 2. Chapter 4 was expanded in 1974 to include procedures to calculate critical properties for all types of hydrocarbon systems. Chapter 6, as revised in 1972, included new methods for saturated liquid densities for pure hydrocarbons, defined hydrocarbon mixtures, and non-hydrocarbons. In the 1976 publication, the vapor density section of Chapter 6 and all of Chapter 7 were revised. Vapor densities and thermodynamic properties for pure hydrocarbons and defined hydrocarbon mixtures were all predicted by the modified Pitzer corresponding-states method of Lee and Kesler. Desk and computer methods were made consistent. New methods for predicting thermodynamic properties of petroleum fractions were presented that use the methods of Chapter 4 to predict critical properties. The acentric factors of Chapter 2 were revised for consistency with Chapters 6 and 7. Certain properties in Chapter 1, as revised by API Research Project 44, were updated.

Fourth Edition (1982)

For the fourth edition, Chapter 5 on vapor pressure, Chapter 8 on vapor-liquid equilibria, Chapter 12 on thermal conductivity, and Chapter 13 on diffusivity were completely revised, with a large amount of new material added. Chapter 2 on characterization and Chapter 3 on distillation relationships were partially revised with new procedures for estimating properties. Chapter 4 on critical properties was updated. Chapter 9 on water-hydrocarbon equilibria and gas hydrates was completely revised and substantially expanded. Data and correlations for water-hydrocarbon systems previously in Chapter 8 were updated and included in Chapter 9. Chapter 10 on surface tension was revised, and methods for prediction of interfacial tension were included for the first time.

Fifth Edition (1992)

For the fifth edition, a revision package was issued in 1985 that completely revises Chapter 14 on combustion, Chapter 11 on viscosity, and the liquid portion of Chapter 6 on density. A new Chapter 15 on gas-solid and liquid-solid adsorption

equilibria was added. In addition, the procedure for computer calculation of vapor-liquid equilibria in Chapter 8 was revised. The ninth revision package, released in 1988, included complete revisions of Chapters 1-4 covering general data, characterization, distillation, and critical properties. The tenth revision package contains a complete update of Chapter 7 on thermal properties. Numerous other changes to the entire book make it consistent with changes previously published (primarily in Chapter 1).

Sixth Edition (1997)

The eleventh revision package (1994) included complete revisions of Chapter 3 on petroleum fraction distillation inter-conversions, Chapter 5 on vapor pressure, and Chapter 8 on vapor-liquid equilibrium K-values. Substantive additions and improvements were made in Chapters 3, 5, and 8.

The twelfth revision package (1996) included complete revisions of Chapter 9 on water-hydrocarbon equilibria, Chapter 11 on viscosity, and Chapter 12 on thermal conductivity as well as an update of all property values and addition of some important compounds in Chapter 1. Ideal gas tables of Chapter 7 and revised procedures to predict Reid vapor pressure in Chapter 5 were also included.

The thirteenth revision package (1998) contains (1) a revised Chapter 2 containing routines for additional inspection properties as well as updates of previous routines, (2) an updated Chapter 4 procedure for calculation of critical properties from an equation of state, (3) a revised Reid vapor pressure prediction method in Chapter 5, (4) changes in Chapter 7 procedures for heat capacity of petroleum fractions, (5) new heat of formation and combustion tables in Chapters 7 and 14, (6) totally revised and updated values and correlations for interaction coefficients for hydrocarbon-non-hydrocarbon systems for the Soave equation of state, and (7) additional revisions and additions to the hydrocarbon-water portion of Chapter 9.

Seventh Edition (2005)

A number of technical improvements are provided in the Seventh Edition as a result of research efforts by Wiltec designed to improve data and correlations of Sulfur containing compounds and through consultation provided by Costa Tsnopolous to revise Chapter 9. Each chapter of the Sixth Edition of the API Technical Data Book was reviewed and revised by the API Technical Data Committee except for Chapter 15 which remains the same as the Sixth Edition.

The new electronic version of API Technical Data Book utilizes the Data Book Explorer™ interface and environment to provide complete coverage of the re-mastered chapters 1 thru 15 that are now provided in searchable, text PDF format. The tree-view navigation of the Data Book Explorer provides directly links from computerized procedures in the Data Book to Windows based software applications. Any desired phrase or keyword can now be searched for and the computer methods can be directly loaded from the Data Book Explorer for a selected Data Book procedure.

Eighth Edition (2006)

A detailed, comprehensive review of the printed Data Book was performed by the API Tech Data Book committee members.

This review process focused on providing a consistent convention of

terminology throughout the Data Book while correction of any errors from past editions. All of the software applications were updated to correct any reported bugs, add additional requested features, and provide compatibility with Windows Vista operating system.

Basic flowsheeting capabilities were included for application of the Data Book to specific refinery problems including flash drums, gas compressors and hydrotreater operations as a simplified version of EPCON International's SYSTEM 7 Process Explorer® software. Molecular based property estimation using Benson and Ambrose methods was also added as a simplified version of the DDBST Artist software (www.ddbst.de).

Ninth Edition (2013)

The Ninth Edition of the API Technical Data Book provides completely new interfaces for all of the software applications and all of the graphs in the Data Book have been remastered. The software interfaces now use the latest MS .Net Visual Studio development languages to provide full compatibility and functionality with Windows 7 and 8. Additionally, all chapters have been reformatted to include the section letter designation both in the text and the table of contents.

Chapter 6 was completely rewritten and updated and new methods have been added throughout the Data Book as indicated in each chapter Preface. Any updates in API methods has also been implemented in the software applications. Process simulation software and thermodynamic property data to compliment the API Technical Data Book are available from EPCON International (www.epcon.com) and DDBST (www.ddbst.de).

Tenth Edition (2016)

The Tenth Edition of the API Technical Data Book provides a 3rd generation interface for the THERMA PRO flash/mixture calculation software with a modern XAML interface. All of the software interfaces have also been upgraded to provide full compatibility and functionality with Windows 10.

Chapter 7 was completely rewritten and updated and Chapter 2 was also updated. Any updates in API methods has also been implemented in the software applications.

API TECHNICAL DATA BOOK 10th Edition

CHAPTER 1

GENERAL DATA

Revised Chapter 1 to First Edition (1966), Second Edition (1970), Third Edition (1977), Fourth Edition (1982), Fifth Edition (1992), Fifth Edition (1992), and Seventh Edition (2005), Eighth Edition (2006), Ninth Edition (2013)

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(2006)

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1-0 Introduction

Chapter 1 – General Data

(2006)

Almost all the procedures in the API Technical Data Book require pure component physical properties. This chapter lists a collection of properties for many hydrocarbons and selected nonhydrocarbons that are provided in electronic database format as described in the Software Applications Chapter 16. The compounds and the properties that were selected for inclusion in the *API Technical Data Book* are those judged most useful for petroleum refining and associated industries. For API components that are also covered in the AIChE DIPPR® Database, the same data is reported in the API Technical Data Book and the DIPPR Database for properties covered by DIPPR. Further information on physical properties may be found in the Design Institute for Physical Properties (DIPPR) *Data Compilation: Tables of Properties of Pure Compounds* (8, 52, 53). The majority of data for the compounds in this chapter were taken from the following sources (in order of priority):

1. DIPPR Compilation (8, 52, 53)
2. GPA 2145-94 (13)
3. API Monograph Series (1-3)
4. TRC Tables (32-34, 39-47)
5. Previous *API Technical Data Book - Petroleum Refining* (9).

Unless otherwise indicated, predictions of hydrocarbon data were made using the current Data Book procedures. Predictions of nonhydrocarbon data were made using DIPPR Compilation (8) procedures.

The *Fundamental Constants and Conversion Factors* section contains a list of constants and lists of conversion factors. The *Letter Symbols Used in Chemical Engineering* section provides a list of letter symbols with their definitions. The *Property Definitions* section enumerates the property

definitions. Other pertinent information on the properties is given in the Pure Component Properties program detailed in Chapter 16 with footnotes for the data source and reference.

In the Seventh Edition (2005), 39 sulfur containing hydrocarbons were added to the API Technical Data Book for use in designing and upgrading refinery processes to further reduce sulfur emissions and improve air quality. Additionally, the pure component properties were updated based on the 2004 DIPPR Database (Public Release). In the final release of the Eighth Edition (version 8.2 - 2008), the pure component properties were updated based on the 2008 DIPPR Database (Public Release). In the Ninth Edition, the pure component properties were updated based on the 2009 DIPPR Database (Public Release).

AIChE DIPPR® Database

The mission of the Design Institute for Physical Properties (DIPPR) is to develop the world's best source of critically evaluated thermophysical and environmental property data. Data and estimation methods developed in DIPPR projects are used by leading chemical, petroleum and pharmaceutical companies throughout the world. For more information on DIPPR membership and benefits, please contact:

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1A Fundamental Constants and Conversion Factors

1A1 Fundamental Constants

Table 1A1.1 - Fundamental Constants

(1987)			
Basic Constants			
<u>Name</u>	<u>Symbol</u>	<u>Value</u>	<u>Units</u>
Velocity of light (vacuum)	c	2.997925×10^8	m per sec
Avogadro constant	N_A	6.02214×10^{23}	molecules per g-mole
Planck constant	h	6.6261×10^{-27}	(ergs) (sec) per molecule
Faraday constant	F	96,485.3	coulombs per mole
Absolute temperature of the "ice" point:			
0 °C	$T_{0^\circ\text{C}}$	273.15	K
32 °F	$T_{32^\circ\text{F}}$	491.67	deg R
Pressure-volume product for 1 mole of a gas at 0 °C (32 °F) and zero pressure (ideal gas)	$(pV)_{T_0}^{p=0}$	2,271.11 22.4141 2.27111×10^6 359.039 5,276.42	joules per g-mole (liters) (atm) per g-mole (m ³) (Pa) per kg-mole (ft ³) (atm) per lb-mol (ft ³) (psia) per lb-mol
Derived Constants			
<u>Name</u>	<u>Symbol</u>	<u>Value</u>	<u>Units</u>
Electronic charge	$e = \frac{F}{N_A}$	1.60218×10^{-19}	coulombs
Gas constant	$R = \frac{(pV)_{T_0}^{p=0}}{T_{0^\circ\text{C}}}$	8.3145 1.9872 1.9859 82.058 1,545.4 10.732 62.364 0.084786 0.73024 554.99 8,314.5	joules per (g-mole) (K) g-cal per (g-mole) (K) Btu per (lb-mole) (°R) (cm ³) (atm) per (g-mole) (K) ft-lb [force] per (lb-mole) (°R) (psia) (ft ³) per (lb-mole) (°R) (mm Hg) (liter) per (g-mole) (K) (kg per cm ³) (liter) per (g-mole) (K) (atm) (ft ³) per (lb-mole) (°R) (mm Hg) (ft ³) per (lb-mole) (°R) (Pa) (m ³) per (kg-mol) (K)
Boltzmann constant	$k = \frac{R}{N_A}$	1.38066×10^{-16}	ergs per (molecule) (K)
Second radiation constant	$C_2 = \frac{hc}{k}$	1.43877	cm-°C
Defined Constants			
<u>Name</u>	<u>Symbol</u>	<u>Value</u>	<u>Units</u>
Standard gravity	g_o	980.665 32.174	cm per sec per sec ft per sec per sec
Standard atmosphere	atm	1,013,250 14.696 101,325	dynes per cm ² psia pascals
Standard millimeter of mercury pressure	mm Hg	1/760	atm
Calorie (thermochemical)	cal	4.1840 4.1840×10^7	joules ergs
Calorie (International Steam Tables)	cal _{IT} ; I.T. cal	4.1868	joules
Liter	l	1,000	cm ³

TABLE 1A1.1 (Continued)

(1987)

Conversion Factors-Engineering Units Vs. Metric Units

<u>Name</u>	<u>Value</u>	<u>Units</u>
1 in	= 2.54 cm	Definition: in = U.S. inch
1 ft	= 30.48 cm	Definition: U.S. foot (1 ft = 12 in)
1 lb	= 453.59237 g	Definition: lb = avoirdupois pound
1 gal	= 231 cu in = 0.133680555 cu ft = 3,785.43449 cu cm = 3.785412 liters	Definition: gal = U.S. gallon
1 I.T. cal	= 1/860 int watt-hr = 4.18674 joules = 4.18605 int joules = 1.000654 cal	Definition: I.T. = International Steam Tables Definition: cal = thermochemical calorie
1 Btu/ lb	= 1/1.8 I.T. cal per g	Definition: Btu = I.T. British thermal unit
1 Btu	= 251.996 I.T. cal = 1,055.040 joules = 1,054.866 int joules = 0.293018 int watt-hr = 252.161 cal = 0.293067 abs watt-hr	Definition: cal = thermochemical calorie
1 hp	= 550 ft-lb [force] per sec = 745.701 watts (abs) = 745.578 int watts	
1 erg	= 1 dyne-cm	

Mathematical Constants

π = 3.14159
 e (base of natural logarithms) = 2.71828
 natural logarithm (base e), $\log_e 10 = \ln 10 = 2.30258509$

Temperature Conversions

$^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$
 $^{\circ}\text{F} = 1.8 ^{\circ}\text{C} + 32$
 $\text{K} = ^{\circ}\text{C} + 273.15$
 $^{\circ}\text{R} = ^{\circ}\text{F} + 459.67$
 $^{\circ}\text{R} = 1.8 \text{ K}$

Where:

$^{\circ}\text{C}$ = degrees centigrade
 $^{\circ}\text{F}$ = degrees Fahrenheit
 K = kelvins
 $^{\circ}\text{R}$ = degrees Rankine

Above values taken from or derived from those given in *Natl. Bur. Std. (U.S.), CODATA Bull. No. 63* (1986).

1A2 Conversion Factors

Table 1A2.1 – Length Conversions

(1987)

To convert the numerical value of a property expressed in one of the units in the left-hand column of the unit conversion tables to the numerical value expressed in one of the units in the top row of the table, multiply the former value by the factor in the block common to both units.

Units	Inches	Feet	Yards	Miles	Microns	Milli-meters	Centi-meters	Meters	Kilo-meters
Inches	1	0.083333	0.027778	1.5783×10^{-5}	25400	25.4	2.54	0.0254	2.5400×10^{-5}
Feet	12	1	0.33333	1.8939×10^{-4}	3.0480×10^5	304.8	30.48	0.3048	3.0480×10^{-4}
Yards	36	3	1	5.6818×10^{-4}	9.144×10^5	914.4	91.44	0.9144	9.1440×10^{-4}
Miles	63360	5280	1760	1	1.6093×10^9	1.6093×10^6	1.6093×10^5	1.6093×10^3	1.6093
Microns	3.9370×10^{-5}	3.2808×10^{-6}	1.0936×10^{-6}	6.2137×10^{-10}	1	10^{-3}	10^{-4}	10^{-6}	10^{-9}
Millimeters	3.9370×10^{-2}	3.2808×10^{-3}	1.0936×10^{-3}	6.2137×10^{-7}	10^3	1	0.1	0.001	10^{-6}
Centimeters	0.39370	0.032808	0.010936	6.2137×10^{-6}	10^4	10	1	0.01	10^{-5}
Meters	39.370	3.2808	1.0936	6.2137×10^{-4}	10^6	1000	100	1	0.001
Kilometers	3.9370×10^4	3.2808×10^3	1.0936×10^3	0.62137	10^9	10^6	10^5	1000	1

Table 1A2.2 - Area Conversions

(1987)

Units	Square Inches	Square Feet	Square Yards	Acres	Square Centimeters	Square Meters
Square Inches	1	6.944×10^{-3}	7.7160×10^{-4}	1.5942×10^{-7}	6.4516	6.4516×10^{-4}
Square Feet	144	1	0.11111	2.2957×10^{-5}	929.03	9.2903×10^{-2}
Square Yards	1296	9	1	2.0661×10^{-4}	8361.3	0.83613
Acres	6.2726×10^6	43560	4840	1	4.0469×10^7	4.0469×10^3
Square Centimeters	0.15500	1.0764×10^{-3}	1.1960×10^{-4}	2.4711×10^{-8}	1	10^{-4}
Square Meters	1550	10.764	1.196	2.4711×10^{-4}	10^4	1

Table 1A2.3 - Volume Conversions
(1987)

Units	Cubic Inches	Cubic Feet	Cubic Yards	Cubic Centimeters	Cubic Meters
Cubic Inches	1	5.7870×10^{-4}	2.1433×10^{-5}	16.387	1.6387×10^{-5}
Cubic Feet	1728	1	3.7037×10^{-2}	2.8317×10^4	2.8317×10^{-2}
Cubic Yards	46656	27	1	7.6455×10^5	0.76455
Cubic Centimeters	6.1023×10^{-2}	3.5315×10^{-5}	1.3080×10^{-6}	1	10^{-6}
Cubic Meters	61023	35.315	1.308	10^6	1

Table 1A2.4 –Liquid Volume Conversions
(1987)

Units	Fluid Ounces (U.S.)	Quarts (U.S.)	Gallons (U.S.)	Imperial gallons	Barrels (Oil)	Cubic Inches	Cubic Feet	Liters	Cubic Centimeters	Cubic Meters
Fluid Ounces (U.S.)	1	0.03125	7.1825×10^{-3}	6.5053×10^{-3}	1.8601×10^{-4}	1.8047	1.0444×10^{-3}	0.029574	29.574	2.9574×10^{-5}
Quarts (U.S.)	32	1	0.25	0.20817	5.924×10^{-3}	57.75	0.03342	0.94635	946.35	9.4635×10^{-4}
Gallons (U.S.)	128	4	1	0.83267	0.023809	231	0.13368	3.7854	3785.4	3.7854×10^{-3}
Imperial gallons	153.72	4.8038	1.20095	1	0.028594	277.42	0.16054	4.5461	4546.1	4.5461×10^{-3}
Barrels (Oil)	5376	168	42	34.973	1	9702	5.6146	158.99	1.5899×10^5	0.15899
Cubic Inches	0.55411	0.017316	4.3290×10^{-3}	3.6047×10^{-3}	1.0307×10^{-4}	1	5.7870×10^{-4}	0.016387	16.387	1.6387×10^{-5}
Cubic Feet	957.51	29.922	7.4805	6.2289	0.17811	1728	1	28.317	28317	0.028317
Liters	33.814	1.0567	0.26417	0.21997	6.2898×10^{-3}	61.024	0.035315	1	1000	1×10^{-3}
Cubic Centimeters	0.033814	1.0567×10^{-3}	2.6417×10^{-4}	2.1997×10^{-4}	6.2898×10^{-6}	0.061024	3.5315×10^{-5}	0.001	1	1×10^{-6}
Cubic Meters	33814	1.056.7	264.17	219.97	6.2898	61024	35.315	1000	1×10^6	1

Note: According to ASME Guides SI-1 (22) and SI-4 (23), 1 ml = 1 cc

Table 1A2.5 - Mass Conversions

(1987)

Units	Grains	Ounces (Avoir)*	Pounds (Avoir)*	Ounces (Troy)†	Pounds (Troy)†	Tons (Short)‡	Tons (Long)§	Grams	Kilograms	Metric Tons
Grains	1	2.2857×10^{-3}	1.4284×10^{-4}	2.0833×10^{-3}	1.7361×10^{-4}	7.1428×10^{-8}	6.3776×10^{-8}	0.064799	6.4799×10^{-5}	6.4799×10^{-8}
Ounces (Avoir)*	437.5	1	0.0625	0.91146	0.075955	3.125×10^{-5}	2.7902×10^{-5}	28.35	0.02835	2.8350×10^{-5}
Pounds (Avoir)*	7000	16	1	14.583	1.2153	5×10^{-4}	4.4643×10^{-4}	453.59	0.45359	4.5359×10^{-4}
Ounces (Troy)†	480	1.0971	0.068571	1	0.083333	3.4285×10^{-5}	3.0612×10^{-5}	31.103	0.031103	3.1103×10^{-5}
Pounds (Troy)†	5760	13.166	0.82286	12	1	4.1143×10^{-4}	3.6735×10^{-4}	373.24	0.37324	3.7324×10^{-4}
Tons (Short)‡	1.400×10^7	32000	2000	29167	2430.6	1	0.89286	9.0718×10^5	9.0718×10^2	0.90718
Tons (Long)§	1.5680×10^7	35840	2240	32667	2722.2	1.12	1	1.0160×10^6	1.0160×10^3	1.016
Grams	15.432	0.035274	2.2046×10^{-3}	0.032151	2.6792×10^{-3}	1.1023×10^{-6}	9.8421×10^{-7}	1	38628	10^{-6}
Kilograms	1.5432×10^4	35.274	2.2046	32.151	2.6792	1.1023×10^{-3}	9.8421×10^{-4}	1000	1	10^{-3}
Metric Tons	1.5432×10^7	3.5274×10^4	2.2046×10^3	3.2151×10^4	2.6792×10^3	1.1023	0.98421	10^6	1000	1

* Used for ordinary commodities.

‡ Common in the United States and Canada.

† Used for drugs, jewels, precious metals.

§ Common in England.

Table 1A2.6 – Density Conversions

(1987)

Units	$\frac{\text{g}}{\text{cm}^3}$	$\frac{\text{lb}}{\text{in}^3}$	$\frac{\text{lb}}{\text{ft}^3}$	$\frac{\text{lb}}{\text{gal (US)}}$	$\frac{\text{kg}}{\text{m}^3}$
$\frac{\text{g}}{\text{cm}^3}$	1	0.036127	62.428	8.3454	1000
$\frac{\text{lb}}{\text{in}^3}$	27.68	1	1728	231	27680
$\frac{\text{lb}}{\text{ft}^3}$	0.016018	5.7870×10^{-4}	1	0.13368	16.018
$\frac{\text{lb}}{\text{gal (US)}}$	0.11983	4.3290×10^{-3}	7.4805	1	119.83
$\frac{\text{kg}}{\text{m}^3}$	0.001	3.6127×10^{-5}	0.062428	0.0083454	1

Table 1A2.7 – Pressure Conversions
(1987)

Units	$\frac{\text{dyns}}{\text{cm}^2}$	Bars	Atmospheres	$\frac{\text{kg}}{\text{cm}^2}$	mm Hg* at 0 °C	in. Hg* at 32 °F	$\frac{\text{lbf}}{\text{in}^2}$	ft H ₂ O at 39.2 °F	Pascals
$\frac{\text{dyns}}{\text{cm}^2}$	1	10 ⁻⁶	0.986923 × 10 ⁻⁶	1.01972 × 10 ⁻⁶	7.5006 × 10 ⁻⁴	2.9530 × 10 ⁻⁵	1.4504 × 10 ⁻⁵	3.3457 × 10 ⁻⁵	0.10000
Bars	10 ⁶	1	0.986923	1.01972	750.06	29.53	14.504	33.457	1 × 10 ⁵
Atmospheres	1.01325 × 10 ⁶	1.01325	1	1.0332	760	29.921	14.696	33.9	1.01325 × 10 ⁵
$\frac{\text{kg}}{\text{cm}^2}$	980670	0.98067	0.96784	1	735.56	28.959	14.223	32.809	98066.5
mm Hg* at 0 °C	1333.2	1.3332 × 10 ⁻³	1.31579 × 10 ⁻³	1.3595 × 10 ⁻³	1	0.03937	0.019337	0.044605	133.32
in. Hg at 32 °F	33864	0.033864	0.033421	0.03453	25.4	1	0.49116	1.133	3386.4
$\frac{\text{lbf}}{\text{in}^2}$	68.948	0.068948	0.068046	0.070307	51.715	2.036	1	2.3066	6894.7
ft H ₂ O at 39.2 °F	29889	0.029889	0.029499	0.030479	22.419	0.88265	0.43352	1	2988.98
Pascals	10.000	1 × 10 ⁻⁵	9.86923 × 10 ⁻⁶	1.01972 × 10 ⁻⁵	7.5006 × 10 ⁻³	2.9530 × 10 ⁻⁴	1.4504 × 10 ⁻⁴	3.3456 × 10 ⁻⁴	1

* 1 Torr = 1 mm Hg.

Table 1A2.8 – Flow Conversions
(1987)

Units	$\frac{\text{gal (US)}}{\text{min}}$	$\frac{\text{gal (US)}}{\text{hr}}$	$\frac{\text{ft}^3}{\text{sec}}$	$\frac{\text{ft}^3}{\text{min}}$	$\frac{\text{bbl (42)}}{\text{hr}}$	$\frac{\text{bbl (42)}}{\text{day}}$	$\frac{\text{liters}}{\text{sec}}$	$\frac{\text{m}^3}{\text{hr}}$
$\frac{\text{gal (US)}}{\text{min}}$	1	60	2.2280 × 10 ⁻³	0.13368	1.4286	34.286	0.063090	0.22712
$\frac{\text{gal (US)}}{\text{hr}}$	0.0167	1	3.7133 × 10 ⁻⁵	2.2280 × 10 ⁻³	0.023810	0.57143	1.0515 × 10 ⁻³	3.7854 × 10 ⁻³
$\frac{\text{ft}^3}{\text{sec}}$	448.83	2.6930 × 10 ⁴	1	60	641.20	1.5388 × 10 ⁴	28.317	101.94
$\frac{\text{ft}^3}{\text{min}}$	7.4805	448.83	0.016667	1	10.686	256.47	0.47195	1.6990
$\frac{\text{bbl (42)}}{\text{hr}}$	0.7000	42	1.5596 × 10 ⁻³	0.093576	1	24	0.044163	0.15899
$\frac{\text{bbl (42)}}{\text{day}}$	0.029167	1.7500	6.4984 × 10 ⁻⁵	3.8990 × 10 ⁻³	0.041667	1	1.8401 × 10 ⁻³	6.6245 × 10 ⁻³
$\frac{\text{liters}}{\text{sec}}$	15.850	951.02	0.035315	2.1189	22.643	543.44	1	3.6
$\frac{\text{m}^3}{\text{hr}}$	4.4029	264.17	0.0098096	0.58858	6.2898	150.96	0.27778	1

Table 1A2.9 - Kinematic Viscosity Conversions
(1987)

Units	$\frac{\text{ft}^2}{\text{hr}}$	$\frac{\text{ft}^2}{\text{sec}}$	$\frac{\text{m}^2}{\text{hr}}$	$\frac{\text{cm}^2}{\text{sec}}$ (Stokes)	Centistokes
$\frac{\text{ft}^2}{\text{hr}}$	1	2.778×10^{-4}	9.290×10^{-2}	0.2581	25.81
$\frac{\text{ft}^2}{\text{sec}}$	3600	1	3.345×10^2	929	9.29×10^4
$\frac{\text{m}^2}{\text{hr}}$	10.76	2.990×10^{-3}	1	2.778	277.8
$\frac{\text{cm}^2}{\text{sec}}$ (Stokes)	3.875	1.076×10^{-3}	0.36	1	100
Centistokes	3.875×10^{-2}	1.076×10^{-5}	3.600×10^{-3}	0.01	1

Table 1A2.10 - Absolute Viscosity Conversions
(1987)

Units	$\frac{\text{lb}}{\text{sec-ft}}$	$\frac{\text{lb}}{\text{hr-ft}}$	$\frac{\text{lbf-sec}}{\text{ft}^2}$	Centipoise	$\frac{\text{kg}}{\text{hr-m}}$
$\frac{\text{lb}}{\text{sec-ft}}$	1	3600	0.03108	1488	5357
$\frac{\text{lb}}{\text{hr-ft}}$	2.778×10^{-4}	1	8.634×10^{-6}	0.4134	1.488
$\frac{\text{lbf-sec}}{\text{ft}^2}$	32.17	1.158×10^5	1	47880	1.724×10^5
Centipoise	6.720×10^{-4}	2.419	2.089×10^{-5}	1	3.600
$\frac{\text{kg}}{\text{hr-m}}$	1.867×10^{-4}	0.672	5.801×10^{-6}	0.2778	1

* 1 poise = 100 centipoises = 1 g/sec-cm. Kinematic viscosity, in centistokes, times density (g/cm^3) at same temperature equals centipoises.

Table 1A2.11 - Energy Conversions

(1987)

Units	Absolute Joules	International Joules	Calories	I. T. Calories	British Thermal Units	Absolute Kilowatt-Hours	Horsepower-Hours	Foot-Pounds [Force]	$\frac{\text{ft}^3 \cdot \text{lbf}}{\text{in}^2}$	Liter Atmospheres	Centigrade Heat Units
Absolute Joules	1	0.99984	0.23901	0.23885	9.4783×10^{-4}	2.7778×10^{-7}	3.7251×10^{-7}	0.73756	5.1220×10^{-3}	9.8690×10^{-3}	5.2657×10^{-4}
International Joules	1.0002	1	0.23905	0.23889	9.4799×10^{-4}	2.7782×10^{-7}	3.7257×10^{-7}	0.73768	5.1228×10^{-3}	9.8706×10^{-3}	5.2666×10^{-4}
Calories	4.184	4.1833	1	0.99935	3.9657×10^{-3}	1.1622×10^{-6}	1.5586×10^{-6}	3.0860	2.1430×10^{-2}	4.1292×10^{-2}	2.2032×10^{-3}
I. T. Calories	4.1867	4.1861	1.0007	0	3.9683×10^{-3}	1.1630×10^{-6}	1.5596×10^{-6}	3.0880	2.1444×10^{-2}	4.1319×10^{-2}	2.2046×10^{-3}
British Thermal Units	1055.0	1054.9	252.16	252.00	1	2.9307×10^{-4}	3.9301×10^{-4}	778.16	5.4039	10.412	0.55556
Absolute Kilowatt-Hours	3.600×10^6	3.5994×10^6	8.6042×10^5	8.5986×10^5	3412.2	1	1.341	2.6552×10^6	18439	35528	1895.7
Horsepower-Hours	2.6845×10^6	2.6841×10^6	6.4162×10^5	6.4120×10^5	2544.5	0.7457	1	1.9800×10^6	13750	26494	1413.6
Foot-Pounds [Force]	1.3558	1.3556	0.32405	0.32384	1.2851×10^{-3}	3.7662×10^{-7}	5.0505×10^{-7}	1	6.9444×10^{-3}	1.3381×10^{-2}	7.1394×10^{-4}
$\frac{\text{ft}^3 \cdot \text{lbf}}{\text{in}^2}$	195.24	195.21	46.663	46.633	0.18505	5.4233×10^{-5}	7.2727×10^{-5}	144	1	1.9268	0.10281
Liter Atmospheres	101.33	101.31	24.218	24.202	0.096042	2.8147×10^{-5}	3.7745×10^{-5}	74.735	5.1900	1	5.3356×10^{-2}
Centigrade Heat Units	1899.1	1898.8	453.89	453.59	1.8	5.2752×10^{-4}	7.0741×10^{-4}	1400.7	9.7269	18.742	1

Table 1A2.12 - Power Conversions
(1987)

Units	$\frac{\text{Btu}}{\text{min}}$	$\frac{\text{Btu}}{\text{hr}}$	$\frac{\text{ft-lb}}{\text{sec}}$	$\frac{\text{ft-lb}}{\text{min}}$	Horsepower	Metric Horsepower	watts (Absolute)	$\frac{\text{cal}}{\text{sec}}$	$\frac{\text{I.T. cal}}{\text{sec}}$	$\frac{\text{joules (abs)}}{\text{sec}}$
$\frac{\text{Btu}}{\text{min}}$	1	60.00	12.969	778.16	0.023580	0.023908	17.584	4.2027	4.1999	17.584
$\frac{\text{Btu}}{\text{hr}}$	0.016667	1	0.21615	12.969	3.9301×10^{-4}	3.9846×10^{-4}	0.29307	0.070045	0.069999	0.29307
$\frac{\text{ft-lb}}{\text{sec}}$	7.7105×10^{-2}	4.6263	1	60.00	1.8182×10^{-3}	1.8434×10^{-3}	1.3558	0.32405	0.32384	1.3558
$\frac{\text{ft-lb}}{\text{min}}$	1.2851×10^{-3}	0.77105	0.016667	1	3.0303×10^{-5}	3.0723×10^{-5}	0.022597	5.4008×10^{-3}	5.3973×10^{-3}	0.022597
Horsepower	42.408	2544.5	550	33000	1	1.0139	745.70	178.23	178.11	745.70
Metric Horsepower	41.828	2509.7	542.48	32549	0.98632	1	735.50	175.79	175.67	735.50
watts (absolute)	0.056869	3.4122	0.73756	44.254	1.3410×10^{-3}	1.3596×10^{-3}	1	0.23901	0.23885	1
$\frac{\text{cal}}{\text{sec}}$	0.23794	14.277	3.0860	185.16	5.6108×10^{-3}	5.6886×10^{-3}	4.1840	1	0.99935	4.1840
$\frac{\text{I.T. cal}}{\text{sec}}$	0.23810	14.286	3.0880	185.28	5.6145×10^{-3}	5.6924×10^{-3}	4.1867	1.0007	1	4.1867
$\frac{\text{joules (abs)}}{\text{sec}}$	0.056869	3.4122	0.73756	44.254	1.3410×10^{-3}	1.3596×10^{-3}	1	0.23901	0.23885	1

Notes:

One boiler horsepower = 33471.9 Btu per hr.

One standard commercial ton of refrigeration = 288000 Btu per day.

Table 1A2.13 - Specific Energy Conversions
(1987)

Units	$\frac{\text{joules (abs)}}{\text{g}}$	$\frac{\text{joules (int)}}{\text{g}}$	$\frac{\text{cal}}{\text{g}}$	$\frac{\text{I.T. cal}}{\text{g}}$	$\frac{\text{Btu}}{\text{lb}}$
$\frac{\text{joules (abs)}}{\text{g}}$	1	0.99984	0.23901	0.23885	0.42993
$\frac{\text{joules (int)}}{\text{g}}$	1.0002	1	0.23905	0.23889	0.43000
$\frac{\text{cal}}{\text{g}}$	4.1840	4.1833	1	0.99935	1.7988
$\frac{\text{I.T. cal}}{\text{g}}$	4.1867	4.1861	1.0007	1	1.8
$\frac{\text{Btu}}{\text{lb}}$	2.3260	2.3256	0.55592	0.55556	1

Table 1A2.14 – Specific Energy per Degree Conversions
(1987)

Units	$\frac{\text{joules (abs)}}{\text{g-K}}$	$\frac{\text{joules (int)}}{\text{g-K}}$	$\frac{\text{cal}}{\text{g-K}}$	$\frac{\text{I.T. cal}}{\text{g-K}}$	$\frac{\text{Btu}}{\text{lb-}^{\circ}\text{F}}$
$\frac{\text{joules (abs)}}{\text{g-K}}$	1	0.99984	0.23901	0.23885	0.23885
$\frac{\text{joules (int)}}{\text{g-K}}$	1.0002	1	0.23905	0.23889	0.23889
$\frac{\text{cal}}{\text{g-K}}$	4.1840	4.1833	1	0.99935	0.99935
$\frac{\text{I.T. cal}}{\text{g-K}}$	4.1867	4.1861	1.0007	1	1
$\frac{\text{Btu}}{\text{lb-}^{\circ}\text{F}}$	4.1867	4.1861	1.0007	1	1

Table 1A2.15 – Heat Flux Conversions
(1987)

Units	$\frac{\text{Btu}}{\text{hr-ft}^2}$	$\frac{\text{cal}}{\text{sec-cm}^2}$	$\frac{\text{kg-cal}}{\text{hr-m}^2}$	$\frac{\text{watts (abs)}}{\text{cm}^2}$	$\frac{\text{joules (abs)}}{\text{sec-m}^2}$
$\frac{\text{Btu}}{\text{hr-ft}^2}$	1	7.5397×10^{-5}	2.714	3.1546×10^{-4}	3.1546
$\frac{\text{cal}}{\text{sec-cm}^2}$	13263	1	36000	4.1840	41840
$\frac{\text{kg-cal}}{\text{hr-m}^2}$	0.3684	2.7778×10^{-5}	1	1.1622×10^{-4}	1.1622
$\frac{\text{watts (abs)}}{\text{cm}^2}$	3170.0	0.23901	8604.2	1	10000
$\frac{\text{joules (abs)}}{\text{sec-m}^2}$	0.31700	2.3901×10^{-5}	0.86042	1×10^{-4}	1

Table 1A2.16 – Heat Transfer Coefficient Conversions
(1987)

Units	$\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$	$\frac{\text{cal}}{\text{sec-cm}^2\text{-K}}$	$\frac{\text{kg-cal}}{\text{hr-m}^2\text{-K}}$	$\frac{\text{watts (abs)}}{\text{cm}^2\text{-K}}$	$\frac{\text{joules (abs)}}{\text{sec-m}^2\text{-K}}$
$\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$	1	1.3571×10^{-4}	4.8857	5.6783×10^{-4}	5.6783
$\frac{\text{cal}}{\text{sec-m}^2\text{-K}}$	7368.4	1	36000	4.184	41840
$\frac{\text{kg-cal}}{\text{hr-m}^2\text{-K}}$	0.20468	2.7778×10^{-5}	1	1.1622×10^{-4}	1.1622
$\frac{\text{watts (abs)}}{\text{cm}^2\text{-K}}$	1761.1	0.23901	8604.2	1	10000
$\frac{\text{joules (abs)}}{\text{sec-m}^2\text{-K}}$	0.17611	2.3901×10^{-5}	0.86042	1×10^{-4}	1

Table 1A2.17 – Thermal Conductivity Conversions
(1987)

Units	$\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F per in}}$	$\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F per ft}}$	$\frac{\text{cal}}{\text{sec-cm}^2\text{-K per cm}}$	$\frac{\text{kg-cal}}{\text{hr-m}^2\text{-K per m}}$	$\frac{\text{watts (abs)}}{\text{cm}^2\text{-K per cm}}$	$\frac{\text{joules (abs)}}{\text{sec-m}^2\text{-K per m}}$
$\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F per in}}$	1	0.08333	3.4471×10^{-4}	0.12410	1.4423×10	0.14423
$\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F per ft}}$	12.000	1	4.1366×10^{-3}	1.4892	0.017307	1.7307
$\frac{\text{cal}}{\text{sec-cm}^2\text{-K per cm}}$	2901.0	241.75	1	360	4.184	418.40
$\frac{\text{kg-cal}}{\text{hr-m}^2\text{-K per m}}$	8.0582	0.67152	2.7778×10^{-3}	1	0.011622	1.1622
$\frac{\text{watts (abs)}}{\text{cm}^2\text{-K per cm}}$	693.35	57.779	0.23901	86.042	1	100
$\frac{\text{joules (abs)}}{\text{sec-m}^2\text{-K per m}}$	6.9335	0.5778	2.3901×10^{-3}	0.86042	0.01	1

1B Letter Symbols Used in Chemical Engineering

(1987)

The letter symbols for the concepts most widely used in chemical engineering are listed in tables 1B1.1 (by category) and 1B1.2 (alphabetically). A letter symbol is a single letter used to represent a primary concept for a physical quantity, and it may be used with a subscript or superscript. A subscript may designate a place in space or time, a system of units, or a constant or reference value. A superscript may designate a dimensionless form, a reference or equilibrium value, a sequence in time or space, or a mathematical identification (average value, derivative, tensor index).

These lists have been adapted from the official tables of the American Institute of Chemical Engineers and of the American National Standards Institute. Suitable modifications have been made in the units to conform with the editorial policies of the American Petroleum Institute. Several additions have been made for symbols used frequently in this book. Listing is alphabetical by concept within each category. Illustrative units or definitions are supplied where appropriate.

Greek Alphabet

A	α	Alpha	I	ι	Iota	P	ρ	Rho
B	β	Beta	K	κ	Kappa	Σ	σ	Sigma
Γ	γ	Gamma	Λ	λ	Lambda	T	τ	Tau
Δ	δ, ∂	Delta	M	μ	Mu	Y	υ	Upsilon
E	ε	Epsilon	N	ν	Nu	Φ	ϕ	Phi
Z	ζ	Zeta	Ξ	ξ	Xi	X	χ	Chi
H	η	Eta	O	$\omicron$	Omicron	Ψ	ψ	Psi
Θ	θ	Theta	Π	π	Pi	Ω	ω	Omega

1B1 Letter Symbols for the Principal Concepts Used in Chemical Engineering

Table 1B1.1 Letter Symbols for the Principal Concepts Used in Chemical Engineering

(1987)

<u>General Symbols</u>	<u>Unit or Definition</u>	<u>General Symbols</u>	<u>Unit or Definition</u>
Acceleration..... a	ft per sec per sec	Newton law of motion, conversion factor in..... g_c	$g_c = ma/F$ (lb)(ft/s ²)/lbf
Of gravity..... g	ft per sec per sec	Number	
Acentric factor ω		In general..... N	
Base of natural logarithms e		Of moles..... n	
Coefficient C		Pressure..... p	lbf/ft ² ; atm lbf/in ² (abs)
Difference, finite..... Δ		Quantity, in general..... Q	
Differential operator..... d		Radius of gyration $\bar{R}$	
Partial..... ∂		Ratio, in general..... R	
Efficiency η		Refractive index n	
Energy, dimension..... E	BTU; ft-lb [force]	Resistance R	
Enthalpy..... H	BTU	Shear stress τ	lb [force] per sq ft
Entropy..... S	BTU per deg R	Temperature	
Force..... F	lb [force]	Absolute..... T	K; deg R
Fugacity Coefficient..... ϕ		Dimension of..... θ	
Function ϕ, ψ, χ		In general..... T, t	deg C; deg F
Gas constant, universal..... R	To distinguish, use R_0	Temperature difference, logarithmic mean..... $\bar{\theta}$	deg F
Gibbs free energy..... G, F	$G = H - TS$, BTU	Time	
Heat Q	BTU	Dimension of..... T	sec
Helmholtz free energy..... A	$A = U - TS$, BTU	In general..... t, τ	sec; hr
Internal energy..... U	BTU	Watson characterization factor K	
Mass, dimension of m	lb	Work..... W	Btu
Mechanical equivalent of heat..... J	ft-lb [force] per BTU		
Moment of inertia..... I	lb-ft ²		
<u>Geometric Property Symbols</u>	<u>Unit or Definition</u>	<u>Geometric Property Symbols</u>	<u>Unit or Definition</u>
Angle..... α, θ, ϕ		In general..... A	sq ft
in x, y plane α		Projected A_p	sq ft
in y, z plane ϕ		Surface	
in z, x plane θ		Per unit mass..... A_w, s	sq ft per lb
Solid angle ω		Per unit volume..... A_v, a	sq ft per cu ft
Area		Linear dimension	
Cross-section S	sq ft	Breadth b	ft
Fraction free cross- section σ		Diameter D	ft
Height above datum plane..... Z	ft	Distance along path..... s, x	ft
Height equivalent..... H	ft (Use subscript p for equilibrium stage and t for transfer unit.)	Mean free path..... λ	cm; ft
Hydraulic radius r_H	ft; sq ft per ft	Radius..... r	ft
Lateral distance from datum plane..... Y	ft	Thickness	
Length, distance or dimension of..... L	ft	In general..... B	ft
Longitudinal distance from datum plane..... X	ft	Of film B_f	ft
		Wavelength λ	cm; ft
		Other	
		Particle-shape factor ϕ_s	
		Volume	
		Fraction voids ϵ	
		Humid volume v_H	cu ft per lb dry air
		In general..... V	cu ft



Table 1B1.1 Letter Symbols for the Principal Concepts used in Chemical Engineering (Continued)
(1987)

<u>Intensive Property Symbols</u>	<u>Unit or Definition</u>	<u>Intensive Property Symbols</u>	<u>Unit or Definition</u>
Absorptivity for radiation..... α		At constant volume..... c_v	Btu/lb-°F
Activity..... a		Heat capacities, ratio of..... γ	
Activity coefficient, molar basis..... γ		Helmholtz free energy..... A	Btu/ lb
Coefficient of expansion		Humid heat..... c_s	Btu /lb dry air-°F
Linear..... α	ft per ft per deg F	Internal energy..... U	Btu/lb
Volumetric..... β	cu ft per cu ft per deg F	Latent heat, phase change..... λ	Btu/lb
Compressibility factor..... z	$z = pV/RT$	Molecular weight..... MW	
Density..... ρ	lb per cu ft	Reflectivity for radiation..... ρ	
Diffusivity		Surface tension..... σ	lb [force] per ft
Molecular, volumetric..... D_v, δ	cu ft per (hr) (ft); sq ft per hr	Thermal conductivity..... k	Btu/hr-ft ² -°F-ft
Thermal..... α	$\alpha = k/c_p$, sq ft per hr	Transmissivity of radiation..... τ	
Emissivity ratio for radiation..... ϵ		Vapor pressure..... p^*	lb/ft ² ; atm; lb/in ² (abs)
Enthalpy..... H	Btu per lb	Viscosity	
Entropy..... S	Btu per (lb) (deg R)	Absolute or coefficient of..... μ	lb per (sec) (ft)
Fugacity..... f	lb [force] per sq ft; atm	Kinematic..... ν	sq ft per sec
Gibbs free energy..... G, F	Btu per lb	Volume, per mole..... V	cu ft per lb-mole
Heat capacity..... c	Btu per (lb) (deg F)		
At constant pressure..... c_p	Btu per (lb) (deg F)		
<u>Concentration Symbols</u>	<u>Unit or Definition</u>	<u>Concentration Symbols</u>	<u>Unit or Definition</u>
Absorption factor..... A	$A=L/KV$	Mole or mass fraction	
Concentration, mass or moles per unit volume.. c	lb per cu ft; lb-moles per ft ³	In heavy or extract phase..... x	
Fraction		In light or raffinate phase..... y	
By volumes..... x_v		Mole or mass ratio	
By weight..... x_w		In heavy or extract phase..... X	
Cumulative beyond a given size..... ϕ		In light or raffinate phase..... Y	
Humidity..... H, Y_H	lb per lb dry air	Number concentration of particles..... n_p	number per cu ft
At adiabatic saturation temperature..... H_a, Y_a	lb per lb dry air	Phase equilibrium ratio..... K	$K = y^*/x$
At saturation..... H_s, Y^*	lb per lb dry air	Relative distribution of two components	
At wet-bulb temperature..... H_w, Y_w	lb per lb dry air	Between two phases in equilibrium..... α	$\alpha = K/K_j$
Mass concentration of particles..... c_p	lb per cu ft	Between successive stages..... β	$\beta_n = \frac{(y_i / y_j)_n}{(x_j / x_i)_{n+1}}$
Moisture content		Relative humidity..... H_R, R_H	
Equilibrium water to bone dry stock..... X^*	lb per lb dry stock	Slope of equilibrium curve..... m	$m = dy^*/dx$
Free water to bone dry stock X	lb per lb dry stock	Stripping factor..... S	$S=KV/L$
Total water to bone dry stock..... X_T	lb per lb dry stock		

Table 1B1.1 Letter Symbols for the Principal Concepts used in Chemical Engineering (Continued)
(1987)

<u>Rate Concept Symbols</u>	<u>Unit or Definition</u>	<u>Rate Concept Symbols</u>	<u>Unit or Definition</u>
Mass transfer coefficient		Quantity per unit time, unit area	
Individual..... k	lb-moles per (hr) (ft ²) (driving force)	Emissive power, total..... W	Btu per (hr) (ft ²)
Gas film k_G	To define driving force, use subscript: c for lb-moles per cu ft p for atm x for mole fraction	Mass velocity, average..... G	$G = w/S$, lb per (sec)(ft ²)
Liquid film..... k_L		Vapor or light phase..... $G, \bar{G}$	lb per (hr) (ft ²)
Overall..... K		Liquid or heavy phase..... $L, \bar{L}$	lb per (hr) (ft ²)
Gas film basis..... K_G		Radiation, intensity of..... I	Btu per (hr) (ft ²)
Liquid film basis..... K_L		Velocity	
Quantity per unit time, in general..... q		Nominal, basis total cross-section of packed vessel..... v_s	ft per sec
Angular velocity..... ω		Volumetric average..... $V, \bar{V}$	(ft ³) per (sec) (ft ²); ft per sec
Feed rate..... F	lb per hr; lb-moles per hr	Quantity per unit time, unit volume	
Frequency..... f, N_f		Quantity reacted per unit time, reactor volume... N_R	mole per (sec) (cu ft)
Friction velocity..... u^*	$u^* = (g_c \tau_w \rho)^{1/2}$, ft per sec	Space velocity, volumetric..... Λ	cu ft per (sec) (cu ft)
Heat transfer rate..... q	Btu per hr	Quantity per unit time, unit area, unit driving force, in general..... k	
Heavy of extract phase rate..... L	lb per hr; lb-moles per hr	Eddy diffusivity..... δ_E	(ft ²) per hr
Heavy or extract product rate..... B	lb per hr; lb-moles per hr	Eddy viscosity..... ν_E	(ft ²) per hr
Light or raffinate phase rate..... V	lb per hr; lb-moles per hr	Eddy thermal diffusivity... α_E	(ft ²) per hr
Light or raffinate product rate..... D	lb per hr; lb-moles per hr	Heat transfer coefficient	
Mass rate of flow..... w	lb per sec; lb per hr	Individual..... H	Btu per (hr) (ft ²) (°F)
Molar rate of transfer..... N	lb-moles per hr	Overall..... U	Btu per (hr) (ft ²) (°F)
Power..... P	ft-lb [force] per sec	Stefan-Boltzmann constant..... σ	0.173×10^{-8} Btu per (hr) (ft ²) (°R) ⁴
Revolutions per unit time..... n			
Velocity			
In general..... u	ft per sec		
Instantaneous local			
Longitudinal (x) component of..... u	ft per sec		
Lateral (y) component of..... v	ft per sec		
Normal (z) component of..... w	ft per sec		
Volumetric rate of flow..... q	cu ft per sec; cu ft per hr		

Table 1B1.2 - Alphabetical Index of Symbols Used in Chemical Engineering
(1987)

<u>Primary Concept</u>	<u>Subscript Concept</u>	<u>Primary Concept</u>	<u>Subscript Concept</u>
<i>a</i> Acceleration Activity Area, alternate for Surface per unit volume	Acoustic Adiabatic Arithmetic	<i>i</i>	Generalized component Interface Internal or inner
<i>A</i> Absorption factor Area Helmholtz free energy	Absolute Area Basis Component A	<i>I</i> Intensity of radiation Moment of inertia	
<i>b</i> Breadth	Baffle Base Normal boiling point	<i>j</i> Transfer factor	Generalized component
<i>B</i> Heavy product rate Thickness	Black body Boiling point Component B	<i>J</i> Mechanical equiv. of heat	
<i>c</i> Concentration, mass or moles per unit volume Specific heat, heat capacity	Concentration basis Contraction Conversion factor Critical Cutoff size Component C	<i>k</i> Mass transfer coefficient, individual Quantity per unit time, unit area, unit driving force, in general Thermal Conductivity	
<i>C</i> Coefficient		<i>K</i> Watson characterization factor Overall mass transfer coefficient Phase concentration ratio	
<i>d</i> Differential operation	Discharge Disperse Drop Dry Component D Distillate	<i>L</i> Heavy or extract phase rate Length Mass velocity of liquid or heavy phase	Liquid Liquid Film basis
<i>D</i> Diameter Diffusivity Light or raffinate product rate		<i>m</i> Mass Dimension of, in general Slope of equilibrium curve	Mass Mean
<i>e</i> Base of natural logarithms	Effective Exit Component E	<i>M</i>	Mass basis Molecular
<i>E</i> Energy Dimension of In General	Eddy Entrainment	<i>MW</i> Molecular Weight	
<i>f</i> Frequency Fanning friction factor Fugacity	Film Fluid Frequency Friction Feed	<i>n</i> Number concentration Number of Moles Refractive Index Revolutions per unit time	Generalized stage number
<i>F</i> Feed Rate Force		<i>N</i> Molar rate Number, in general	
<i>g</i> Acceleration of gravity	Gage Gravity Vapor Vapor Vapor film basis	<i>o</i>	Initial Outer Overall
<i>G</i> Gibbs free energy Mass Velocity, Vapor In General		<i>O</i>	Constant Pressure Particle Plate or stages Pressure basis Projected
<i>h</i> Individual coefficient of heat transfer	Heat Heated Heat basis Humidity Hydraulic	<i>P</i> Power	
<i>H</i> Enthalpy Height equivalent Humidity		<i>pc</i>	Pseudocritical
		<i>q</i> Quantity per unit time in general Rate of heat flow Rate of volumetric flow	Rate Basis

Table 1B1.2 - Alphabetical Index of Symbols Used in Chemical Engineering (Continued)

(1987)				
	<u>Primary Concept</u>	<u>Subscript Concept</u>	<u>Primary Concept</u>	<u>Subscript Concept</u>
Q	Heat		α	Absorptivity for radiation
	Quantity, in general			Angle
r	Radius	Radius or radial		Angle in x,y, plane
		Reduced		Coefficient of linear expansion
R	Gas Constant	Radiation		Relative distribution of two
	Ratio, in general	Reactor volume basis		components between two
	Reflux ratio	Relative value		phases at equilibrium
	Resistance			Thermal diffusivity
$\bar{R}$	Radius of gyration		β	Coefficient of volumetric
s	Distance along path	Saturation		expansion
	Specific surface	Shape		Relative distribution of two
		Stress		components between
		Surface basis		successive stages
S	Cross-section	Cross-section basis	γ	Activity coefficient, molar
	Entropy	Solid		basis
	Stripping factor	Solvent		Ratio of heat capacities
t	Temperature	Tangential	∂	Differential operator, partial
	Time	Terminal	δ	Diffusivity, volumetric
		Transfer unit or units	Δ	Difference, finite
T	Absolute temperature	Constant temperature	ε	Emissivity ratio for radiation
	Temperature, in general	Total		Fraction voids
u	Longitudinal component of	Upper	η	Efficiency
	local velocity		θ	Angle
	Velocity, in general			Angle in z,x plane
U	Heat transfer coefficient,			Temperature, dimension of
	overall		$\bar{\theta}$	Log mean temperature difference
	Internal energy		λ	Latent heat of phase change
v	Lateral component of local	Constant volume		Mean free path
	velocity	Velocity basis		Wavelength
	Nominal velocity	Volumetric	Λ	Volumetric space velocity
	Specific volume		μ	Viscosity, absolute
V	Light or raffinate phase rate	Vapor	ν	Viscosity, kinematic
	Volume, in general		ρ	Density
	Volumetric average velocity			Reflectivity for radiation
w	Mass flow rate	Mass basis	σ	Fraction free cross-section
	Normal component of local	Wet bulb		Stefan-Boltzmann constant
	velocity			Surface tension
W	Work		τ	Shear stress
	Total emissive power			Time, alternate for
x	Distance along path	Mole fraction basis		Transmissivity for radiation
	Fraction		Φ	Angle
	Mole or mass fraction in			Angle in y,z plane
	heavy or extract phase			Fraction cumulative, larger
X	Longitudinal distance from	Mole ratio basis		than a given size
	datum plane			Partial factor
	Mole or mass ratio in heavy			Function
	or extract phase			Fugacity coefficient
y	Mole or mass fraction in			Particle factor
	light or raffinate phase		χ	Function
Y	Humidity		ψ	Function
	Lateral distance from datum		ω	Acentric factor
	plane			Angular frequency
Y	Mass or mole ratio in light			Angular velocity
	or raffinate phase			Solid angle
z	Compressibility factor			
Z	Height above datum plane			

1C Property Definitions

(2005)

The physical property data in the 7th -9th Editions have been combined into an electronic database, replacing the following printed tables in the 6th Edition of the API Technical Data Book:

1C1 Hydrocarbons – Primary Properties

1C2 Hydrocarbons – Secondary Properties

1C3 Nonhydrocarbons – Primary Properties

1C4 Nonhydrocarbons – Secondary Properties

A list of physical properties in the API Technical Data Book as well as a definition of the property and any other pertinent information follows.

1C1 Primary Properties

(2006)

Compound Name

The compound name or component name is listed by "Common Name" name convention as defined by DIPPR (8, 52, 53).

Chemical Formula

The chemical formula is listed as defined by DIPPR (8, 52, 53).

Molecular Weight

The molecular weight (MW) reported is based on IUPAC "Atomic Weights of the Elements," 1986 (102).

Boiling Point

The boiling point is defined at one atmosphere in degrees Fahrenheit.

Freezing Point

The freezing point is in air at one atmosphere in degrees Fahrenheit.

Critical Properties

The conditions of equilibrium for coexisting vapor and liquid phases of a pure substance are defined on a pressure-temperature diagram by the vapor pressure curve. This curve starts at the triple point, where vapor, liquid, and solid phases are in equilibrium, and ends at the critical point. As the critical point is approached by the coexisting phases, their properties approach each other until they become identical at the critical temperature and pressure, where a single homogeneous phase is present.

Values of critical temperature in degrees Fahrenheit, pressure in pounds per square inch absolute, volume in cubic feet per pound, and compressibility factor are given. Further information on critical properties is given in Chapter 4.

Acentric Factor

The acentric factor is calculated from the definition:

$$\omega = -\log P_{r,0.7}^* - 1.000$$

Where:

ω = acentric factor.

$P_{r,0.7}^*$ = the reduced vapor pressure at a reduced temperature, T_r , of 0.7, P^*/P_c

P^* = vapor pressure, in pounds per square inch absolute.

P_c = critical pressure, in pounds per square inch absolute.

T_r = reduced temperature, T/T_c

T = temperature, in degree Rankine.

T_c = critical temperature, in degrees Rankine.

When vapor pressure data were not available at $T_r = 0.7$, Procedure 2A1.1 was used. Further information on the acentric factor is given in Chapter 2.

Density of Liquids

$$\text{Specific gravity, } 60^\circ\text{F}/60^\circ\text{F} = \frac{\rho(60^\circ\text{F, lb/gal})}{\rho(\text{water, } 60^\circ\text{F, lb/gal})}$$

$$\text{sp gr} = \frac{\rho(60^\circ\text{F, lb/gal})}{8.33718}$$

Where:

ρ = liquid density

Liquid densities at 60 °F are given in pounds per gallon at one atmosphere when 60 °F is below the normal boiling point or at saturation pressure when 60 °F is at or above the normal boiling point. For compounds that are solid at 60 °F, the liquid density is the liquid value extrapolated back to 60 °F.

Densities at other temperatures can be calculated from the density at 60 °F by

$$\rho(T \text{ deg F}) = \frac{\rho(60 \text{ °F})}{1 + \left[\frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_p (T - 60) \right]}$$

Where:

T = temperature, in degrees Fahrenheit.

$\frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_p$ = coefficient of expansion, in degrees Fahrenheit.

API gravity is defined as:

$$\text{deg API} = \frac{141.5}{\text{sp gr}} - 131.5$$

Further information on liquid density is given in Chapter 6.

Refractive Index of Liquids

Values of the refractive index, n_D , of the air saturated hydrocarbon relative to air at the sodium D-line (5892.6Å) are reported at 77 °F.

Vapor Pressure

Vapor pressure is the pressure at which the vapor phase of a substance is in equilibrium with the liquid phase of that substance at a specified temperature. Values of vapor pressure at 100 degrees F are reported in units of pounds per square inch absolute. Further information on vapor pressure is given in Chapter 5.

Heat Capacity of the Liquid and Gas

Heat capacities at constant pressure are reported for the liquid and ideal gas at 60 °F and 1 atm pressure. These are related to the enthalpy by:

$$C_p = \left(\frac{\partial H}{\partial T} \right)_p$$

The observed heat capacity for a saturated liquid or vapor is C_s . This may be converted to the heat capacity at constant pressure by:

$$C_p = T \left(\frac{\partial V}{\partial T} \right)_p \frac{dP^*}{dT} + C_s$$

Where:

dP^*/dT = the temperature derivative of the vapor pressure, in pounds per square inch absolute per degree Rankine.

When values of the ideal gas heat capacity calculated from spectroscopic data were not available, they were predicted by the second order method of Benson using the CHETAH program (31). Heat capacities are reported in units of British thermal units per pound degree F. For compounds where the normal boiling point is below 60 °F, liquid heat capacity is reported at the saturation pressure. Further information on heat capacity is given in Chapter 7.

Viscosity of Liquids

The kinematic viscosity in centistokes is reported at 100 °F and 210 °F and 1 atmosphere pressure. The kinematic viscosity, ν , is related to the absolute viscosity, μ , by:

$$\nu(\text{stokes}) = \frac{\mu(\text{poise})}{\rho(\text{gm/cu cm})}$$

Where:

ρ = liquid density.

Further information on viscosity is given in Chapter 11.

Heat of Vaporization

The heat of vaporization λ , is defined as the enthalpy of the real gas at the equilibrium vapor pressure, minus the enthalpy of the liquid at the same pressure and temperature. When experimental data were not available, λ was predicted at the normal boiling point by the Clapeyron Equation:

$$\lambda = \left(\frac{dP^*}{dT} \right) T (V_g - V_L) (144 / 778)$$

Where:

λ = latent heat of vaporization, in Btu/lb

P^* = pure substance vapor pressure, in psia

T = temperature, in degrees Rankine

V_g = specific volume of saturated vapor, in ft³/lb

V_L = specific volume of saturated liquid, in ft³/lb

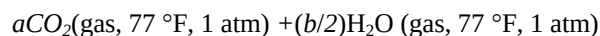
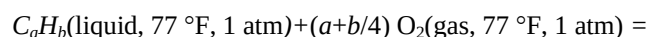
(144/778 = conversion factor)

Further information on heat of vaporization is given in Chapter 7.

Net Heat of Combustion of the Liquid

Hydrocarbons:

The net heat of combustion at 77 °F, ΔH_c , is the change in enthalpy for the reaction:



Net heat of combustion is related to gross heat of combustion by the relationship:

$$\Delta H_c (\text{net, Btu/lb}) = \Delta H_c (\text{gross, Btu/lb}) - \left(\frac{b}{2} \right) * \lambda_w \frac{MW(H_2O)}{MW(C_a H_b)}$$

Where:

λ_w = heat of vaporization of water at 77 °F and saturation pressure = 1,050.0 Btu/lb (20).

For compounds which are gaseous at 77 °F and 1 atm (i.e., C₁ to C₄ hydrocarbons), the net heat of combustion of the vapor is given. This is related to the net heat of combustion of the liquid as follows:

$$\Delta H_c (\text{vapor}) = \Delta H_c (\text{liquid}) + \lambda$$

Where:

λ = heat of vaporization at 77 °F, in Btu/lb.

Nonhydrocarbons: For nonhydrocarbons, the standard combustion products are:

CO₂ (gas)
H₂O (gas)
F₂ (gas)
Cl₂ (gas)
Br₂ (gas)
I₂ (gas)
SO₂ (gas)
N₂ (gas)

For compounds where the heat of formation was not available, the net heat of formation was predicted by the second order method of Benson using the CHETAH program (31) after which the heat of combustion as calculated from the definition.

The heat of combustion is defined as heat evolved, therefore, the values for heat of combustion that are reported are positive. Further information on heat of combustion is given in Chapter 14.

Surface Tension

Surface tension is tension exhibited by the free surface of a liquid. The liquid surface tension at 77 °F is reported in units of dynes per centimeter. Further information on surface tension is given in Chapter 10.

1C2 Secondary Properties

(2006)

Solubility Parameter

The solubility parameter is defined by

$$\delta = \left(\frac{\Delta U^{vap}}{V^L} \right)^{1/2}$$

Where:

ΔU^{vap} = internal energy change on vaporization to the ideal gas, in cal/mol

V^L = liquid molar volume at 25 °C, in cm³/mole

An approximation of the internal energy change yields:

$$\delta = \left(\frac{\lambda - RT}{V^L} \right)^{1/2}$$

Where:

λ = heat of vaporization at 25 °C, in cal/mole

V^L = liquid molar volume at 25 °C, in cm³/mole

R = gas constant = 1.9872 cal/mole-K

T = absolute temperature, 298.15 K

The above equation was used to calculate solubility parameters in units of (cal/cm³)^{1/2}.

Flash Point Temperature

The flash point of a liquid or solid is the lowest temperature at which sufficient vapor is given off through evaporation or sublimation to form an ignitable mixture with the air near the surface of the liquid or in the vessel used.

Heat of Formation

Heat of formation of a hydrocarbon C_aH_b in the ideal gas state is reported at 77 °F in units of Btu/lb. Heats of formation of the hydrocarbon in the liquid state are related to those in the ideal gas state by the following equation:

$$\Delta H_f^{liq} (\text{Btu} / \text{lb}) = \Delta H_f^{gas} (\text{Btu} / \text{lb}) - \lambda (\text{Btu} / \text{lb})$$

Where:

λ = the heat of vaporization at 77 °F

To derive a liquid heat of formation of a hydrocarbon, C_aH_b, from a heat of combustion, the following equations, which neglect pressure corrections, can be used:

$$\Delta H_f^{liq} (\text{Btu} / \text{lb}) = \Delta H_c (\text{net}, \text{Btu} / \text{lb}) + a \frac{MW(\text{CO}_2)}{MW(\text{C}_a\text{H}_b)} \Delta H_f (\text{CO}_2, \text{gas}) + \frac{b}{2} \frac{MW(\text{H}_2\text{O})}{MW(\text{C}_a\text{H}_b)} \Delta H_f (\text{H}_2\text{O}, \text{gas})$$

$$\Delta H_f^{liq} (\text{Btu} / \text{lb}) = \Delta H_c (\text{net}, \text{Btu} / \text{lb}) + a \frac{(44)(-3844.28)}{MW(\text{C}_a\text{H}_b)} + \frac{b}{2} \frac{(18)(-5770.9)}{MW(\text{C}_a\text{H}_b)}$$

ΔH_f = net heat of combustion, in Btu/lb

MW = molecular weight, in lb/lb-mol

ΔH_f = heat of formation at 77 °F.

–3844.28 Btu/lb = heat of formation of CO₂ gas, in British thermal units per pound.

–5770.9 = heat of formation of H₂O gas, in British thermal units per pound (20).

The heats of formation of nonhydrocarbons are obtained using the same techniques with standard products of combustion as given earlier. Values are taken from DIPPR Compilation where available. For compounds where heats of formation were not derived from experimental data, heats of formation were predicted by the second order method of Benson using the CHETAH program (31).

Gibbs Free Energy of Formation

The Gibbs free energy of formation for the ideal gas state is reported at 77 °F in units of British thermal units per pound.

Heat of Fusion

The heat of fusion is reported at 77 °F in units of British thermal units per pound.

Flammability Limits

Lower and upper limits of flammability are reported as volume percent in a mixture with air.

When experimental data were not available, lower flammability limits were predicted by the method of Shebeko et al. (36), and upper flammability limits were predicted by the DIPPR Compilation method (8, 52, 53).

1C3 Secondary Properties – Hydrocarbons Only

(1999)

Coefficient of Expansion

The coefficient of expansion is calculated by the definition:

$$\beta = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_p$$

Values are reported at 60 °F in units of (deg F)⁻¹

Aniline Point

The aniline point of a petroleum product is the critical solution temperature of a mixture of equal volumes of aniline and the hydrocarbon. It is the lowest temperature at which a petroleum product is completely miscible with an equal volume of freshly distilled aniline.

ASTM Octane Numbers

The octane number of a motor fuel indicates its relative tendency to knock under specified conditions of laboratory engine operation. It is equal to the percentage of iso-octane in the reference fuel whose knock characteristics equal those of the sample under test.

Octane numbers are reported for both the motor method and the research method of testing.

Watson K Factor

The Watson characterization factor, K, is defined by the equation:

$$K = \frac{(MeABP)^{\frac{1}{3}}}{sp\ gr}$$

Where:

MeABP = mean average boiling point, the normal boiling point for a pure component in degrees Rankine.

Further information on the Watson characterization factor is given in Chapter 2.

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API TECHNICAL DATA BOOK

10th Edition

CHAPTER 2

CHARACTERIZATION OF HYDROCARBONS

Revised Chapter 2 to First Edition (1966), Second Edition (1970), Third Edition (1976), Fourth Edition (1982), Fifth Edition (1992), Sixth Edition (1997), Seventh Edition (2005), Eighth Edition (2006), Tenth Edition (2016)

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Preface to the Sixth Edition

This revised chapter is based on an expanded experimental data base for petroleum characterizing parameters. Existing correlations were evaluated and new correlations for predicting some characterizing properties were developed. Correlations for aniline point, smoke point, freezing point, cloud point and cetane index were added to the chapter. Existing correlations for flash point, pour point and refractive index were evaluated and revised. Detailed results of the correlations added to this chapter are provided in Documentation Report 2-98 available from Global Engineering Documents.

The work on this revision was primarily carried out by Research Assistant Paul M. Hinderliter with Research Aides Tony B. Hollobaugh and Douglas M. Ruhe under the direction of Project Director Thomas E. Daubert. The Technical Data Committee chapter coordinator was Dr. S. J. Kramer, Bechtel Corporation.

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Preface to the Ninth Edition

Significant additions and corrections were introduced in the ninth edition of Chapter 2. First, with the assistance of L. Hugo DeAngelis, Marathon Oil Company (retired in 2008), the new Procedure 2B1.3 – Average Boiling Points from Simulated Distillation Data (ASTM D2887) was added. This provides a better estimate of the average boiling point of a given petroleum fraction and minimizes the errors due to asymmetric boiling curves. Also extensive improvements were made to Procedure 2B7.1 – Flash Point of Petroleum Fractions, thanks to the extensive evaluations of the equations for closed cup and open cup carried out by Calvin F. Spencer, KBR.

Preface to the Tenth Edition

Various changes were made in the tenth edition of Chapter 2. Procedures 2B7.1 through 2B15.1 are concerned with *inspection properties* of the petroleum products (more generally, petroleum fractions), and thus they were grouped in a new Section 2C: Inspection Properties of Petroleum Fractions. The titles of Procedures 2B2.1 and 2B2.3 were corrected to emphasize that the main difference between the two procedures is the use of MeABP in 2B2.1 and Kinematic Viscosity at (100, 210) °F in 2B2.3 (along with SG for both). Finally, the primary ASTM method was adopted for the Cetane Index. There were also plans for revising the Smoke Point correlation, but the existing correlation was found to be sufficiently reliable.

As always, the revision of Chapter 2 was reviewed by API's Technical Data Committee. More extensive discussions were carried out with the chapter coordinators, Joel Glassett of BP, Homy Maerefat of CBI, and Howard Wilson of Phillips 66. In addition, Calvin F. Spencer, KBR, carried extensive evaluations of the Cetane Index correlations found in the literature.

Constantine (Costa) Tsionopoulos
Consultant
November 2013

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Chapter 2 – Characterization of Hydrocarbons

2-0 Introduction

(1999)

For correlational purposes, it is often necessary to designate the individual hydrocarbons in the various series by numerical parameters, which characterize them. The properties of methane, the smallest and the most spherical hydrocarbon, are well represented by the simple (two-parameter) corresponding states principle. But the molecules of larger hydrocarbons deviate from spherical symmetry, and thus we need to add to the corresponding states principle a third parameter as a measure of molecular size and shape. The most popular third parameter is the acentric factor (12, 13). The acentric factor is useful for correlating physical and thermodynamic properties and is defined as:

$$\omega = -\log p_r^* - 1.000 \quad (2-0.1)$$

Where:

- p_r^* = reduced vapor pressure, p^*/p_c .
- p^* = vapor pressure at $T = 0.7 T_c$, in pounds per square inch absolute.
- p_c = critical pressure, in pounds per square inch absolute.
- T = temperature, in degrees Rankine
- T_c = critical temperature, in degrees Rankine.

The acentric factor is used in hydrocarbon correlations in several chapters of this book. Accordingly, Procedure 2A1.1 is presented as a general method of estimation consistent with Procedure 5A1.19. Alternately if experimental vapor pressure data are available, the defining equation (2-0.1) should be used.

For mixtures of identifiable hydrocarbons, the acentric factor is given by the following equation:

$$\omega = \sum_{i=1}^n x_i \omega_i \quad (2-0.2)$$

Where:

- n = number of components in the mixture.
- x_i = mole fraction of component i .
- ω_i = acentric factor of component i .

This equation is an oversimplification, but it is quite satisfactory in most cases. No better substitute is currently available.

For hydrocarbon mixtures for which the composition is known, the pure-component physical properties and acentric factors adequately characterize the system. For more complex mixtures such as petroleum fractions, it is impractical and not always possible to analyze the entire mixture to define the concentration of all the components. These undefined mixtures are usually characterized by parameters that are derived from the normal inspection tests, an ASTM D86 or D1160 distillation, and the specific gravity of the mixture. Many characterization parameters have been proposed, but very few are generally useful.

Among the useful parameters are five different boiling points and the Watson (22) characterization factor, K . Each boiling point reduces to the normal boiling point for pure hydrocarbons and is significant for a different group of correlations. These five quantities are defined by the following equations (18):

Volume average boiling point:

$$VABP = \sum_{i=1}^n x_{vi} T_{bi} \quad (2-0.3)$$

Where:

x_{vi} = volume fraction of component i .

T_{bi} = normal boiling point of component i .

Either Fahrenheit or Rankine units may be used for the volume, molar, and weight average boiling points to give the same units for the average boiling point. Rankine units must be used for the cubic average boiling point, however. The *MABP* and *CABP* must be in the same units to calculate the mean average boiling point (both defined below).

Molar average boiling point:

$$MABP = \sum_{i=1}^n x_i T_{bi} \quad (2-0.4)$$

Where:

x_i = mole fraction of component i .

Weight average boiling point:

$$WABP = \sum_{i=1}^n x_{wi} T_{bi} \quad (2-0.5)$$

Where:

x_{wi} = weight fraction of component i .

Cubic average boiling point:

$$CABP = \left(\sum_{i=1}^n x_{vi} T_{bi}^{1/3} \right)^3 \quad (2-0.6)$$

Mean Average Boiling Point:

$$MeABP = \frac{MABP + CABP}{2} \quad (2-0.7)$$

In as much as the volume, molar and weight fractions are not known for undefined mixtures, the boiling points are conveniently correlated in an empirical plot (Figure 2B1.2) based on the ASTM D86 distillation curve. Analytical correlations developed by Zhou (26) are also included for use on a digital computer. For high molecular-weight fractions which are vacuum distilled by ASTM Method D1160, the results must be converted to an ASTM D86 basis before obtaining a boiling point (see Chapter 3).

The **Watson characterization factor, K** , is defined by the equation:

$$K = \frac{(MeABP)^{1/3}}{SG \ 60 \ ^\circ F / 60 \ ^\circ F} \quad (2-0.8)$$

where *MeABP* must be in degrees Rankine and *SG* is the relative density at 60 °F relative to water at 60 °F.