New Equation of State for Ethylene Covering the Fluid Region for Temperatures From the Melting Line to 450 K at Pressures up to 300 MPa

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This work reviews the available data on thermodynamic properties of ethylene and presents a new equation of state in the form of a fundamental equation explicit in the Helmholtz energy. The functional form of the residual part of the Helmholtz energy was developed by using state-of-the-art linear optimization strategies. The new equation of state contains 35 coefficients which were fitted to selected data of the following properties: (a) thermal properties of the single phase ($p\rho T$) and (b) of the liquid–vapor saturation curve (p_s, ρ', ρ'') including the Maxwell criterion, (c) speed of sound w of the single-phase region and the saturated vapor and liquid, (d) isochoric heat capacity c_v, (e) specific isobaric heat capacity c_p of the single-phase region and of the saturated liquid, and (f) second and third thermal virial coefficients B and C. For the density, the estimated uncertainty of the new equation of state is less than ±0.02% for pressures up to 12 MPa and temperatures up to 340 K with the exception of the critical region. Outside the range mentioned above, the estimated uncertainty is less than ±0.03% for pressures up to 30 MPa and temperatures between 235 and 350 K. The new formulation shows reasonable extrapolation behavior up to very high pressures and temperatures. Independent equations for the vapor pressure, for the pressure on the sublimation and melting curve, and for the saturated-liquid and saturated-vapor densities are also included. Tables for the thermodynamic properties of ethylene from 104 to 450 K for pressures up to 300 MPa are given in the appendix. © *2001 American Institute of Physics.* [S0047-2689(00)00405-0]

Key words: correlation; data evaluation; equation of state; ethylene; fundamental equation; melting line; property tables; sublimation line; thermal and caloric properties; vapor–liquid coexistence curve.

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Nomenclature

a,d,n,t	adjustable parameters
B	second viral coefficient
C	third viral coefficient
c_p	isobaric heat capacity
c_v	isochoric heat capacity
a	specific Helmholtz energy
g	specific Gibbs energy
h	specific enthalpy
i,j	serial numbers
I,J	maximum value of the serial numbers i,j,k,l
M	number of data, molar mass
p	pressure
R	specific gas constant
s	specific entropy
T	thermodynamic temperature, ITS-90
u	specific internal energy
v	specific volume
w	speed of sound
x,y	independent variables
y	any thermodynamic property
z	any thermodynamic property, compression factor

Greek

α	dimensionless Helmholtz energy ($\alpha=a/RT$)
β, γ, ε, η	adjustable parameters
δ	reduced density ($\delta=\rho/\rho_c$)
δ_T	isothermal throttling coefficient
Δ	difference in any quantity
∂	partial differential
ϑ	reduced temperature ($\vartheta=1-T/T_c$)
μ	Joule–Thomson coefficient
ρ	density
σ	variance, uncertainty
τ	inverse reduced temperature ($\tau=T_c/T$)
χ^2	weighted sum of squares

Superscripts

o	ideal-gas property
r	residual
$'$	saturated-liquid state
$''$	saturated-vapor state
	denotes a vector

Subscripts

c	at the critical point
calc	calculated
cor	corrected
exp	experimental
i,j	indices
m	denotes the melting pressure
p	isobaric
s	denotes states at saturation
sub	denotes the sublimation pressure
σ	along the saturated-liquid line
t	at the triple point
t,2	at the solid–solid–liquid triple point
v	denotes vaporization
v	isochoric
wt	weighting
0	in the reference state

Physical Constants for Ethylene

M	molar mass $M=(28.053\,16\pm0.001)\ \mathrm{g\,mol^{-1}}$, see Copler (1997)
R_m	universal gas constant

	$R_m = (8.3145\,1 \pm 0.000\,210)^a$ J mol^{-1} K^{-1}, see Cohen and Taylor (1988)
R	specific gas constant $R = R_m/M = 0.296\,384\,079$ kJ kg^{-1} K^{-1}
T_c	critical temperature $T_c = (282.35 \pm 0.010)$ K, see Sec. 2.2
p_c	critical pressure $p_c = (5.0418 \pm 0.0011)$ MPa, see Sec. 2.2
ρ_c	critical density $\rho_c = (214.24 \pm 0.1)$ kg m^{-3}, see Sec. 2.2
T_t	triple-point temperature $T_t = (103.989 \pm 0.003)$ K, see Sec. 2.1
p_t	triple-point pressure $p_t = (122.65 \pm 3)$ Pa, see Sec. 2.1
$T_{t,2}$	triple-point temperature (solid–solid–liquid) $T_{t,2} = (110.369 \pm 0.1)$ K, see Sec. 2.1
$p_{t,2}$	triple-point pressure (solid–solid–liquid) $p_{t,2} = (46.8 \pm 0.6)$ MPa, see Sec. 2.1
T_0	reference temperature $T_0 = 298.15$ K
p_0	reference pressure $p_0 = 0.101\,325$ MPa
h_0^o	reference enthalpy in the ideal-gas state at T_0 $h_0^o = 0$ kJ kg^{-1}
s_0^o	reference entropy in the ideal-gas state at T_0, p_0 $s_0^o = 0$ kJ (kg K)$^{-1}$

1. Introduction

1.1. Background

Ethylene, as the simplest form of unsaturated hydrocarbons, is one of the most important materials used in chemical industries. Accurate knowledge of thermodynamic properties of ethylene is of substantial importance for many technological applications. Within the past 50 years numerous experimental and theoretical investigations on the thermodynamic properties of ethylene have been carried out. To condense information on the thermodynamic properties, in 1972 and 1988 the International Union of Pure and Applied Chemistry (IUPAC) published monographs [Angus *et al.* (1972); Jacobsen *et al.* (1988)] which presented extensive tables of its thermal and caloric properties.

Nevertheless, Jacobsen *et al.* (1988) already pointed out the shortcomings of today's internationally accepted standard equation when discussing possible improvements of the 1988 IUPAC tables. Although the large amount of available data comes near to that for water, the inadequacies of the IUPAC equation were mainly caused by a poor data situation in several parts of the fluid region. During the last few years this situation has remarkably improved because highly accurate experimental information has become available for large parts of the fluid region. Even though many of the older data sets can be regarded as obsolete today, all of the available data are discussed in this article to give a complete overview.

In addition to the increased quality of the experimental data, correlation techniques have significantly improved during the last decade. Sophisticated multiproperty fitting procedures [Schmidt and Wagner (1985); Setzmann and Wagner (1991)] and new optimization procedures [Setzmann and Wagner (1989)] have resulted in a new basis for the development of empirical equations of state.

1.2. Prior Equations of State

Numerous correlation equations for thermodynamic properties of ethylene can be found in the literature, but most of them cover only a limited part of the fluid region and do not meet present demands on accuracy. In most cases, they were developed only to represent experimental results from one publication. Table 1 summarizes the equations of state for ethylene which have been developed since 1972 as far as they are of interest due to theoretical features or because of widespread use in industrial applications. When Angus *et al.* (1972) prepared the IUPAC tables for ethylene, no equation of state was available which was valid in the whole fluid region. To cover the whole fluid region, two different equations were used to construct the tables. To represent the high-pressure region the equation of Featherstone and Gibson (1972) was selected for the calculation of the tables, while Angus *et al.* themselves fitted a virial equation to different sets of $p\rho T$ data to represent the low-pressure region. Nowadays, these equations are only of interest from a historic point of view. In 1975, Bender published the first equation of state for ethylene which was established considering the so-called "Maxwell criterion" and which could be used directly to calculate consistent data of thermal properties under saturation conditions. The equations of Thomas and Zander (1980) and Sychev *et al.* (1987) are of importance because of their widespread use in certain countries. The equation of Jahangiri *et al.* (1986) forms the basis of the second publication of IUPAC tables for ethylene [Jacobsen *et al.*, (1988)] and is nowadays used in most applications that demand highly accurate property data of ethylene. Nevertheless, a critical re-evaluation of the data sets used in the development of the equation of state which was performed by Jacobsen *et al.* (1988) led to critical conclusions concerning limitations on accuracy and applicability of the equation.

In order to describe the critical region of ethylene accurately, several nonanalytic equations of state have been developed in the last 20 years. All of them are valid only in a narrow temperature and pressure range. State-of-the-art scaling techniques, which allow the extension of the range of validity [crossover models, see, e.g., Albright *et al.* (1986)], have not yet been used for ethylene. The most common nonanalytic equation is the revised-and-extended-scaling equation of Levelt Sengers *et al.* (1984), which was used by Jacobsen *et al.* (1988) within the critical region to calculate the IUPAC tables for ethylene.

[a]With a standard deviation of $\pm 0.000\,070$ J mol^{-1} K^{-1} given by Cohen and Taylor, the uncertainty for R_m corresponds to $\pm 3\sigma$. The more recent value for R_m by Mohr and Taylor (1999) became available after this work was completed.

TABLE 1. Selected equations of state for ethylene

Authors	Year	Temperature range/K	Pressure range/MPa	Structure of the equation	Number of coefficients	Data used in the correlation
Angus *et al.*	1972	273–423	0–4.7	Virial	15	$p\rho T$
Featherstone and Gibson	1972	223–423	4.7–300	Polynomial	32	$p\rho T$
Bender	1975	143–423	0–50	Extended BWR[a]	20	$p\rho T, p_s\rho'\rho''$
Hastings *et al.*	1980	279–303	4.3–8.6	Revised and extended scaling	13	$p\rho T$
Jacobsen and Jahangiri	1980	281–293	4.9–6.9[b]	Simple scaling	4	$p\rho T, c_v$
Thomas and Zander	1980	243–353	0–25	Extended BWR[a]	13+13+13[c]	$p\rho T$
McCarty and Jacobsen	1981	104–450	0–40	Extended BWR[a]	32	$p\rho T, p_s\rho'\rho'', c_v, c_\sigma, w$
Nehzat *et al.*	1983	280–284	4.7–5.8[d]	Nonanalytic	16	$p\rho T$
Levelt Sengers *et al.*	1984	279–300	4.7–8.6[e]	Revised and extended scaling	11	$p\rho T, w$
Jahangiri *et al.*	1986	104–450	0–260	Optimized[f]	41	$p\rho T, p_s\rho'\rho'', c_v, w, B$
Sychev *et al.*	1987	110–600	0–300	Polynomial	52	$p\rho T, p_s\rho'\rho''$[g]

[a]Benedict–Webb–Rubin [Benedict *et al.* (1940)]
[b]The equation is valid for densities between 148.7 and 277.7 kg m^{-3}.
[c]Three equations of state represent the fluid region, except states in the enlarged critical region and near the phase boundary.
[d]The equation is valid for densities between 126.2 and 308.6 kg m^{-3}.
[e]The equation is valid for densities between 161.3 and 294.6 kg m^{-3}.
[f]Mathematical structure optimized for the representation of the selected data using the stepwise regression analysis of Wagner (1974).
[g]Values of the following derivatives, calculated from $p\rho T$ data, were used additionally: $(\partial p/\partial \rho)_T$ and $(\partial p/\partial T)_\rho$.

All in all, each of the existing equations of state has several of the following disadvantages:

- State-of-the-art data for the thermodynamic properties of ethylene are not represented to within their experimental uncertainty.
- The range of validity is restricted to a narrow temperature or pressure range.
- Unreasonable behavior is observed in regions with a poor data situation.
- Data in the extended critical region are not represented to within their uncertainty.
- Extrapolation to temperatures and pressures outside the range of validity yields unreasonable results.
- The temperature values used do not correspond to the current International Temperature Scale of 1990 (ITS-90).

It is the purpose of this article to present an equation of state for ethylene which overcomes the disadvantages of the existing correlations. The new equation describes the thermodynamic surface of ethylene in the range covered by reliable experimental data within the uncertainties of the best data. The equation was developed using state-of-the-art fitting and optimization procedures [Setzmann and Wagner (1989)], while special attention has been paid to the extrapolation behavior as outlined by Span and Wagner (1997).

2. Phase Equilibria of Ethylene

An accurate description of phase equilibria by auxiliary equations is an important precondition for the development of a wide-range equation of state and it is also helpful for users who are only interested in phase equilibria. To provide an experimental basis for such equations, all available information on the triple points, the critical point, the melting pressure, the sublimation pressure, the vapor pressure, the densities of the saturated-liquid and saturated-vapor, and on caloric properties on the liquid–vapor-phase boundary, have been reviewed. Simple correlation equations are given for the temperature dependency of the thermal properties.

In order to condense the description of the data situation, the characteristic information on the single data sets is summarized in the tables for the corresponding property. The data sets have been divided into three groups allowing for the critically assessed uncertainty of the data, size of the data set, and covered temperature range. In addition, attention is paid to the data situation for the respective property. Group 1 contains the data sets suitable for the development of the corresponding correlation equation. Group 2 contains data sets suitable for comparisons. Compared with group 1 data, the quality of group 2 data deteriorates at least under one of the three aspects mentioned above. Group 3 contains very small data sets and data sets with rather high uncertainty. Further consideration of these data is not reasonable on the level of accuracy aspired to here. Nevertheless, this does not mean a devaluation of these data sets — the whole ranking is influenced more by the quality in relation to the best available reference data than by an absolute level of uncertainty; for other purposes group 3 data sets may be very useful.

Since the correlation equations and all temperature values in this paper correspond to the ITS-90 temperature scale [Preston-Thomas (1990); Preston-Thomas *et al.* (1990)], the temperature values of the available data, based on older temperature scales, were converted to ITS-90. The conversion from the IPTS-68 temperature scale to ITS-90 temperatures was carried out based on the equations given by Rusby (1991). The revised conversion equations by Rusby *et al.* (1994), which cover the range $903.15\,\mathrm{K} \leq T \leq 1397.15\,\mathrm{K}$, were not used, since no data are available in the applicable temperature range for ethylene. Data corresponding to the IPTS-48 temperature scale were converted to the IPTS-68 according to the procedure given by Bedford and Kirby (1969). Where values calculated from older equations are

TABLE 2. Available data for the triple point of ethylene

Authors	Year	T_t/K	p_t/Pa
Eucken and Hauck	1928	103.62	
Kistiakowsky *et al.*	1935	103.67±0.1	
Egan and Kemp	1937	103.967±0.05	120.92
Clusius and Weigand	1940	103.987±0.03	133
Tickner and Lossing	1951	104.02±0.3	
Davies *et al.*	1967	103.96	
Diller	1976	103.9	
Bigeleisen *et al.*	1977		121.32±1.2
Gammon	1978	103.997±0.003	
Ligthart *et al.*	1979	103.999±0.01	
Lobo and Staveley	1979	104.021	125±7
Straty	1980	103.9965±0.003	
Staveley *et al.*	1981	104.00	122.6±1
Nowak *et al.*	1996b	103.989±0.003	122.0±3

plotted for comparison, the necessary temperature conversions were considered as well.

The algorithm used for the conversion from the IPTS-68 to the ITS-90 scale causes an additional uncertainty of ± 1.5 mK for temperatures below 273.15 K and ±1 mK for temperatures above 273.15 K. This additional uncertainty is *not* considered in the uncertainties given in the tables of this section, since these uncertainties were mainly used for consistency tests between data of different authors. In this case, the uncertainty in the absolute temperature, which is influenced by the uncertainty of the conversion, is less important. The comparison between two very similar temperature values is not influenced by the uncertainty of the conversion if both temperatures are converted with the same procedure.

2.1. Triple Points

Temperature and pressure of the vapor–liquid–solid triple point of ethylene have been determined by numerous authors. Table 2 shows selected data for the triple-point properties of ethylene. After a comprehensive review of the existing data and tests regarding their consistency with both vapor-pressure and sublimation-pressure measurements, we have chosen the following values:

$$T_t = (103.989 \pm 0.003)\ \text{K}, \tag{2.1}$$

$$P_t = (122.65 \pm 3)\ \text{Pa}. \tag{2.2}$$

Experimental data of the density of the saturated liquid and the saturated vapor at the triple point are not available. However, these properties can accurately be determined by extrapolation of the saturated-liquid and saturated-vapor equations given in Secs. 2.6 and 2.7. Evaluation of the corresponding correlations yields

$$\rho'(T_t) = (654.62 \pm 0.1)\ \text{kg m}^{-3}, \tag{2.3}$$

$$\rho''(T_t) = (0.003\,969 \pm 0.000\,010)\ \text{kg m}^{-3}. \tag{2.4}$$

Moreover, a second triple point exists for ethylene. Trappeniers and Ligthart (1973) were the first to describe an equilibrium of two solid phases with the liquid. Temperature and pressure of this solid–solid–liquid triple point were determined by Ligthart *et al.* (1979):

$$T_{t,2} = (110.369 \pm 0.1)\ \text{K}, \tag{2.5}$$

$$p_{t,2} = (46.8 \pm 0.6)\ \text{MPa}. \tag{2.6}$$

2.2. Critical Point

Table 3 gives a survey of values for the critical parameters of ethylene found in the literature. Differences in the critical pressure can, in most cases, be explained by the variation of the vapor pressure with the assumed critical temperature. In some cases they result from a pollution of the specimen that was not detected at the time of the measurements.

The critical parameters published by Nowak *et al.* (1996b) were determined from their accurate measurements of vapor pressures and saturated-vapor and saturated-liquid densities. These data are consistent with the highly accurate density measurements in the homogeneous region, published by Nowak *et al.* (1996a). The evaluation of Nowak *et al.* (1996b) was tested under different aspects. No indication for any kind of error or inconsistency became obvious. Thus, we selected the values

$$T_c = (282.35 \pm 0.010)\ \text{K}, \tag{2.7}$$

$$p_c = (5.0418 \pm 0.0011)\ \text{MPa}, \tag{2.8}$$

$$\rho_c = (214.24 \pm 0.10)\ \text{kg m}^{-3}. \tag{2.9}$$

2.3. Melting Pressure

Table 4 summarizes the available data sets for the melting pressure of ethylene. Additionally, the publication of Reeves *et al.* (1964) deals with the locus of the equilibrium curve of the two solid phases. The existence of two solid phases was unrecognized by Reeves *et al.* but strongly supported by the work of Ligthart *et al.* (1979). The melting pressure in the temperature interval between the triple points of ethylene was determined by Straty (1980) with high accuracy. The

TABLE 3. Available data for the critical point of ethylene. Uncertainties are given where the original articles contain such estimates

Authors	Year	Method	T_c/K	p_c/MPa	ρ_c/(kg m^{-3})
van der Waals	1880	a	282.35	5.88	
Cailletet	1882	a	286.14		
Sarrau	1882	b	283.84	4.408	148
Dewar	1884	a	283.44	5.17	
Cailletet and Mathias	1886	a	285.64		210
Olszewski	1895	a	283.14	5.17	
Villard	1897	a	283.14		
Cardoso	1912	a	282.66±0.1	5.132±0.01	
Cardoso and Arni	1912	a	282.644±0.1	5.132±0.01	
Maass and Wright	1921	a	283.04±0.2		
Britton	1929	a	282.09	5.27	
Cawood and Patterson	1933	b	282.49	5.14	
Maass and Geddes	1937	a	282.644±0.01	5.064±0.001	206.3
McIntosh and Maass	1938	a	282.644		
Dacey *et al.*	1939	b		5.073	209±11
McIntosh *et al.*	1939	b	283.04±0.01	5.117±0.001	227
Meissner and Redding	1942	c	283.99	4.945	217.47
Kay	1948	a	282.394	5.072	
Lambert *et al.*	1949	c	282.84	5.16	
Kobe and Lynn	1953	c	282.344	5.066	227
Whiteway and Mason	1953	b	282.404±0.01		209.8±0.7
Dick and Hedley	1956	c	282.649	5.06	219.78
Kudchadker *et al.*	1968	c	282.354	5.0318	217.47
Angus *et al.*	1972	c	282.648±0.25	5.076±0.02	218±2
Moldover	1974	a	282.342±0.004	5.0390	214.6±0.6
Diller	1976	c	282.298		213.21
Douslin and Harrison	1976	b	282.348±0.0105	5.04197±0.0002	214.19±0.2
Trappeniers *et al.*	1976	b	282.448±0.05		215.16±1.3
Golovskii and Tsymarnii	1977	b	283.05		211
Hastings and Levelt Sengers	1977	d	282.282	5.0336±0.0048	
Nehzat	1978	d	282.3480±0.0005	5.04197±0.00014	214.19±0.03
Hastings *et al.*	1980	d	282.3430±0.0017	5.0403±0.0002	214.164±0.025
Thomas and Zander	1980	a	282.368±0.02		
Barkan	1981	c	282.348±0.02	5.041±0.0025	214.2±0.64
Nehzat *et al.*	1983	d	282.3480±0.0105	5.04197±0.0026	214.19±0.17
Brunner	1985	a	282.328±0.1	5.055±0.005	
Mohan *et al.*	1986	c	282.348	5.042	214.33
Simmrock *et al.*	1986	c	282.798±0.31		220.5±6.2
Smith and Srivastava	1986	c	282.341		214.1
van Poolen *et al.*	1986	d			214.13±0.03
de Bruyn and Balzarini	1987	b	282.3728±0.001		214.86±0.2
Goldstein *et al.*	1987	d	282.378		
Pestak *et al.*	1987	d	282.3768	5.040	215.0
Jacobsen *et al.*	1988	c	282.342±0.004	5.0408±0.0008	214.2±0.4
Yaws *et al.*	1989	c	282.797	5.11	220.55
Singh and Pitzer	1990	b	282.348	5.0345	214.1
Nowak *et al.*	1996b	b	282.350±0.010	5.0418±0.0011	214.24±0.10
Shimanskaya *et al.*	1996	d	282.384±0.009		

Methods used to determine the critical-point parameters:
(a) disappearance of the meniscus;
(b) evaluation of measurements of thermal or optical properties;
(c) evaluation of published data; and
(d) results from fits to power laws respective scaled equations of state for the description of the critical region

TABLE 4. Summary of the data sets for the melting pressure of ethylene. Uncertainties are given where the original articles contain such estimates. Uncertainty values given in parentheses were estimated by ourselves

Authors	Year	No. of data	Temperature range/K	ΔT	Δp	Group
Clusius and Weigand	1940	13	103–105	0.02 K	5kPa	3
Ligthart *et al.*	1979	11	104–110.2	0.003 K	(0.5%)	2
		13	110.6–141	0.003 K	(0.1%)	1
Straty	1980	16	104–109	(0.01 K)	(0.15%)	1

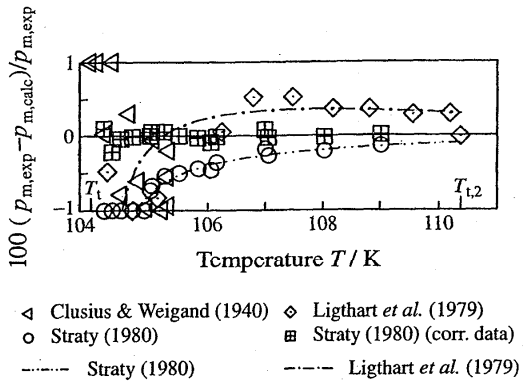

FIG. 1. Percentage deviations of experimental melting-pressure data from values calculated from the melting-pressure equation valid in the temperature interval $T_t = 103.989\ \mathrm{K} \leq T < T_{t,2} = 110.369\ \mathrm{K}$, Eq. (2.10).

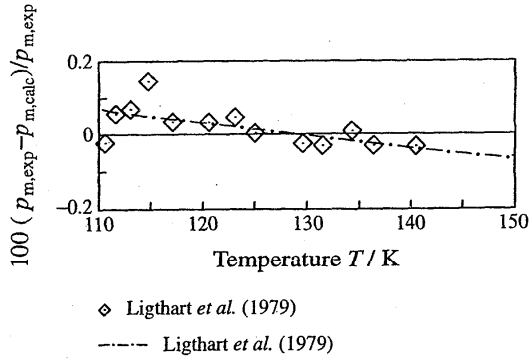

FIG. 2. Percentage deviation of experimental melting-pressure data from values calculated from the melting-pressure equation valid for temperatures $T \geq T_{t,2} = 110.369$ K, Eq. (2.11).

triple-point temperature which results from these measurements differs by +7.5 mK from the one given in Eq. (2.1). Straty did not publish details on the uncertainty of his temperature measurements. However, he gave hints on systematic deviations of vapor-pressure measurements performed with his apparatus from the results of Douslin and Harrison (1976), which can be explained by an error of ±10 mK in temperature. Thus, the temperature values of the melting-pressure data of Straty have been corrected by −7.5 mK to cause useful accordance with the more precise values for T_t and p_t given in Eqs. (2.1) and (2.2), respectively.

The corrected data together with the values of temperature and pressure of the second triple point [see Eqs. (2.5) and (2.6)] were used to establish a simple correlation equation for the melting pressure in the temperature interval $T_t = 103.989\ \mathrm{K} \leq T < 110.369\ \mathrm{K} = T_{t,2}$:

$$\frac{p_m}{p_t} = 1 + a_1\left[\left(\frac{T}{T_t}\right)^{2.045} - 1\right], \tag{2.10}$$

with $T_t = 103.989$ K, $p_t = 122.65$ Pa, and $a_1 = 2\,947\,001.84$. The equation is constrained to the triple-point pressure by its functional form. Calculation of $p(T_{t,2})$ from Eq. (2.10) gives a value that differs from Eq. (2.6) by +0.01%. Figure 1 compares all available melting pressure data in this temperature interval with values calculated from Eq. (2.10). The dash-dotted lines correspond to values calculated from the melting-pressure equations of Straty (1980) and of Ligthart *et al.* (1979).

The only experimental results for the melting pressure at temperatures above $T_{t,2}$ were published by Ligthart *et al.* (1979). These data were used to establish the melting-pressure equation for temperatures $T \geq 110.369$ K:

$$\frac{p_m}{p_{t,2}} = 1 + a_1\left[\left(\frac{T}{T_{t,2}}\right)^{1.089} - 1\right], \tag{2.11}$$

with $T_{t,2} = 110.369$ K, $p_{t,2} = 46.8$ MPa, and $a_1 = 6.826\,934\,21$. Similar to Eq. (2.10), Eq. (2.11) is constrained to the pressure of the solid–solid–liquid triple-point by its functional form. The simple form of the equation should ensure reasonable extrapolation to temperatures beyond the range covered by experimental data.

Figure 2 compares the melting-pressure data of Ligthart *et al.* (1979) with values calculated from Eq. (2.11). The dash-dotted line corresponds to values calculated from the melting-pressure equation of Ligthart *et al.* (1979). Both equations represent the experimental data to within their uncertainties. Within the scatter of the data, the equation of Ligthart *et al.* seems to fit the majority of the data better than Eq. (2.11). However, it fails to represent $p_{t,2}$, which is known with rather high accuracy.

TABLE 5. Summary of the data sets for the sublimation pressure of ethylene. Uncertainties are given where the original articles contain such estimates

Authors	Year	No. of data	Temperature range/K	ΔT	Δp	Group
Tickner and Lossing	1951	9	79–103	0.3 K		1–2[a]
Liang	1952	3	77–90			3
Lister and McDonald	1955	16	77–90			1–2[a]
Bigeleisen *et al.*	1977	48	92–103.9	0.05 K	2.7 Pa	1
Menaucourt	1982	15	77–103	0.05 K	5%	1–2[a]

[a]Group 1 for $T < 89$ K, group 2 for $T \geq 89$ K.

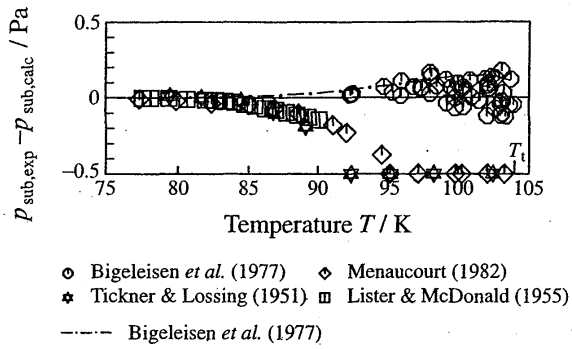

FIG. 3. Absolute deviations of experimental data for the sublimation pressure assigned to groups 1 and 2 from values calculated from the sublimation-pressure equation, Eq. (2.12).

2.4. Sublimation Pressure

For the pressure on the sublimation curve of ethylene, five publications are available, as listed in Table 5. Both the data of Bigeleisen *et al.* (1977) and, in the temperature interval from 77 to 87 K, the data of Menaucourt (1982) were used to determine the parameters of the new correlation equation for the sublimation pressure:

$$\ln\left(\frac{p_{sub}}{p_t}\right)=a_1\left(\frac{T_t}{T}-1\right), \tag{2.12}$$

with $T_t=103.989$ K, $p_t=122.65$ Pa, and $a_1=-22.450\,366\,6$. Equation (2.12) is constrained to the triple-point pressure by its functional form.

Figure 3 compares the group 1 and 2 data with values calculated from Eq. (2.12). Additionally, values calculated from the sublimation-pressure equation of Bigeleisen *et al.* (1977) are represented by a dash-dotted line. The absolute deviations in sublimation pressure shown in Fig. 3 indicate good agreement between both correlation equations, which results from a very similar mathematical structure. All group 1 data are reproduced by Eq. (2.12) with deviations of less than ±0.2 Pa. Thus, Eq. (2.12) represents the available experimental data for the sublimation-pressure curve to within their experimental uncertainties.

2.5. Vapor Pressure

Table 6 summarizes the 42 available data sets for the vapor pressure of ethylene. The very accurate data set of Nowak *et al.* (1996b) describes the whole vapor-pressure curve from the triple-point temperature up to the critical temperature with an uncertainty which ranges from ±0.007% above 250 K to ±0.1% at 145 K. Below 145 K, the combined uncertainty of these data corresponds to less than ±30 Pa. Reference data for the vapor pressure, which confirm each other within ±0.015% in pressure, were assigned to group 1. Group 2 is restricted to data that deviate by less than ±0.2% from the group 1 data in general. Most of the older data sets had to be placed in group 3 because of their large scatter or because of large systematic deviations from the group 1 data. However, with a total of four group 1 and nine group 2 data sets, the data situation is extremely good for the vapor pressure of ethylene.

The vapor-pressure equation established by Nowak *et al.* (1996b) represents the group 1 data without any systematic deviation and was thus adopted for this work:

$$\ln\left(\frac{p_s}{p_c}\right)=\frac{T_c}{T}(a_1\vartheta+a_2\vartheta^{1.5}+a_3\vartheta^{2.5}+a_4\vartheta^{3}+a_5\vartheta^{4.5}), \tag{2.13}$$

with $\vartheta=(1-T/T_c)$, $T_c=282.35$ K, $p_c=5.0418$ MPa, $a_1=-6.390\,574\,1$, $a_2=1.406\,033\,8$, $a_3=-1.658\,992\,3$, $a_4=1.027\,802\,8$, and $a_5=-2.507\,171\,6$.

In Fig. 4, the group 1 and group 2 data are compared with values calculated from Eq. (2.13). The upper diagram of Fig. 4 is split up into two parts. On the left, absolute deviations are shown for temperatures below 140 K; on the right, percentage deviations are given for higher temperatures. In the lower diagram of Fig. 4, selected data for temperatures above 278 K are presented in higher resolution. This plot shows the excellent agreement between the group 1 data in the critical region and values calculated from Eq. (2.13). The dash-dotted line corresponds to values calculated from the IUPAC vapor-pressure equation [Jacobsen *et al.* (1988)], which was originally developed by Jahangiri *et al.* (1986).

2.6. Saturated-Liquid Density

Twenty-one data sets for the saturated-liquid density are available in the literature. Information on these experimental results is summarized in Table 7. Only the data of Nowak *et al.* (1996b), with a typical uncertainty of ±0.015%, were assigned to group 1. Group 2 is restricted to data sets that deviate by less than ±0.1% from the group 1 data in general. Other data sets with large and systematic deviations were assigned to group 3.

Based on a critical assessment of previously published correlation equations, the saturated-liquid density equation developed by Nowak *et al.* (1996b) was adopted for this work:

$$\ln\left(\frac{\rho'}{\rho_c}\right)=a_1\vartheta^{0.343}+a_2\vartheta^{3/6}+a_3\vartheta^{8/6}+a_4\vartheta^{12/6}, \tag{2.14}$$

with $\vartheta=(1-T/T_c)$, $T_c=282.35$ K, $\rho_c=214.24$ kg m^{-3}, $a_1=1.867\,307\,9$, $a_2=-0.615\,338\,92$, $a_3=-0.058\,973\,772$, and $a_4=0.107\,447\,20$.

Figure 5 shows a comparison between values calculated from Eq. (2.14) and those experimental data which were assigned to groups 1 and 2. The dash-dotted line corresponds to values calculated from the IUPAC saturated liquid density equation [Jacobsen *et al.* (1988)]. While Eq. (2.14) gives an excellent representation of all available data to within their experimental uncertainties, the equation of Jacobsen *et al.* cannot represent the most accurate data for the saturated-liquid density.

TABLE 6. Summary of the data sets for the vapor pressure of ethylene. Uncertainties are given where the original articles contain such estimates

Authors	Year	No. of data	Temperature range/K	ΔT	Δp	Group
Olszewski	1895	7	123–151			3
Villard	1897	10	169–282			3
Burrell and Robertson	1915	16	113–169	0.04 K		3
Henning and Stock	1921	4	131–163	0.02 K	13 Pa	3
Stock *et al.*	1921	32	132–163			3
Crommelin and Watts	1927a	10	203–281	0.02 K	0.025%	3
Britton	1929	24	168–277			3
Egan and Kemp	1937	11	123–170	0.05 K	3 kPa	3
Lamb and Roper	1940	6	147–173	0.01 K	13 Pa	3
Volová	1940	9	127–253	0.2 K	50 kPa	3
Michels and Wassenaar	1950	30	149–281	0.0004 K	0.1 kPa	2
Tickner and Lossing	1951	11[a]	105–139	0.3 K		3
Clark and Din	1953	14	140–170			3
Dick and Hedley	1956	10	273–298			3
Pavlovich and Voinov	1966	13	247–281	0.01 K		3
Ishida and Bigeleisen	1968	75	113–181		13 Pa	3
Golovskii *et al.*	1969	6	205–250	0.08 K	16 kPa	3
Vashchenko *et al.*	1971	37	173–281			3
Nagahama *et al.*	1974	2	231–253	0.05 K	20 kPa	3
Mollerup	1975	3	223–263	0.01 K	0.1%	3
Douslin and Harrison	1976	18	238–282	0.0005 K	4 Pa	1
Bigeleisen *et al.*	1977	80	105–176	0.05 K	3 Pa	2–3[b]
Calado and Soares	1977a	2	104–116			3
Calado and Soares	1977b	1	161			2
Grauso *et al.*	1977	2	200–260	0.01 K	0.02%	3
Hastings and Levelt Sengers	1977	36	219–282	0.0005 K	0.005%	1
Miller *et al.*	1977	5	150–190	0.02 K	1–5 kPa	3
Calado *et al.*	1978	1	116			3
Gammon	1978	28	104–282	0.005 K	[c]	2
Hastings *et al.*	1980	68	219–282	0.001 K	0.005%	1
Straty	1980	27	200–282		0.015%	2
Thompson and Miller	1980	2	228			3
Gasem *et al.*	1981	10	120–200	0.02 K	0.1 kPa	3
Bae *et al.*	1982	2	263–273	0.03 K	0.1%	3
Barclay *et al.*	1982	7	198–278			2
Calado *et al.*	1982	13	110–250	0.01 K	0.1%	2
Menaucourt	1982	12	104–119	0.05 K	5%	3
Calado *et al.*	1983	1	161			2
Bohn *et al.*	1986	6	104–223	[d]	[d]	3
Mohan *et al.*	1986	10	238–278	[d]	[d]	3
Zeck and Knapp	1986	14	238–273			2
Nowak *et al.*	1996b	63	104–282	0.0015 K[e]	0.004%	1

[a]Only four vapor pressure data published by Tickner and Lossing (1951), the remaining seven data points are displayed graphically. Values of these data were communicated to Angus by Lossing and published by Angus *et al.* (1972).
[b]Group 2 for $T<140$ K, Group 3 for $T\geqslant 140$ K.
[c]Accuracy of vapor pressure measurements: $\Delta p_s/p_s=(3\times10^{-5}+6\times10^{-7}p_s/\mathrm{MPa})^{0.5}$.
[d]Vapor pressure data derived from molecular dynamics. Founded estimates on uncertainties cannot be given.
[e]Value for $T\geqslant 250$ K. Uncertainty of temperature measurement at 104 K: 0.0026 K. Values in between can be interpolated linearily.

2.7. Saturated-Vapor Density

Table 8 summarizes the 14 available data sets for the saturated-vapor density of ethylene. Again, only the data set of Nowak *et al.* (1996b) could be assigned to group 1. The same criteria as for the saturated-liquid density were used to distinguish between group 2 and group 3 data.

After a critical assessment of previously published correlation equations, the saturated-vapor density equation established by Nowak *et al.* (1996b) was adopted for this work:

$$\ln\left(\frac{\rho''}{\rho_c}\right)=a_1\vartheta^{0.349}+a_2\vartheta^{4/6}+a_3\vartheta+a_4\vartheta^{14/6}+a_5\vartheta^{29/6}+a_6\vartheta^{56/6}, \tag{2.15}$$

with $\vartheta=(1-T/T_c)$, $T_c=282.35$ K, $\rho_c=214.24\,\mathrm{kg\,m^{-3}}$, $a_1=-1.903\,455\,6$, $a_2=-0.758\,379\,29$, $a_3=-3.771\,796\,9$, $a_4=-8.747\,858\,6$, $a_5=-23.885\,296$, and $a_6=-54.197\,979$.

Figure 6 shows a comparison between selected experimental data and values calculated from Eq. (2.15). The dash-

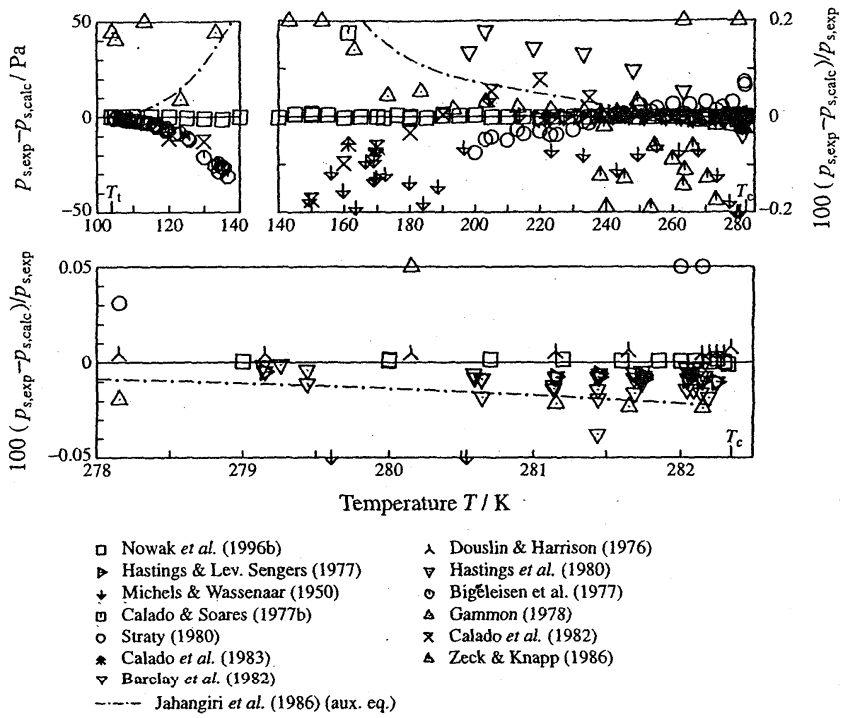

FIG. 4. Absolute and percentage deviations of experimental data for the vapor pressure assigned to groups 1 and 2 from values calculated from the vapor-pressure equation. Eq. (2.13).

TABLE 7. Summary of the data sets for the saturated-liquid density of ethylene. Uncertainties are given where the original articles contain such estimates

Authors	Year	No. of data	Temperature range/K	ΔT	$\Delta\rho'$	Group
Maass and McIntosh	1914	6	159–174			3
Maass and Wright	1921	8	164–204	0.2 K	0.05%	3
Mathias *et al.*	1927	15	128–281			3
Dick and Hedley	1956	10	273–298			3
Pavlovich and Voinov	1966	13	247–281	10 mK	0.2%	3
Menes *et al.*	1970	39	105–174	30 mK	0.01%	2
Vashchenko *et al.*	1971	52	163–281			3
Douslin and Harrison	1976	14	238–282	0.5 mK	0.03%–0.08%	3
Calado and Soares	1977a	1	104			2
Calado and Soares	1977b	1	161			2
Golovskii and Tsymarnii	1977	30	105–260		0.15%	3
Calado *et al.*	1978	1	116			3
Haynes	1978	7	105–200	20–30 mK	0.1%	2
Hastings *et al.*	1980	7	279–282	2–5 mK	0.03%	2
Thompson and Miller	1980	2	228			2
Calado *et al.*	1982	13	110–250	10 mK	0.1%	2–3[a]
Haynes	1985	8[b]	105–270	20–30 mK	0.1%	2
Bohn *et al.*	1986	6	104–223	[c]	[c]	3
Mohan *et al.*	1986	10	238–278	[c]	[c]	3
Pestak *et al.*	1987	35	276–282	0.1 mK	0.1%	3
Nowak *et al.*	1996b	69	104–282	1.5–3 mK	0.015%	1

[a]Group 2 for $T<200$ K, group 3 for $T\geqslant 200$ K.
[b]Additionally contains the seven data points already published by Haynes (1978).
[c]Saturated-liquid density data derived from molecular dynamics. Founded estimates on uncertainties cannot be given.

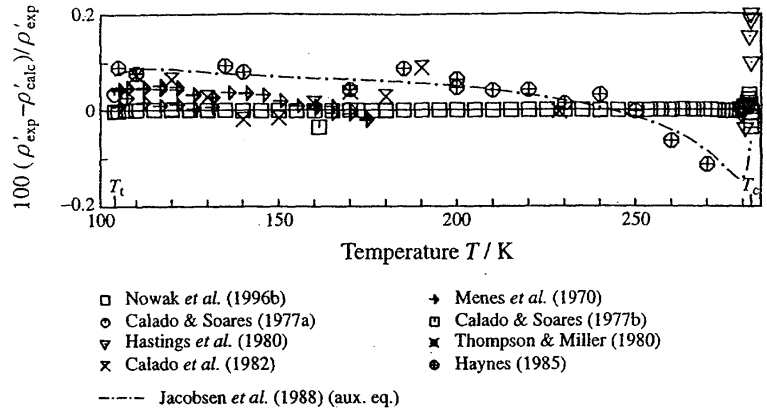

FIG. 5. Percentage deviations of experimental data for the saturated-liquid density assigned to groups 1 and 2 from values calculated from the saturated-liquid density equation, Eq. (2.14).

dotted line corresponds to values calculated from the IUPAC saturated-vapor density equation [Jacobsen *et al.* (1988)], which was originally developed by Jahangiri *et al.* (1986). Equation (2.15) represents the group 1 data to within their experimental uncertainty. The saturated-vapor density equation of Jahangiri *et al.* yields values which are significantly larger than the corresponding experimental results (especially for temperatures below 220 K). However, when the equation of Jahangiri *et al.* was developed, no reliable data for the saturated-vapor density at temperatures below 200 K were available at all.

2.8. Caloric Data on the Liquid–Vapor-Phase Boundary

No auxiliary equations have been developed for caloric properties on the liquid–vapor-phase boundary, but the group 1 data of the respective property have been taken into account in the development of the new equation of state.

2.8.1. Speed of Sound

Only two data sets are available for both the speed of sound in the saturated liquid and in the saturated vapor. The

TABLE 8. Summary of the data sets for the saturated-vapor density of ethylene. Uncertainties are given where the original articles contain such estimates

Authors	Year	No. of data	Temperature range/K	ΔT	$\Delta\rho''$	Group
Mathias *et al.*	1927	15	128–281			3
Dick and Hedley	1956	10	273–298			3
Pavlovich and Voinov	1966	13	247–281	10 mK	0.2%	3
Vashchenko *et al.*	1971	39	163–280			3
Douslin and Harrison	1976	14	238–282	0.5 mK	0.03%–0.08%	2
Calado and Soares	1977b	1	161			3
Hastings *et al.*	1980	2	281–282	50 mK	0.4%[a]	2
Levelt Sengers and Hastings	1981	6	219–263	1 mK	0.08%	2
van Poolen and Haynes	1981	20	104–282	[b]	[b]	3
Calado *et al.*	1982	11	130–250	10 mK	0.1%	3
van Poolen *et al.*	1984	21	104–282	[c]	[c]	3
Mohan *et al.*	1986	10	238–278	[d]	[d]	3
Pestak *et al.*	1987	35	276–282	0.1 mK	0.1%	3
Nowak *et al.*	1996b	60	104–282	1.5–3 mK	[e]	1

[a]Uncertainty of calculated saturated vapor densities determined from deviations from the scaled equation of state of Hastings *et al.* (1980).

[b]Values of saturated vapor densities calculated from a theoretical model which was fitted to saturated-liquid densities. No information concerning the saturated-liquid density data used in the fit is given in the original article. An assessment of uncertainties can only result from comparison with data from other sources.

[c]Values of saturated-vapor densities calculated from a theoretical model which was previously fitted to saturated-liquid densities calculated from the fundamental equation of Jahangiri (1986).

[d]Saturated-vapor density data derived from molecular dynamics. Founded estimates on uncertainties cannot be given.

[e]For $\rho < 10\ \mathrm{kg\,m^{-3}}$: $\Delta\rho'' = 0.0015\ \mathrm{kg\,m^{-3}}$; for $\rho \geq 10\ \mathrm{kg\,m^{-3}}$: $(\Delta\rho''/\rho'') = 0.015\%$.

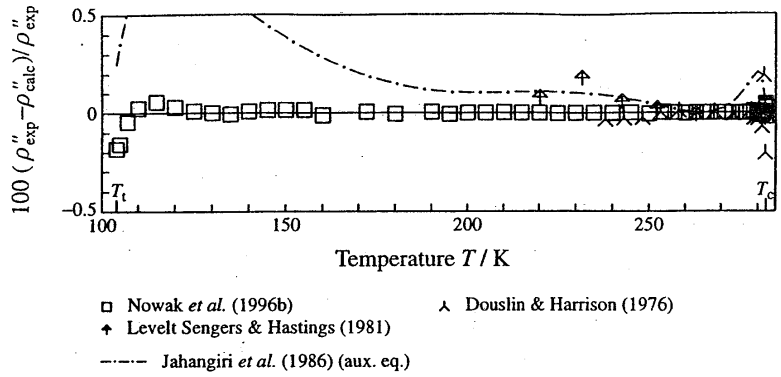

FIG. 6. Percentage deviations of selected experimental data for the saturated-vapor density from values calculated from the saturated-vapor density equatior Eq. (2.15)

corresponding information is summarized in Table 9. A graphical comparison showing all available data is given in Sec. 5.1.2.

The data sets of Gammon (1978) show high consistency with a scatter of less than ±0.1%. For the speed of sound on the saturated-vapor line and in the homogeneous gas region (see Sec. 3.2), Gammon provides an analysis of possible and known experimental errors, of reasonable corrections, and of their influence on the uncertainty of the data. No corresponding information is given for the speed of sound on the saturated-liquid line and in the homogeneous-liquid region. Based on our data analysis, the liquid data are believed to be less accurate. However, due to a lack of more reliable data, both the experimental results of Gammon on the saturated-liquid line and on the saturated-vapor line were selected for the development of the new equation of state. The data of Dregulyas and Stavtsev (1985), which show a large scatter of more than ±0.4%, were assigned to group 3.

2.8.2. Heat Capacities

Data for isobaric or isochoric heat capacities of either the saturated liquid or the saturated vapor are not available for ethylene. Only one data set exists for the heat capacity c_σ along the saturated-liquid line [Weber (1982)]. This data set represents c_σ for temperatures below 210 K with an uncertainty of ±2%. At temperatures above 210 K the data show a systematic scatter of about ±(1%–4%). This scatter is caused by the transformation of the measured values for the isochoric heat capacity in the two-phase region to values fo c_σ. The relation between both properties is given by

$$c_\sigma(T)=c_{v,\exp}-\frac{T_{\exp}}{\rho'}\times\left[\left(\frac{d\rho'}{dT}\right)\left(\frac{dp_s}{dT}\right)\frac{1}{\rho'}+\left(\frac{\rho'}{\rho_{\exp}}-1\right)\left(\frac{d^2p_s}{dT^2}\right)\right]. \quad (2.16$$

Weber calculated the required derivatives of thermal properties from the equation of state of McCarty and Jacobsei (1981). In order to consider the most recent information oı thermal properties at phase equilibrium, the values for th isochoric heat capacity published by Weber were re evaluated according to Eq. (2.16) using a preliminary equation of state developed in this work. The resulting c_σ data ar given in Table 10.

The obvious scatter of the data of Weber could be significantly reduced by the re-evaluation. For the data given ii Table 10 an uncertainty of ±1% is applicable for temperatures below 270 K. Above 270 K, the temperature value assigned to the original c_v data seem to be incorrect. Thus the systematic errors of the three points at $T>270$ K coul not be reduced significantly. An uncertainty of ±3% is assumed for these data. Table 11 summarizes the data sets fo the heat capacity along the saturated-liquid line. For botl data sets, a graphical comparison is given in Sec. 5.1.2.

TABLE 9. Summary of the data sets for the speed of sound on the liquid–vapor-phase boundary of ethylene. Given values of uncertainties result from an assessment of data in the homogeneous fluid region

Authors	Year	Property	No of data	Temperature range/K	ΔT	Δw	Group
Gammon	1978	w'	28	104–282	5 mK	0.4%	1
		w''	21	143–282	5 mK	0.4%	1
Dregulyas and Stavtsev	1985	w'	11	193–282	3 mK	1.5%	3
		w''	11	193–282	3 mK	1.5%	3

TABLE 10. Values for the heat capacity along the saturated-liquid line of ethylene determined in this work [re-evaluation of data for the isochoric heat capacity in the two-phase region determined by Weber (1982), see the text]

T/K	c_σ / kJ kg^{-1} K^{-1}	T/K	c_σ / kJ kg^{-1} K^{-1}	T/K	c_σ / kJ kg^{-1} K^{-1}
108.434	2.4517	163.657	2.3967	206.211	2.5382
109.323	2.4569	168.890	2.4047	210.778	2.5765
113.033	2.4395	172.412	2.4132	213.030	2.5831
117.585	2.4349	173.526	2.4288	220.100	2.6431
119.616	2.4367	178.242	2.4248	222.321	2.6761
122.098	2.4260	181.068	2.4298	228.576	2.7291
127.115	2.4117	186.403	2.4556	233.458	2.7958
129.866	2.4180	186.584	2.4513	236.920	2.8344
131.570	2.4072	189.600	2.4596	244.193	2.9955
135.992	2.4024	195.687	2.4816	255.465	3.2848
139.902	2.3978	197.927	2.4927	271.353	4.2958
149.703	2.3953	198.009	2.4935	274.552	4.8996
157.394	2.4003	198.783	2.5058	275.436	5.1501
159.384	2.3969	204.619	2.5179		

The relation between the dimensionless Helmholtz energy and c_σ contains the first derivative of the vapor pressure, see Table 26. Therefore, the inclusion of this property into the nonlinear fit in a direct way would have involved an interlocked relation to the Maxwell criterion according to Eq. (4.2). To avoid numerical problems, the specific heat capacity along the saturated-liquid line has been transformed into the specific isobaric heat capacity at saturated-liquid density according to the relation

$$c_p'(T)=c_\sigma(T)-\frac{T}{(\rho')^2}\frac{\left(\frac{\partial\rho}{\partial T}\right)_p\frac{\mathrm{d}p_s}{\mathrm{d}T}}{\left(\frac{\partial p}{\partial\rho}\right)_T}. \tag{2.17}$$

The contribution of the fraction in Eq. (2.17) is small except for temperatures close to T_c and can be determined from a preliminary equation of state with an estimated uncertainty of less than ±0.5%. Thus, for temperatures below 270 K the uncertainty caused by the transformation is less than ±0.05% in c_p' and is, therefore, negligible compared to the experimental uncertainty of the c_σ data.

2.8.3. Enthalpy of Vaporization

Data on the enthalpy of vaporization are given in 12 sources, which are listed in Table 12. The enthalpy of vaporization is related to the vapor pressure and to the densities of the saturated liquid and the saturated vapor by the equation of Clausius–Clapeyron. Since there are very accurate data for the thermal properties on the phase boundary, experimental values for the enthalpy of vaporization were not taken into account in the development of the new equation of state.

TABLE 11. Summary of the data sets for the heat capacity along the saturated-liquid line

Authors	Year	No. of data	Temperature range/K	ΔT	Δc_σ	Group
Weber	1982	42	108–280	0.005 K	2%–6%	2
Table 10		41	108–275	0.005 K	1%–3%	1

TABLE 12. Summary of the data sets for the enthalpy of vaporization of ethylene

Authors	Year	Method	No. of data	Temperature range/K	Group
Egan and Kemp	1937	a	1	169	2
Lamb and Roper	1940	b	1	169	3
York and White	1944	b	18	104–282	3
Clusius and Konnertz	1949	a	6	143–254	3
Dick and Hedley	1956	b	10	273–282	3
Tully and Edmister	1967	a	3	244–271	3
Douslin and Harrison	1976	b	14	238–282	2
Hejmadi and Powers	1979	a	2	280–282	3
Kozlov	1979	a	4	180–240	3
Calado *et al.*	1982	b	13	110–250	2
Fan	1982	a	1	280	3
Yaws *et al.*	1990	c	1	169	2

Methods to determine the enthalpy of vaporization:
(a) experimental determination,
(b) analysis of thermal property data, and
(c) evaluation of literature data.

3. Experimental Results for the Single-Phase Region

In this section, experimental data sets for thermodynamic properties in the single-phase region of ethylene are presented. For each of the considered properties, both general information on all available data sets and more-detailed information on the selected data sets are given in corresponding tables. Again, the data sets are classified into three groups, as explained in Sec. 2. Since the data situation in the homogeneous region is less unequivocal than the situation of the different properties on the phase boundaries, numerous data sets are associated with more than one group. Usually, these data sets are selected in regions with a poor data situation, but they are used only for comparison in regions in which more reliable data exist.

Where uncertainties are given, these values usually correspond to estimations given by the authors. Since we noticed, however, that a few authors have published none or overly optimistic estimations of the experimental uncertainties of their data, we had to estimate more realistic values for the uncertainties in some cases. In the tables, these uncertainty values are presented in parentheses.

3.1. Thermal Properties

3.1.1. $p\rho T$ Data

During the last 106 years, the thermal behavior of ethylene has been examined by numerous authors. For the $p\rho T$ relation in the single-phase region, 49 data sets are available, but most of them do not meet present quality standards. Table 13 gives detailed information on the data sets which were as-

TABLE 13. Summary of the $p\rho T$ data sets which were assigned to group 1. Uncertainties are given where the original articles contain such estimates. Uncertainty values in parentheses were estimated by ourselves

Authors	Year	No. of data total	selected	Temperature range/K	Pressure range/MPa	ΔT/mK	Uncertainty[a] Δp	$\Delta\rho_{total}$
Golovskii *et al.*	1973	164	56[b]	199–330	5.7–201	10	0.02%	(0.1%)[c]
Douslin and Harrison	1976	662	···	238–448	1.3–40	0.5	40 Pa	0.03%–0.08%
Trappeniers *et al.*	1976	675	293[b]	273–423	1.6–290			(0.05%–0.1%)
Hastings *et al.*	1980	141	···	279–303	4.7–8.4	1	0.005%	(0.05%)
Straty	1980	244	125	105–320	0.6–37		0.015%	0.1%–0.15%
Levelt Sengers and Hastings	1981	60	···	223–273	0.2–3.5	1	0.005%	0.03%
Calado *et al.*	1982	808	114[d]	110–280	0.001–131	10	0.1%	0.1%
Waxman	1983	111	68[b]	273–448	0.2–3.6	2[e]	0.003%[e]	0.012%[e]
Guo *et al.*	1992	14	···	283	1.5–4.2			0.02%
Nowak *et al.*	1996a	691	691	104–340	0.0001–12	1.5–3	0.004%	0.015%
Nowak *et al.*	1996b	188	188	281–282	4.8–5.1	3	0.004%	0.007%–0.015%[f]
Claus *et al.*	1998	91	58	235–350	2–30	10	0.006%	0.02%

[a]The uncertainty values for ΔT and Δp correspond to the uncertainty of the measured values for T and p, whereas $\Delta\rho_{total}$ in general corresponds to the total uncertainty which covers all contribution from ΔT, Δp, and $\Delta\rho$.
[b]Adjusted data, see the text.
[c]This uncertainty value is valid only within the selected temperature and pressure range. The assignment to group 1 holds only for temperatures between 200 and 273 K. All other data of Golovskii *et al.* (1973) were assigned to group 2.
[d]Only selected isotherms in a limited pressure range can be assigned to group 1, see the text.
[e]Waxman (1983) gives no information with regard to uncertainties. Jacobsen *et al.* (1988) state that the data of Waxman (1983) were determined with the apparatus described by Waxman and Davis (1979). The given uncertainties were taken from the articles.
[f]Total uncertainty in pressure (critical region).

signed to group 1. Thus, group 1 contains the data sets which are basically *suitable* for the development of a reference equation of state. However, not all of the group 1 data have been used to establish the final equation of state. The number of data points which were actually used in the final data set is specified in the row "selected data." Table 14 summarizes data sets which were assigned to group 2 and group 3.

Up to temperatures of 340 K and pressures of 12 MPa, the description of the $p\rho T$ relation is mainly based on measurements performed with the "two-sinker" buoyancy method, which probably provides the most accurate $p\rho T$ data today. Among these measurements, the most comprehensive data set was published by Nowak *et al.* (1996a). These data are supported by the values of Nowak *et al.* (1996b) for states near the phase boundary at temperatures close to the critical temperature and by the data set of Guo *et al.* (1992) for pressures up to 4.2 MPa at 283 K. The data from the different two-sinker apparatuses are consistent with each other clearly within their estimated uncertainties. Nevertheless, the data of Guo *et al.* (1992) deviate systematically by up to ±0.012% in density.

As described by Wagner *et al.* (1995), a new "single-sinker" densimeter was developed for pressures up to 30 MPa at temperatures from 233 to 523 K to enlarge the operational range of buoyancy densimeters without substantial loss of accuracy. After a careful examination of the densimeter and additional test measurements, several modifications were implemented by Klimeck *et al.* (1998) to improve the single-sinker method. With this apparatus, Claus *et al.* (1998) measured densities of ethylene up to temperatures of 350 K and up to pressures of 30 MPa, which supplement the data of Nowak *et al.* (1996a). The temperature range investigated by Claus *et al.* was limited due to previous examinations on the polymerization behavior of ethylene in order to avoid polymerization inside the apparatus. The total uncertainty of the data from single- and two-sinker densimeters is generally less than ±0.02% in density, except for data in the critical region and at very low densities.

The data sets of Golovskii *et al.* (1973), Trappeniers *et al.* (1976), and Waxman (1983) extend the range in which the $p\rho T$ relation is precisely known to temperatures of 448 K and pressures of 290 MPa. Nevertheless, for each of these data sets systematic deviations from the highly accurate reference data occur in regions where the data sets overlap. Thus, reasonable adjustments could be applied. The following simple "corrections" were used for the respective data sets:

$$\text{Golovskii } et\ al.\ (1973):\quad \rho=\rho_{Go}\ 0.999\,60, \tag{3.1}$$

$$\text{Trappeniers } et\ al.\ (1976):\quad \rho=\rho_{Tr}\ 0.999\,83, \tag{3.2}$$

$$\text{Waxman } (1983):\quad \rho=\rho_{Wa}\ 1.000\,05. \tag{3.3}$$

The adjusted experimental results of Golovskii *et al.* (1973) were assigned to group 1 only for temperatures from 200 to 273 K at pressures above 35 MPa. The remaining data from this source were assigned to group 2.

The results of Calado *et al.* (1982) represent the liquid region at temperatures below 200 K and pressures above 40 MPa with an uncertainty of ±0.1%. Obviously, systematic errors occur within this data set on several isotherms. Thus, only selected isotherms were assigned to group 1 within the mentioned pressure range, namely, those at temperatures of 120, 140, 160, 170, and 190 K.

In a p-T diagram, Fig. 7 shows the $p\rho T$ data that were used to establish the new equation of state. Although the data

TABLE 14. Summary of the $p\rho T$ data sets which were assigned to groups 2 and 3

Authors	Year	No. of data	Temperature range/K	Pressure range/MPa	Group
Amagat	1893	426	273–472	0.1–101	3
Masson and Dolley	1923	25	298	0.5–12.7	3
Crommelin and Watts	1927b	17	272–293	2–3.8	3
Danneel and Stoltzenberg	1929	238	288–318	2–2	3
Cawood and Patterson	1933	4	273	0.001–0.004	3
Michels *et al.*	1936	110	273–423	1.6–27.8	3
Maass and Geddes	1937	75	281–288	5.05–5.6	3
McIntosh and Maass	1938	4	283	5	3
Dacey *et al.*	1939	61	282–283	5–5.12	3
McIntosh *et al.*	1939	98	282–283	5–5.14	3
Roper	1940	7	198–343	0.05–0.15	2
Michels and Geldermans	1942	312	273–423	1.6–320	3
Walters *et al.*	1954	164	266–311	0.3–4.2	3
Dick and Hedley	1956	385	273–423	0.1–250	2
Pfennig and McKetta	1957	14	305–339	0.08–0.2	3
Turlington and McKetta	1961	10	243–303	0.06–0.2	3
Thomas and Zander	1966	43	273–323	0.3–3	2
Ku and Dodge	1967	11	373	1–26	3
Sass *et al.*	1967	30	313–373	0.7–50	3
Golovskii *et al.*	1969	93	200–307	1.3–60	3
McMath and Edmister	1969	15	266–298	0.005–0.025	3
Babb and Robertson	1970	26	308	145–798	2
Boiko and Voityuk	1970	71	193–273	0.5–6	3
Lee and Edmister	1970	90	298–348	0.2–82	3
Golovskii *et al.*	1976	114	106–231	1.2–60	2
Saville	1976	90	243–293	0.2–4.1	2
Prasad and Visvanath	1980	144	298–423	0.2–5.6	3
Rätzsch and Findeisen	1980	153	298–448	49–393	3
Thomas and Zander	1980	208	243–363	0.3–25.5	2
Trappeniers and Arends	1980	38	123–233	7–270	3
Findeisen and Rätzsch	1981	350	298–398	0.6–393	3
Mollerup	1985	120	310	0.009–72	3
Mohan *et al.*	1986	20	298–423	10–103	3
Achtermann *et al.*	1989	555	283–373	0.3–30	3
Achtermann *et al.*	1990	159	283–373	0.8–5.1	2
McElroy and Fang	1993	62	283–333	0.8–6.2	3
Gainar and Anitescu	1994	15	298	0.21–5.3	3

sets of Douslin and Harrison (1976), Hastings *et al.* (1980), Levelt Sengers and Hastings (1981), and Guo *et al.* (1992) were assigned to group 1, they were not used in the end. For the development of an equation of state, these data do not contain significant additional experimental information since they confirm other data sets, which cover a larger region with at least the same accuracy, far within their uncertainties.

3.1.2. Virial Coefficients

In most cases, virial coefficients are determined from isothermal fits to $p\rho T$ measurements. Therefore, such data do not contain new information if the original $p\rho T$ data are used to establish an equation of state. However, since a reasonable representation of the virial coefficients is considered as important for an equation of state, selected data for the second and third virial coefficients were used to establish the equation presented here.

Table 15 summarizes the 41 data sets for the second and third virial coefficients which are available for ethylene. In Table 16, additional information is given for the data sets assigned to group 1.

The data set of Bohn *et al.* (1986) results from a molecular dynamics study in which the parameters of a Lennard-Jones (12–6) potential model were optimized for the description of ethylene. Using these parameters, values for the second virial coefficient were calculated that yield the only reliable information for virial coefficients at temperatures below 200 K. During this work, preliminary equations of state were developed which showed an unreasonable inflection point within the metastable vapor region on isotherms below 170 K. This problem could be solved by using suitable data for the second and third virial coefficients at low temperatures together with an appropriate starting solution for the optimization algorithm (see Sec. 4.3.2).

3.2. Speed of Sound Data

Numerous publications on the speed of sound of ethylene can be found in the literature. New experimental data have

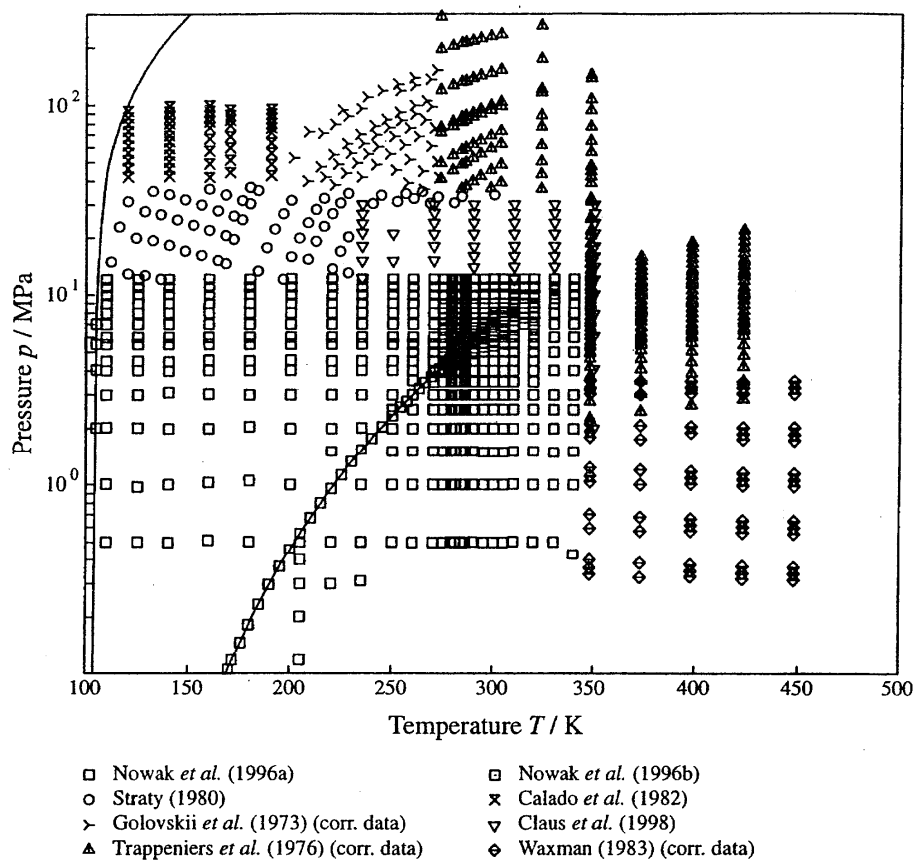

FIG. 7. Distribution of the experimental $p\rho T$ data used for the establishment of the residual part ot the new equation of state, Eq. (4.1), in a $p-T$ diagram

been published in ten sources. Table 17 gives information on the data sets that were assigned to group 1. Table 18 summarizes the data sets that were assigned to groups 2 and 3.

The comprehensive data set of Gammon (1978) covers the gas region up to temperatures of 298 K with an uncertainty of less than ±0.1%, while the experimental uncertainty rises up to ±2% in the critical region of ethylene. Some of the data describe liquid states as well. However, these data are considered as less accurate than data in the gas phase. Three data points at a temperature of $T-282.3478$ K (2.2 mK below T_c) have not been used in the final data set since they resulted in significant inconsistencies in the critical region. However, very close to the critical point those inconsistencies are no proof for experimental shortcomings — they may result from limitations of the used weighting algorithms [see Sec. 4.3.1 and Span (2000)] or from limitations of the equation of state itself (see Sec. 5.3.2) as well.

The data set of Mehl and Moldover (1981) results from measurements performed with a spherical resonator, which is the most accurate technique available for speed of sound measurements in the gas region today. Based on an evaluation of the specific isobaric heat capacity data in the ideal-gas state by Mehl and Moldover (1982), which were derived from the speed of sound data of Mehl and Moldover (1981) and on studies on the consistency of the speeds of sound to highly accurate $p\rho T$ data (see Sec. 3.1), we estimated ai uncertainty of ±0.05% for these speed of sound data.

In a $p-T$ diagram, Fig. 8 shows the speed of sound dat which were used to establish the new equation of state.

3.3. Isochoric Heat Capacity

Table 19 summarizes the four available data sets for th isochoric heat capacity of ethylene. Only 47 selected value from the data set of Weber (1982) were used to establish th new equation of state since all the other experimental dat show a large scatter. On the following isochores data of We ber were used in the final data set: $\rho=130\,\mathrm{kg\,m^{-3}}$ with ar uncertainty of ±5%; $\rho=165$ and $\rho=331\,\mathrm{kg\,m^{-3}}$ with an un certainty of ±3%; and $\rho=437$, $\rho=499$, $\rho=560$, and ρ $=606\,\mathrm{kg\,m^{-3}}$ with an uncertainty of ±1.5%. Figure 9 show the selected data for the isochoric and isobaric heat capacit in a $p-T$ diagram.

3.4. Isobaric Heat Capacity

With regard to the specific isobaric heat capacity, the de scription of the data situation has to distinguish between dat sets that describe the caloric behavior of the ideal gas an data sets that contain residual effects. While the data situa

TABLE 15. Summary of data sets available for the second and third virial coefficient of ethylene

Authors	Year	No. of data B	No. of data C	Temperature range/K	Group B	Group C
Crommelin and Watts	1927b	7	7	272–343	3	3
Eucken and Parts	1933	17	···	181–273	3	···
Cawood and Patterson	1937	2	···	273–294	3	···
Roper	1940	4	···	198–343	3	···
Michels and Geldermans	1942	7	7	273–423	3	3
Bird *et al.*	1950	6	6	298–423	2–3	3
Walters *et al.*	1954	13	13	244–311	3	3
Ashton and Guggenheim	1956	5	···	300–337	3	···
Pfennig and McKetta	1957	3	···	305–338	3	···
Ashton and Halberstadt	1958	8	···	299–337	3	···
Turlington and McKetta	1961	12	···	243–338	3	···
Butcher and Dadson	1964	13	13	263–473	3	3
Rätzsch and Bittrich	1964	4	···	293–333	3	···
Thomas and Zander	1966	6	···	273–323	3	···
Ku and Dodge	1967	1	···	373	3	···
Sass *et al.*	1967	4	2	313–373	3	3
Dorfmüller and Göpel	1969	1	···	236	3	···
McMath and Edmister	1969	3	1	266–288	3	3
Lee and Edmister	1970	6	6	298–348	3	3
Dawe and Snowdon	1974a	8	8	170–450	3	3
Douslin and Harrison	1976	21	21	238–448	1–2	1–2
Trappeniers *et al.*	1976	13	13	273–423	2	3
Calado and Soares	1977a	3	···	104–298	2	···
Calado *et al.*	1978	1	···	116	2	···
Waxman and Davis	1979	14	11	273–448	1	1
Dymond and Smith	1980	9	···	240–450	2	···
Prasad and Viswanath	1980	6	6	298–423	3	3
Thomas and Zander	1980	12	···	253–348	3	···
Findeisen and Rätzsch	1981	5	···	298–398	3	···
Levelt Sengers and Hastings	1981	6	6	223–273	2	2
Levelt Sengers and Hastings	1982	6	6	223–273	3	3
Ohgaki *et al.*	1982	1	2	398	2	2
Orbey and Vera	1983	···	6	298–343	···	2
Mollerup	1985	1	1	310	2	3
Bohn *et al.*	1986	9	···	104–450	1–2	···
Häusler and Kerl	1988	10	10	257–318	3	3
Achtermann *et al.*	1990	8	8	283–373	2	1
Bell *et al.*	1992	3	···	290–310	3	···
McElroy and Fang	1993	6	6	283–333	2–3	2
Nowak *et al.*	1996a	19	19	205–340	1	1
Ricardo *et al.*	1996	10	···	205–273	3	···

TABLE 16. Summary of data sets for the second and third virial coefficients which were assigned to group 1. Uncertainties are given where the original articles contain such estimates. Uncertainty values in parentheses were estimated by ourselves

Authors	Year	Property	No. of data total	No. of data selected	Temperature range/K	Uncertainty
Bohn *et al.*	1986	B	9	4	104–223	(5%)
Nowak *et al.*	1996a	B	19	19	205–340	0.3 $cm^3\ mol^{-1}$ [a]
		C	19	19	205–340	100–200 $cm^6\ mol^{-2}$ [a]

[a]In the temperature range 205 K$\leqslant T \leqslant$235 K the following uncertainty values apply: $\Delta B = 1.1-1.8\ cm^3\ mol^{-1}$ and $\Delta C = 1500-5000\ cm^6\ mol^{-2}$.

TABLE 17. Summary of data sets for the speed of sound which were assigned to group 1. Unceretainty values were estimated by ourselves

Authors	Year	No. of data total	No. of data selected	Temperature range/K	Pressure range/MPa	Δw
Gammon	1978	152	149	183–298	0.14–7.9	(0.1%–2%)
Mehl and Moldover	1981	24	24	273–373	0.13–1	(0.05%)
Dregulyas and Stavtsev	1985	371	135	193–473	0.1–60	(0.5%)

TABLE 18. Summary of the data sets for the speed of sound which were assigned to groups 2 and 3

Authors	Year	No. of data	Temperature range/K	Pressure range/MPa	Group
Richards and Reid	1934	40	288–318	0.008–0.1	3
Herget	1940	60	282–296	3.6–7.3	3
Terres *et al.*	1957	93	296–448	0.1–11.8	2
Dregulyas and Soldatenko	1968	64	273–363	0.2–10	3
Soldatenko and Dregulyas	1968	220	193–473	0.06–10	3
Vashchenko *et al.*	1971	242	193–473	0.06–10	3
Dregulyas and Stavtsev	1982	86	193–473	0.15–5	2

tion for the caloric properties of the ideal gas is dominated by theoretical approaches, only experimental results allow an accurate description of the real fluid behavior, where both the ideal and the residual part of the heat capacity have to be considered. Therefore, this section is divided into two subsections.

3.4.1. Experimental Results for the Specific Isobaric Heat Capacity

Information on the eight data sets published for the specific isobaric heat capacity of ethylene is given in Table 20. Today, calorimetric measurements performed with flow apparatuses provide accurate data of the specific isobaric heat capacity over wide ranges of temperature and pressure. In the low-density region, these results are usually more accurate than isochoric heat capacity measurements. Since the lov pressure limit of the isobaric heat capacity, c_p^o, is know very well (see Sec. 3.4.2), temperature-dependent errors measured isobaric heat capacities can be determined easil Figure 10 shows systematic deviations of data measured b Bender (1982). A systematic error of the new equation f the residual part of the Helmholtz energy, Eq. (4.11), wou result in deviations which increase with pressure since th residual contribution to the isobaric heat capacity increase Thus, the observed deviation is obviously caused by a sy tematic experimental error. To compensate for th (temperature-dependent) experimental error, the data set Bender (1982) was corrected according to the values given Table 21.

The data set of Watanabe (1980) was adjusted by +1%

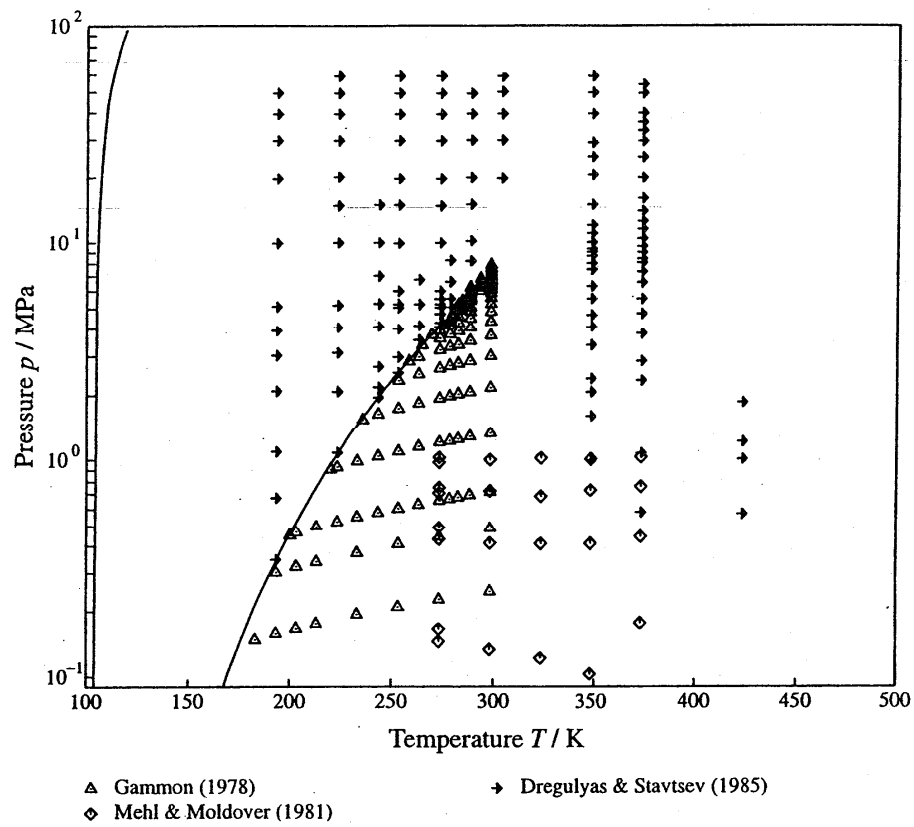

FIG. 8. Distribution of the experimental speed of sound data used to establish the residual part of the new equation of state, Eq. (4.1), in a $p-T$ diagram.

TABLE 19. Summary of data sets for the isochoric heat capacity of ethylene

Authors	Year	No. of data	Temperature range/K	Density range /(kg m^{-3})	Group
Pall *et al.*	1938	37	278–300	226	3
Michels *et al.*	1946	130[a]	273–423	1–600	3
Dick and Hedley	1956	255[a]	273–423	0.8–597	2
Weber	1982	59	144–338	130–606	1

[a]Data were calculated from $p\rho T$ data from different sources.

TABLE 20. Summary of data sets for the isobaric heat capacity of ethylene

Authors	Year	No. of data	Temperature range/K	Pressure range/MPa	Group
Egan and Kemp	1937	12	107–169	0.1	1
Dick and Hedley	1956	258[a]	273–423	0.1–250	3
Senftleben	1964	4	298–473	0.1	3
Vashchenko *et al.*	1971	104	168–282	0.5–6.3	3
Hejmadi and Powers	1979	70	278–323	6.2–10	3
Watanabe	1980	29	244–364	0.5–3	1–2
Bender	1982	69	233–473	0.1–1.5	1
Fan	1982	11	280–286	4.9–11.4	3

[a]Values calculated from experimentally determined values of thermal properties.

account for systematic deviations from the corrected data of Bender and to increase the consistency of the final data set. Table 22 summarizes the data sets assigned to group 1. Figure 9 shows the selected data for the isobaric heat capacity together with the selected data for the isochoric heat capacity in a $p-T$ diagram.

3.4.2. Results for the Specific Isobaric Heat Capacity in the Ideal-Gas State

According to Eq. (4.4), knowledge of the specific isobaric heat capacity in the ideal-gas state forms the basis for the description of the ideal-gas part of the Helmholtz energy, $a^{o}(\rho,T)$. Results for c_p^{o} obtained by the extrapolation of c_p measurements are neither accurate enough for this application nor do they cover a sufficiently wide temperature range. Therefore, theoretical approaches which describe the caloric behavior of ethylene in the ideal-gas state were reviewed. Information on the data sets published for the isobaric heat capacity in the ideal-gas state is summarized in Table 23.

Information on the fundamental frequencies of the ethyl-

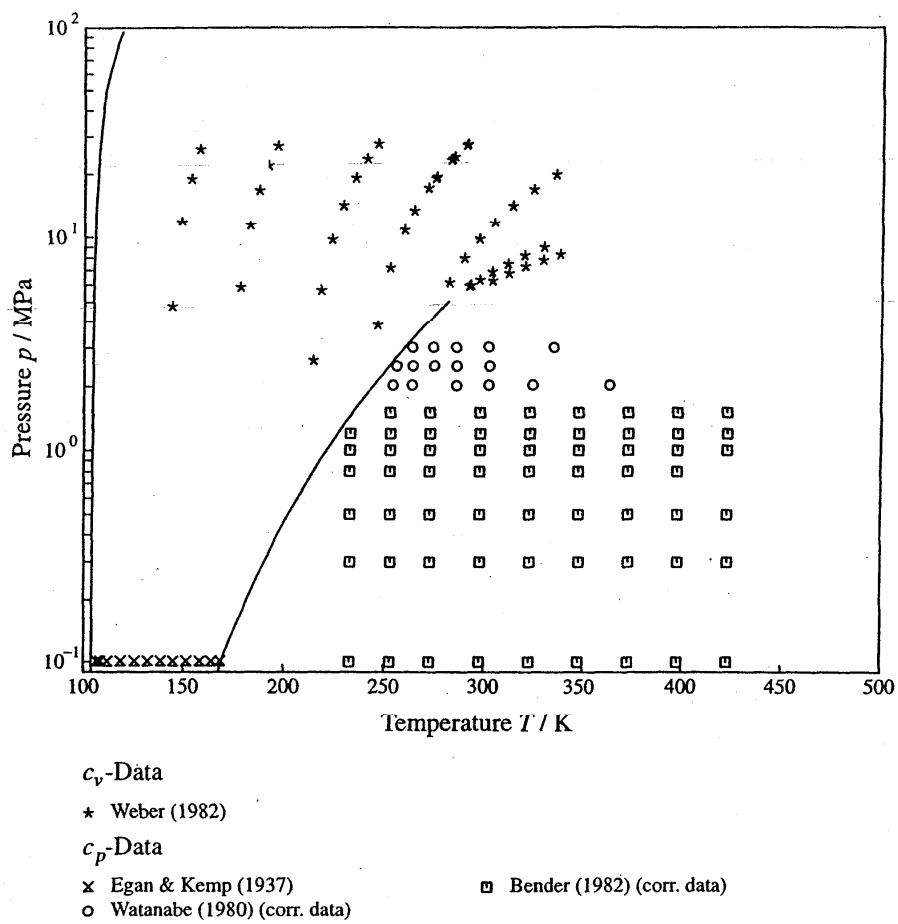

FIG. 9. Distribution of the experimental data for the isochoric and isobaric heat capacity used to establish the residual part of the new equation of state, Eq. (4.1), in a $p-T$ diagram.

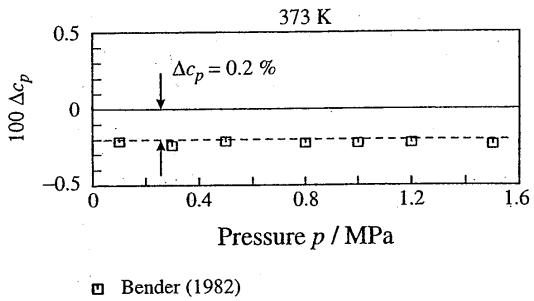

FIG. 10. Relative deviations $100\Delta c_p = 100\ (c_{p,\mathrm{exp}} - c_{p,\mathrm{calc}})/c_{p,\mathrm{exp}}$ of experimental c_p data from specific isobaric heat capacities calculated from Eq. (4.1). This figure illustrates the reason for correcting the data of Bender (1982) (see Sec. 3.4.1).

ene molecule is given in various compilations, but none of them contains c_p^o data where corrections to the simple rigid rotator, harmonic-oscillator model were taken into account as it is state of the art for other substances. However, in general, such corrections are required only for high temperatures where ethylene is chemically instable anyway.

The data sets of Chao and Zwolinski (1975) and Gurvich *et al.* (1991) are essential for the description of the heat capacity of the ideal gas. The data of Chao and Zwolinski are considered as the most accurate theoretical results. However, these data are subject to random errors which obviously result from too few decimal numbers given for the published values. Thus, the corresponding calculations were repeated on the basis of vibrational frequencies published by Shimanouchi (1972) which were adopted by Chao and Zwolinski as well. In this way an accurate and consistent data set was provided for the establishment of the new correlation equation for the ideal-gas heat capacity, Eq. (4.5).

3.5. Enthalpy Differences

Table 24 summarizes the nine available data sets for the enthalpy of ethylene. To avoid problems with different reference states, enthalpy data are considered as enthalpy differences $\Delta h = h_1(T_1,p_1) - h_2(T_2,p_2)$ in this work. Where absolute values for the enthalpy have been published, one data point was used as the reference value to obtain enthalpy differences again. Some of the available publications deal with enthalpy values calculated from $p\rho T$ data. Ayber (1965), Zemlin (1971), and Dawe and Snowdon (1974a)

TABLE 21. Temperature-dependent corrections of the isobaric heat capacity data of Bender (1982)

Temperature/K	$\frac{c_{p,\mathrm{cor}} - c_{p,\mathrm{exp}}}{c_{p,\mathrm{exp}}}$
233	+0.26%
253	+0.26%
273	+0.20%
298	+0.08%
373	+0.20%
398	+0.04%

TABLE 22. Summary of data sets for the isobaric heat capacity which we assigned to group 1. All uncertainty values were estimated by us

Authors	Year	No. of data total	No. of data selected	Δc_p
Egan and Kemp	1937	12	12	(3%)
Watanabe	1980	29	16[a]	(2.5%)
Bender	1982	69	61[b]	(0.15%)

[a]Adjusted values.
[b]Values corrected according to Table 21.

measured temperature and pressure on lines of constant ei thalpy. The data of Ayber and of Zemlin are only presente graphically, so these experimental results could not be coı sidered here. The data of Dawe and Snowdon (1974a) resu from measurements [Dawe and Snowdon, (1974b)] whic were represented by polynomial equations. Taking into ac count the corrections published by Dawe and Snowdc (1975), values of temperature and pressure on lines of coı stant enthalpy were calculated from the polynomial equa tions for comparisons. Due to the lack of reliable experimeı tal information, no data for enthalpy differences were used i the final data set.

3.6. Throttling Coefficients

Table 25 summarizes the data sets for the Joule–Thomso coefficient $\mu = (\partial T/\partial p)_h$ and for the isothermal throttling cc efficient $\delta_T = (\partial h/\partial p)_T$ of ethylene. The only experiment results for the Joule–Thomson coefficient were published b Bender (1982). They show small but systematic deviatior from values calculated from the final and from all prelim nary equations of state developed in the course of this worl No theoretically founded correction could be given for thes data which were, therefore, used only for comparisons.

The results of Charnley *et al.* (1953) on the isotherm throttling coefficient are given only graphically. The publ cation of Charnley *et al.* (1955) contains values of the isc thermal throttling coefficient in the limit of zero pressuı derived by extrapolation of primary data. No data for thro tling coefficients were used to develop the new equation c state.

4. New Fundamental Equation of State

The new equation of state for ethylene is an empiric description of the Helmholtz free energy. For the develop ment of such empirical formulations, the application of linea optimization procedures and nonlinear multiproperty fittin algorithms is state of the art. The details of this strategy weı extensively discussed, e.g., by Setzmann and Wagner (198 1991) and by Span (2000). Thus, this section is restricted t some basic facts to give a rough understanding of the proc dures used for the development of the new equation.

TABLE 23. Summary of data sets for the isobaric heat capacity in the ideal-gas state of ethylene

Authors	Year	No. of data	Measured property	Temperature range/K
Data calculated from models based on spectroscopic data				
Thompson	1941	19	···	291–1500
Stull and Mayfield	1943	16	···	250–1500
Kilpatrick and Pitzer	1946	14	···	298–1500
Stull and Prophet	1971	61	···	100–6000
Dawe and Snowdon	1974a	8	···	170–450
Chao and Zwolinski	1975	50	···	298–1500
Gurvich *et al.*	1991	61	···	100–6000
Data extrapolated from experimental results				
Heuse	1919	4	c_p	182–291
Haas and Stegeman	1932	7	c_p	275–340
Eucken and Parts	1933	31	c_p	178–464
Burcik *et al.*	1941	3	c_p	271–321
Bender	1982	10	c_p	233–473
Dregulyas and Stavtsev	1982	42	w	190–480
Mehl and Moldover	1982	5	w	273–373

4.1. Thermodynamic Properties Derived from the Helmholtz Energy

The equation of state described in this paper is explicit in the Helmholtz energy a with the independent variables density ρ and temperature T. The dimensionless Helmholtz energy $\alpha = a/(RT)$ is commonly split into a part α^{o}, which represents the properties of the ideal gas at given T and ρ, and a part α^{r}, which takes into account the residual fluid behavior. This convention can be written as

$$\alpha(\delta,\tau) = \alpha^{\mathrm{o}}(\delta,\tau) + \alpha^{\mathrm{r}}(\delta,\tau), \tag{4.1}$$

where $\delta = \rho/\rho_{\mathrm{c}}$ is the reduced density and $\tau = T_{\mathrm{c}}/T$ is the inverse reduced temperature. Both the density ρ and the temperature T are reduced with their critical values ρ_{c} and T_{c}, respectively.

Since the Helmholtz energy as a function of density and temperature is one of the four fundamental forms of an equation of state, all thermodynamic properties of a pure substance can be obtained by combining derivatives of Eq. (4.1). Table 26 gives the relations between Eq. (4.1) and its derivatives and the thermodynamic properties considered in this paper. At a given temperature, the vapor pressure and the densities of the coexisting phases can be determined by simultaneous solution of the equations

$$\frac{p_{\mathrm{s}}}{RT\rho'} = 1 + \delta'\alpha^{\mathrm{r}}_{\delta}(\delta',\tau), \tag{4.2a}$$

$$\frac{p_{\mathrm{s}}}{RT\rho''} = 1 + \delta''\alpha^{\mathrm{r}}_{\delta}(\delta'',\tau), \tag{4.2b}$$

$$\frac{p_{\mathrm{s}}}{RT}\left(\frac{1}{\rho''} - \frac{1}{\rho'}\right) - \ln\left(\frac{\rho'}{\rho''}\right) = \alpha^{\mathrm{r}}(\delta',\tau) - \alpha^{\mathrm{r}}(\delta'',\tau). \tag{4.2c}$$

These equations represent the phase equilibrium conditions, i.e., the equality of pressure, temperature, and specific Gibbs energy (Maxwell criterion) in the coexisting phases.

4.2. Equation for the Helmholtz Energy of the Ideal Gas

The Helmholtz energy of the ideal gas is given by

$$a^{\mathrm{o}}(\rho,T) = h^{\mathrm{o}}(T) - RT - Ts^{\mathrm{o}}(\rho,T). \tag{4.3}$$

The enthalpy h^{o} of the ideal gas is a function of temperature only, and the entropy s^{o} of the ideal gas depends on temperature and density. Both properties can be derived from an equation for the ideal-gas heat capacity $c_p^{\mathrm{o}}(T)$. When c_p^{o} is inserted into the expression for $h^{\mathrm{o}}(T)$ and $s^{\mathrm{o}}(\rho,T)$ in Eq. (4.3), one obtains

TABLE 24. Summary of data sets for the enthalpy of ethylene

Authors	Year	No. of data	Temperature range/K	Pressure range/MPa
Michels *et al.*	1946	130[a]	273–423	0.1–56
Dick and Hedley	1956	385[a]	273–423	0.1–250
Ayber	1965	9[b]	285	1–5
Zemlin	1971	86[b]	168–326	1–12
Dawe and Snowdon	1974a	···[c]	273–368	0.1–7
Douslin and Harrison	1976	19[d]	248–282	2.2–5
Harrison and Douslin	1977	448[a]	238–448	1–40
Hejmadi and Powers	1979	230	262–316	3.3–17
Fan	1982	131	279–286	4.6–10

[a]Values calculated from $p\rho T$ data.
[b]Experimental results presented only graphically.
[c]Experimental data represented by polynomial equations.
[d]Enthalpies calculated from $p\rho T$ data. Enthalpy values are given for the two-phase system at critical density.

TABLE 25. Summary of data sets for the Joule–Thomson coefficient μ and the isothermal throttling coefficient δ_T of ethylene

Authors	Year	Property	No. of data	Temperature range/K	Pressure range/MPa
de Groot and Geldermans	1947	μ	84[a]	298–423	0.1–253
Charnley *et al.*	1953	δ_T	63[b]	273–318	0.2–4.8
Charnley *et al.*	1955	δ_T	3[c]	273–318	0
Bender	1982	μ	49	233–473	0.4–1.5

[a]Values calculated from $p\rho T$ data.
[b]Experimental results presented only graphically.
[c]Values extrapolated to the zero-pressure limit.

TABLE 26. Relations of thermodynamic properties to the dimensionless Helmholtz function α consisting of α^o and α^r, see Eq. (4.1)

Property and common thermodynamic definition	Relation to the reduced Helmholtz energy α and its derivatives[a]
Pressure $p(T,\rho)=-(\partial a/\partial v)_T$	$\frac{p(\delta,\tau)}{\rho RT}=1+\delta\alpha^r_\delta$
Entropy $s(T,\rho)=-(\partial a/\partial T)_v$	$\frac{s(\delta,\tau)}{R}=\tau(\alpha^o_\tau+\alpha^r_\tau)-\alpha^o-\alpha^r$
Internal energy $u(T,\rho)=a-T(\partial a/\partial T)_v$	$\frac{u(\delta,\tau)}{RT}=\tau(\alpha^o_\tau+\alpha^r_\tau)$
Isochoric heat capacity $c_v(T,\rho)=(\partial u/\partial T)_v$	$\frac{c_v(\delta,\tau)}{R}=-\tau^2(\alpha^o_{\tau\tau}+\alpha^r_{\tau\tau})$
Enthalpy $h(T,p)=a-T(\partial a/\partial T)_v-v(\partial a/\partial v)_T$	$\frac{h(\delta,\tau)}{RT}=1+\tau(\alpha^o_\tau+\alpha^r_\tau)+\delta\alpha^r_\delta$
Isobaric heat capacity $c_p(T,p)=(\partial h/\partial T)_p$	$\frac{c_p(\delta,\tau)}{R}=-\tau^2(\alpha^o_{\tau\tau}+\alpha^r_{\tau\tau})+\frac{(1+\delta\alpha^r_\delta-\delta\tau\alpha^r_{\delta\tau})^2}{1+2\delta\alpha^r_\delta+\delta^2\alpha^r_{\delta\delta}}$
Saturated-liquid heat capacity $c_\sigma(T)=(\partial h/\partial T)_p+T(\partial p/\partial T)_v\cdot(\mathrm{d}p_s/\mathrm{d}T)/(\partial p/\partial v)_T\vert_{v=v'}$	$\frac{c_\sigma(\tau)}{R}=-\tau^2(\alpha^o_{\tau\tau}+\alpha^r_{\tau\tau})+\frac{1+\delta\alpha^r_\delta-\delta\tau\alpha^r_{\delta\tau}}{1+2\delta\alpha^r_\delta+\delta^2\alpha^r_{\delta\delta}}\times\left[(1+\delta\alpha^r_\delta-\delta\tau\alpha^r_{\delta\tau})-\frac{\rho_c}{R\delta}\frac{\mathrm{d}p_s}{\mathrm{d}T}\right]$
Speed of sound $w(T,p)=\sqrt{(\partial p/\partial\rho)_s}$	$\frac{w^2(\delta,\tau)}{RT}=1+2\delta\alpha^r_\delta+\delta^2\alpha^r_{\delta\delta}-\frac{(1+\delta\alpha^r_\delta-\delta\tau\alpha^r_{\delta\tau})^2}{\tau^2(\alpha^o_{\tau\tau}+\alpha^r_{\tau\tau})}$
Joule–Thomson coefficient $\mu(T,p)=(\partial T/\partial p)_h$	$\mu R\rho=\frac{-(\delta\alpha^r_\delta+\delta^2\alpha^r_{\delta\delta}+\delta\tau\alpha^r_{\delta\tau})}{(1+\delta\alpha^r_\delta-\delta\tau\alpha^r_{\delta\tau})^2-\tau^2(\alpha^o_{\tau\tau}+\alpha^r_{\tau\tau})(1+2\delta\alpha^r_\delta+\delta^2\alpha^r_{\delta\delta})}$
Isothermal throttling coefficient $\delta_T(T,p)=(\partial h/\partial p)_T$	$\delta_T\rho=1-\frac{1+\delta\alpha^r_\delta-\delta\tau\alpha^r_{\delta\tau}}{1+2\delta\alpha^r_\delta+\delta^2\alpha^r_{\delta\delta}}$
Second thermal virial coefficient $B(T)=\lim_{\rho\to0}\{\partial[p/(\rho RT)]/\partial\rho\}_T$	$B(\tau)\rho_c=\lim_{\delta\to0}\alpha^r_\delta(\delta,\tau)$
Third thermal virial coefficient $C(T)=\frac{1}{2}\lim_{\rho\to0}\{\partial^2[p/(\rho RT)]/\partial\rho^2\}_T$	$C(\tau)\rho_c^2=\lim_{\delta\to0}\alpha^r_{\delta\delta}(\delta,\tau)$

[a] $\alpha_\delta=\left[\frac{\partial\alpha}{\partial\delta}\right]_\tau$, $\alpha_{\delta\delta}=\left[\frac{\partial^2\alpha}{\partial\delta^2}\right]_\tau$, $\alpha_\tau=\left[\frac{\partial\alpha}{\partial\tau}\right]_\delta$, $\alpha_{\tau\tau}=\left[\frac{\partial^2\alpha}{\partial\tau^2}\right]_\delta$, and $\alpha_{\delta\tau}=\left[\frac{\partial^2\alpha}{\partial\delta\partial\tau}\right]$.

$$a^{\circ}(\rho,T)=\left[\int_{T_0}^{T} c_p^{\circ}\mathrm{d}T+h_0^{\circ}\right]-RT-T\left[\int_{T_0}^{T}\frac{c_p^{\circ}-R}{T}\mathrm{d}T-R\ln\left(\frac{\rho}{\rho_0^{\circ}}\right)+s_0^{\circ}\right], \tag{4.4}$$

where all variables with the index "0" refer to an arbitrary reference state. Usually, the enthalpy h_0° and the entropy s_0° are taken to be zero for $T_0=298.15$ K, $p_0=0.101\,325$ MPa, and the corresponding density $\rho_0^{\circ}=p_0/(RT_0)$.

A correlation equation for $c_p^{\circ}(T)$ has been established by means of a nonlinear fitting routine using 53 c_p° data in the temperature range from 7 to 6000 K as input values. The input data were calculated based on the vibrational frequencies determined by Shimanouchi (1972), see also Sec. 3.4.2. With the coefficients given in Table 27, the obtained equation

$$\frac{c_p^{\circ}(T)}{R}=1+a_3^{\circ}+\sum_{i=4}^{7} a_i^{\circ}(\theta_i^{\circ}\tau)^2\frac{e^{(\theta_i^{\circ}\tau)}}{[e^{(\theta_i^{\circ}\tau)}-1]^2}, \tag{4.5}$$

represents the input data with deviations of less than $\pm 0.0005\%$. The range of validity of Eq. (4.5) is limited to temperatures below 1000 K as corrections to the simple rigid rotator, harmonic-oscillator model are supposed to be necessary above this temperature for an accurate description of the isobaric heat capacity in the ideal-gas state. None of the available data sets for c_p° considers such corrections, see also Sec. 3.4.2.

From Eqs. (4.4) and (4.5) the expression for the ideal-gas part of the Helmholtz energy α° can be derived by integration:

$$\alpha^{\circ}=\ln(\delta)+a_1^{\circ}+a_2^{\circ}\tau+a_3^{\circ}\ln(\tau)+\sum_{i=4}^{7} a_i^{\circ}\ln[1-e^{(-\theta_i^{\circ}\tau)}]. \tag{4.6}$$

The coefficients a_i° and θ_i° are given in Table 27. The coefficients a_1° and a_2° were adjusted to give zero for the ideal-gas enthalpy at $T_0=298.15$ K and the ideal-gas entropy at $T_0=298.15$ K and $p_0=0.101\,325$ MPa. In Table 28, all derivatives of the ideal-gas part α° required for the calculation of thermodynamic properties are explicitly given.

4.3. Equation for the Residual Part of the Helmholtz Energy

While statistical thermodynamics can predict the behavior of fluids in the ideal-gas state with high accuracy, no physically founded equation is known which accurately describes the real thermodynamic behavior of fluids in the whole fluid region. Thus, for this purpose an equation for the residual fluid behavior, in this case for the residual part of the Helmholtz energy α^{r}, has to be determined in an empirical way. Since the Helmholtz energy itself is not accessible to direct measurements, it is necessary to determine a suitable mathematical structure and the fitted coefficients from properties for which experimental data are available. The algorithms which were used to do so are described here only very briefly; for details see Span (2000).

4.3.1. Fitting an Equation for α^{r} to Data

If a certain functional form has been selected for $\alpha^{r}(\delta,\tau,\bar{n})$, data for J different properties z_j (e.g., pressure p, speed of sound w, etc.) can be used to determine the unknown coefficients n_i (expressed as vector $\bar{n}$) by minimizing the following sum of squares:

$$\chi^2=\sum_{j=1}^{J}\chi_j^2=\sum_{j=1}^{J}\sum_{m=1}^{M_j}\left[\frac{[z_{\mathrm{exp}}-z_{\mathrm{calc}}(x_{\mathrm{exp}},y_{\mathrm{exp}},\bar{n})]^2}{\sigma_{\mathrm{tot}}^2}\right]_{j,m}, \tag{4.7}$$

where M_j is the number of data points used for the jth property, z_{exp} the experimental value for any property z, and z_{calc} the value for the property calculated from the equation for α with the parameter vector $\bar{n}$ at x_{exp} and y_{exp}. The measured independent variables x and y may vary for the different properties z, but usually one of them corresponds to temperature T while the other corresponds to density ρ or pressure p [e.g., $p(T,\rho)$ or $w(T,p)$]. When data sets of different properties are used for the development of a correlation equation, it is necessary that the residual $\Delta z=(z_{\mathrm{exp}}-z_{\mathrm{calc}})$ of Eq. (4.7) is reduced with a suitable measure for the uncertainty of the data point. According to the Gaussian error propagation formula, the uncertainty of a measured data point is given by

$$\sigma_{\mathrm{exp}}^2=\left[\frac{\partial\Delta z}{\partial x}\right]_{y,z}^2\sigma_x^2+\left[\frac{\partial\Delta z}{\partial y}\right]_{x,z}^2\sigma_y^2+\left[\frac{\partial\Delta z}{\partial z}\right]_{x,y}^2\sigma_z^2, \tag{4.8}$$

where σ_x, σ_y, and σ_z are the isolated uncertainties of the single variables x, y, and z, respectively. The partial derivatives of Δz have to be calculated from a preliminary equation of state.

In order to have an additional influence on the data set, a weighting factor f_{wt} is introduced. The total variance σ_{tot} of a data point used in Eq. (4.7) is defined as

$$\sigma_{\mathrm{tot}}^2=\sigma_{\mathrm{exp}}^2/f_{\mathrm{wt}}^2. \tag{4.9}$$

In this way, weighting factors $f_{\mathrm{wt}}>1$ enlarge the influence of a data point with respect to the sum of spares and weighting factors $f_{\mathrm{wt}}<1$ reduce it. Usually, f_{wt} is equal to 1 and σ_{tot}^2 is equal to σ_{exp}^2. However, in some cases different weighting factors are used to compensate for effects caused by the structure of the data set.

TABLE 27. Coefficients of the correlation equations for c_p° and α°, Eqs. (4.5) and (4.6)

i	a_i°	θ_i°	i	a_i°	θ_i°
1	8.688 155 23		5	3.002 715 20	5.748 401 49
2	−4.479 605 64		6	2.512 658 40	7.802 782 50
3	3.000 000 00		7	3.990 642 17	15.585 115 4
4	2.493 958 51	4.432 668 96			

TABLE 28. Ideal-gas part α^o of the dimensionless Helmholtz function and its derivatives[a]

α^o	=	$\ln\delta$	+	α_1^o	+	$\alpha_2^o\tau$	+	$\alpha_3^o \ln\tau$	+	$\sum_{i=4}^{7} \alpha_i^o \ln[1-\exp(-\theta_i^o\tau)]$
α_δ^o	=	$1/\delta$	+	0	+	0	+	0	+	0
$\alpha_{\delta\delta}^o$	=	$-1/\delta^2$	+	0	+	0	+	0	+	0
$\alpha_{\delta\tau}^o$	=	0	+	0	+	0	+	0	+	0
α_τ^o	=	0	+	0	+	α_2^o	+	α_3^o/τ	+	$\sum_{i=4}^{7} \alpha_i^o\theta_i^o\{[1-\exp(-\theta_i^o\tau)]^{-1}-1\}$
$\alpha_{\tau\tau}^o$	=	0	+	0	+	0	−	α_3^o/τ^2	−	$\sum_{i=4}^{7} \alpha_i^o(\theta_i^o)^2 \exp(-\theta_i^o\tau)[1-\exp(-\theta_i^o\tau)]^{-2}$

[a] $\alpha_\delta^o=\left[\frac{\partial\alpha^o}{\partial\delta}\right]_\tau$, $\alpha_{\delta\delta}^o=\left[\frac{\partial^2\alpha^o}{\partial\delta^2}\right]_\tau$, $\alpha_\tau^o=\left[\frac{\partial\alpha^o}{\partial\tau}\right]_\delta$, $\alpha_{\tau\tau}^o=\left[\frac{\partial^2\alpha^o}{\partial\tau^2}\right]_\delta$, and $\alpha_{\delta\tau}^o=\left[\frac{\partial^2\alpha^o}{\partial\delta\partial\tau}\right]$.

The determination of $\bar{n}$ by minimizing χ^2 for data of more than one property is called "multiproperty fitting." This problem leads to a linear system of normal equations if each of the properties z depends on the same independent variables as the used function (e.g., T and ρ for the Helmholtz energy) and if the relations between z and the function or its derivatives are linear for all considered properties. Data for such properties are called "linear data." For functions in terms of the Helmholtz energy, such properties are, e.g., $p(T,\rho)$ and $c_v(T,\rho)$, see Table 26. If one or both of the conditions are not fulfilled [e.g., for $h(T,p)$, $w(T,p)$, $c_p(T,p)$, etc.], more complicated and time-consuming nonlinear algorithms have to be used to minimize the sum of squares, Eq. (4.7).

4.3.2. Optimizing the Mathematical Form of α^r

Since the functional form of an equation for the residual part of the Helmholtz energy is not known from the start, a suitable mathematical structure has to be established before any coefficients n_i can be fitted to data. In the past, the structure of most correlation equations had been determined subjectively, based on the experience of the correlator or by trial and error. To improve this situation, Wagner and co-workers developed different optimization strategies [Wagner (1974), Ewers and Wagner (1982), Setzmann and Wagner (1989), and Tegeler *et al.* (2000)], which introduce objective criteria for the selection of the mathematical structure.

In this work, a modified form of the optimization method developed by Setzmann and Wagner (1989) was used to determine a suitable mathematical structure. Improvements were introduced both in the stochastic and in the deterministic part of the original algorithm, see Span (2000). More importantly, however, are the changes made with regard to the handling of different functional forms in the "bank of terms."

A sophisticated correlation equation for the residual part of the Helmholtz energy consists of an extensive sum of terms. Hence, the mathematical form of a single term can be associated with different functional groups ranging from simple polynomials of the reduced density δ and the inverse reduced temperature τ to complicated exponential expressions (see the bank of terms given in Sec. 4.4). During our work on carbon dioxide, see Span and Wagner (1996), additional limitations with respect to the number of terms belonging to certain functional groups turned out to be useful and the optimization algorithm was modified to allow for suc limitations, see Span (1993/2000). The new equation of stat for ethylene was developed limiting the optimization algc rithm to a maximum number of five modified Gaussian bel shaped terms.

4.4. Used Data Sets and the Bank of Terms

The experimental data which were selected to establish th new equation of state have been presented in Secs. 2 and 3 Table 29 gives a brief summary of the data used in the linea optimization and in the nonlinear fit and refers to the table where more-detailed information on the data sets is given. I addition, several data, which are not considered in Table 29 have been generated in order to guarantee reasonable behavior in regions where the existing measurements yield insufficient information. In detail, these are:

TABLE 29. Summary of the selected data which were used in the linea optimization procedure and in the nonlinear fit

		Number of data	
Property	For details see	Linear optimization	Nonlinear fit
$p(\rho,T)$	Table 13	1399	1399
$p(\rho,T)$	Sec. 5.4.1	24	24
$p_s(\rho',T)$		103[a]	...
$p_s(\rho'',T)$		103[a]	...
Maxwell criterion		103[a]	...
$p_s(T)$	Table 6	...	62
$\rho'(T)$	Table 7	...	69
$\rho''(T)$	Table 8	...	45
$B(T)$	Table 16	23	23
$C(T)$	Table 16	19	19
$c_v(\rho,T)$	Table 19, Sec. 3.3	47	47
$c_p(\rho,T)$	Table 22	89[b]	89
$c_p'(T)$	Table 11	41[b]	41
$w(p,T)$	Table 17	308[b]	308
$w'(T)$	Table 9	28[b]	28
$w''(T)$	Table 9	21[b]	21

[a] Linearized solution of the Maxwell criterion using data calculated from the auxiliary equations Eqs. (2.13–2.15), see Wagner (1972).
[b] Linearized data used in the optimization procedure, see Setzmann and Wagner (1991).

TABLE 30. Coefficients and exponents of Eq. (4.11)

i	n_i	d_i	t_i
1	$0.186\,174\,291\,006\,70\times10^{1}$	1	0.50
2	$-0.309\,137\,084\,608\,44\times10^{1}$	1	1.00
3	$-0.173\,848\,170\,955\,16$	1	2.50
4	$0.803\,709\,856\,928\,40\times10^{-1}$	2	0.00
5	$0.236\,827\,073\,173\,54$	2	2.00
6	$0.219\,227\,866\,102\,47\times10^{-1}$	4	0.50

i	n_i	d_i	t_i	c_i
7	$0.118\,278\,858\,131\,93$	1	1.00	1
8	$-0.217\,363\,843\,967\,76\times10^{-1}$	1	4.00	1
9	$0.440\,079\,906\,611\,39\times10^{-1}$	3	1.25	1
10	$0.125\,540\,588\,638\,81$	4	2.75	1
11	$-0.131\,679\,455\,772\,41$	5	2.25	1
12	$-0.521\,169\,845\,758\,97\times10^{-2}$	7	1.00	1
13	$0.152\,360\,812\,654\,19\times10^{-3}$	10	0.75	1
14	$-0.245\,053\,353\,427\,56\times10^{-4}$	11	0.50	1
15	$0.289\,705\,249\,240\,22$	1	2.50	2
16	$-0.180\,758\,366\,742\,88$	1	3.50	2
17	$0.150\,572\,728\,784\,61$	2	4.00	2
18	$-0.140\,931\,517\,544\,58$	2	6.00	2
19	$0.227\,551\,090\,702\,53\times10^{-1}$	4	1.50	2
20	$0.140\,260\,705\,290\,61\times10^{-1}$	4	5.00	2
21	$0.616\,974\,542\,962\,14\times10^{-2}$	6	4.50	2
22	$-0.412\,860\,834\,513\,33\times10^{-3}$	7	15.00	3
23	$0.128\,853\,887\,147\,85\times10^{-1}$	4	20.00	4
24	$0.691\,286\,921\,570\,93\times10^{-1}$	5	23.00	4
25	$0.109\,362\,255\,684\,83$	6	22.00	4
26	$-0.818\,188\,752\,717\,94\times10^{-2}$	6	29.00	4
27	$-0.564\,184\,721\,171\,70\times10^{-1}$	7	19.00	4
28	$0.165\,178\,677\,506\,33\times10^{-2}$	8	15.00	4
29	$0.959\,040\,065\,170\,01\times10^{-2}$	9	13.00	4
30	$-0.262\,365\,729\,848\,86\times10^{-2}$	10	10.00	4

i	n_i	d_i	t_i	η_i	β_i	γ_i	ε_i
31	$-0.502\,424\,140\,113\,55\times10^{2}$	2	1.00	25	325	1.16	1
32	$0.748\,464\,201\,192\,99\times10^{4}$	2	0.00	25	300	1.19	1
33	$-0.687\,342\,992\,326\,25\times10^{4}$	2	1.00	25	300	1.19	1
34	$-0.935\,779\,828\,143\,38\times10^{3}$	3	2.00	25	300	1.19	1
35	$0.941\,330\,247\,861\,13\times10^{3}$	3	3.00	25	300	1.19	1

$R=0.296\,384\,079\ \mathrm{kJ\,kg^{-1}\,K^{-1}}$ $T_c=282.35\ \mathrm{K}$ $\rho_c=214.24\ \mathrm{kg\,m^{-3}}$

- 303 values of the specific isochoric heat capacity, which have been calculated from the revised-and-extended-scaling equation of Levelt Sengers *et al.* (1984) in order to guarantee reasonable behavior of c_v in the critical region. For this purpose, the scaled equation was transformed to the critical parameters given in Eqs. (2.7)–(2.9).
- Twenty-four $p\rho T$ data within the high-temperature/high-pressure region calculated from the reference equation of state for nitrogen [Span *et al.* (1998)] and transferred to ethylene via a simple corresponding states approach.
- Eighteen $T\rho$ points describing the course of the Joule curve, which have been determined by graphical extrapolation (see Sec. 5.4.2).

The bank of terms used in the optimization of the final equation of state consisted of 906 terms and can be written as

$$\alpha^r=\sum_{i=1}^{2}\sum_{j=-1}^{8} n_{ij}\delta^i\tau^{j/2}+\sum_{i=3}^{4}\sum_{j=0}^{8} n_{ij}\delta^i\tau^{j/2}+e^{-\delta}\sum_{i=1}^{12}\sum_{j=2}^{20} n_{ij}\delta^i\tau^{j/4}+e^{-\delta^2}\sum_{i=1}^{10}\sum_{j=1}^{20} n_{ij}\delta^i\tau^{j/2}+e^{-\delta^3}\sum_{i=4}^{10}\sum_{j=5}^{15} n_{ij}\delta^i\tau^{j}+e^{-\delta^4}\sum_{i=1}^{15}\sum_{j=10}^{30} n_{ij}\delta^i\tau^{j}+\sum_{i=1}^{48} n_i\delta^{d_i}\tau^{t_i}e^{-\eta_i(\delta-\varepsilon_i)^2-\beta_i(\tau-\gamma_i)^2}. \tag{4.10}$$

In view of the extrapolation behavior of the new equation of state, no terms with negative exponents for the inverse reduced temperature τ combined with exponents greater to or

TABLE 31. Residual part α^r of the dimensionless Helmholtz function and its derivatives[a]

$$\alpha^r=\sum_{i=1}^{6} n_i\delta^{d_i}\tau^{t_i}+\sum_{i=7}^{30} n_i\delta^{d_i}\tau^{t_i}e^{-\delta^{c_i}}+\sum_{i=31}^{35} n_i\delta^{d_i}\tau^{t_i}e^{-\eta_i(\delta-\varepsilon_i)^2-\beta_i(\tau-\gamma_i)^2}$$

$$\alpha^r_\delta=\sum_{i=1}^{6} n_i d_i\delta^{d_i-1}\tau^{t_i}+\sum_{i=7}^{30} n_i e^{-\delta^{c_i}}[\delta^{d_i-1}\tau^{t_i}(d_i-c_i\delta^{c_i})]+\sum_{i=31}^{35} n_i\delta^{d_i}\tau^{t_i}e^{-\eta_i(\delta-\varepsilon_i)^2-\beta_i(\tau-\gamma_i)^2}\left[\frac{d_i}{\delta}-2\eta_i(\delta-\varepsilon_i)\right]$$

$$\alpha^r_{\delta\delta}=\sum_{i=1}^{6} n_i d_i(d_i-1)\delta^{d_i-2}\tau^{t_i}+\sum_{i=7}^{30} n_i e^{-\delta^{c_i}}\{\delta^{d_i-2}\tau^{t_i}[(d_i-c_i\delta^{c_i})(d_i-1-c_i\delta^{c_i})-c_i^2\delta^{c_i}]\}+\sum_{i=31}^{35} n_i\tau^{t_i}e^{-\eta_i(\delta-\varepsilon_i)^2-\beta_i(\tau-\gamma_i)^2}$$
$$\cdot[-2\eta_i\delta^{d_i}+4n_i^2\delta^{d_i}(\delta-\varepsilon_i)^2-4d_i\eta_i\delta^{d_i-1}(\delta-\varepsilon_i)+d_i(d_i-1)\delta^{d_i-2}]$$

$$\alpha^r_\tau=\sum_{i=1}^{6} n_i t_i\delta^{d_i}\tau^{t_i-1}+\sum_{i=7}^{30} n_i t_i\delta^{d_i}\tau^{t_i-1}e^{-\delta^{c_i}}+\sum_{i=31}^{35} n_i\delta^{d_i}\tau^{t_i}e^{-\eta_i(\delta-\varepsilon_i)^2-\beta_i(\tau-\gamma_i)^2}\left[\frac{t_i}{\tau}-2\beta_i(\tau-\gamma_i)\right]$$

$$\alpha^r_{\tau\tau}=\sum_{i=1}^{6} n_i t_i(t_i-1)\delta^{d_i}\tau^{t_i-2}+\sum_{i=7}^{30} n_i t_i(t_i-1)\delta^{d_i}\tau^{t_i-2}e^{-\delta^{c_i}}+\sum_{i=31}^{35} n_i\delta^{d_i}\tau^{t_i}e^{-\eta_i(\delta-\varepsilon_i)^2-\beta_i(\tau-\gamma_i)^2}\left[\left(\frac{t_i}{\tau}-2\beta_i(\tau-\gamma_i)\right)^2-\frac{t_i}{\tau^2}-2\beta_i\right]$$

$$\alpha^r_{\delta\tau}=\sum_{i=1}^{6} n_i d_i t_i\delta^{d_i-1}\tau^{t_i-1}+\sum_{i=7}^{30} n_i e^{-\delta^{c_i}}\delta^{d_i-1}t_i\tau^{t_i-1}(d_i-c_i\delta^{c_i})$$
$$+\sum_{i=31}^{35} n_i\delta^{d_i}\tau^{t_i}e^{-\eta_i(\delta-\varepsilon_i)^2-\beta_i(\tau-\gamma_i)^2}\left[\frac{d_i}{\delta}-2\eta_i(\delta-\varepsilon_i)\right]\left[\frac{t_i}{\tau}-2\beta_i(\tau-\gamma_i)\right]$$

[a] $\alpha^r_\delta=\left[\frac{\partial\alpha^r}{\partial\delta}\right]_\tau$, $\alpha^r_{\delta\delta}=\left[\frac{\partial^2\alpha^r}{\partial\delta^2}\right]_\tau$, $\alpha^r_\tau=\left[\frac{\partial\alpha^r}{\partial\tau}\right]_\delta$, $\alpha^r_{\tau\tau}=\left[\frac{\partial^2\alpha^r}{\partial\tau^2}\right]_\delta$, and $\alpha^r_{\delta\tau}=\left[\frac{\partial^2\alpha^r}{\partial\delta\partial\tau}\right]$.

equal to 3 for the reduced density δ were introduced into the bank of terms. Based on the experience that equations of state, which include polynomial terms with density exponents d_i greater than 4, tend to behave unreasonably when being extrapolated to high densities, we restricted the exponents of these terms to $d_i \leq 4$ [see also Span and Wagner (1997)]. The modified Gaussian bell-shaped terms [last sum in Eq. (4.10)] were originally introduced by Setzmann and Wagner (1991). Forty-eight of these expressions were used in the bank of terms covering the following parameter ranges: $1 \leq d_i \leq 3$, $0 \leq t_i \leq 3$, $15 \leq \eta_i \leq 25$, $275 \leq \beta_i \leq 325$, and $1.13 \leq \gamma_i \leq 1.22$, with $\varepsilon_i = 1$.

4.5. New Equation of State

Proceeding from the bank of terms defined by Eq. (4.10), the following combination of terms was obtained for the residual part of the Helmholtz energy using the optimization method briefly described in Sec. 4.3.2:

$$\alpha^r=\sum_{i=1}^{6} n_i\delta^{d_i}\tau^{t_i}+\sum_{i=7}^{30} n_i\delta^{d_i}\tau^{t_i}e^{-\delta^{c_i}}+\sum_{i=31}^{35} n_i\delta^{d_i}\tau^{t_i}e^{-\eta_i(\delta-\varepsilon_i)^2-\beta_i(\tau-\gamma_i)^2}. \quad (4.11)$$

The final values of the coefficients n_i of Eq. (4.11) have been determined by a direct nonlinear fit to the linear and nonlinear data summarized in Table 29. The values of the coefficients n_i are given in Table 30 together with the parameters resulting from the optimization process.

The new equation of state for ethylene, Eq. (4.1) in combination with the formulation for α^o given in Eq. (4.6) and the formulation for α^r given in Eq. (4.11), was constrained t the critical parameters given in Sec. 2.2 and to the first an second partial derivatives of pressure with respect to densit being zero at the critical point. It is valid for the entire flui region covered by reliable experimental data, namely, for

$$104\ \text{K} \leq T \leq 450\ \text{K}$$

and

$$p \leq 300\ \text{MPa}.$$

Estimations for the uncertainty of Eq. (4.1) are given in Se 6 and the quality of the new equation of state is discusse in Sec. 5. The necessary derivatives of α^r are given i Table 31.

5. Comparison of the New Equation of State with Experimental Data and Othe Equations of State

In this section, the quality of the new equation of state discussed based on comparisons with selected experiment data. Most figures also show results of the IUPAC equatic of state for ethylene [Jacobsen *et al.* (1988)], which was fir published by Jahangiri *et al.* (1986) and which is commonl accepted as the international standard for thermodynam properties of ethylene. Additionally, the revised-an extended-scaling equation of Levelt Sengers *et al.* (1984 which was used by Jacobsen *et al.* (1988) to calculate pro erties in the critical region, is included in comparisons whe it is applicable. The representation of thermodynamic pro erties in the critical region is discussed in Sec. 5.3.

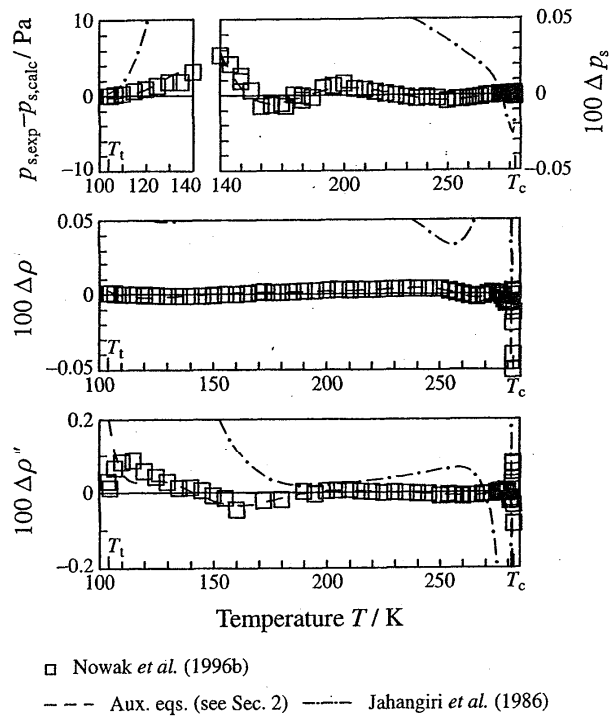

FIG. 11. Absolute and percentage deviations $[\Delta y=(y_{exp}-y_{calc})/y_{exp}$ with $y=p_s,\rho',\rho'']$ of the selected thermal data at saturation from values calculated from Eq. (4.1). Values calculated from the auxiliary equations presented in Sec. 2 and from the IUPAC equation of state are plotted for comparison.

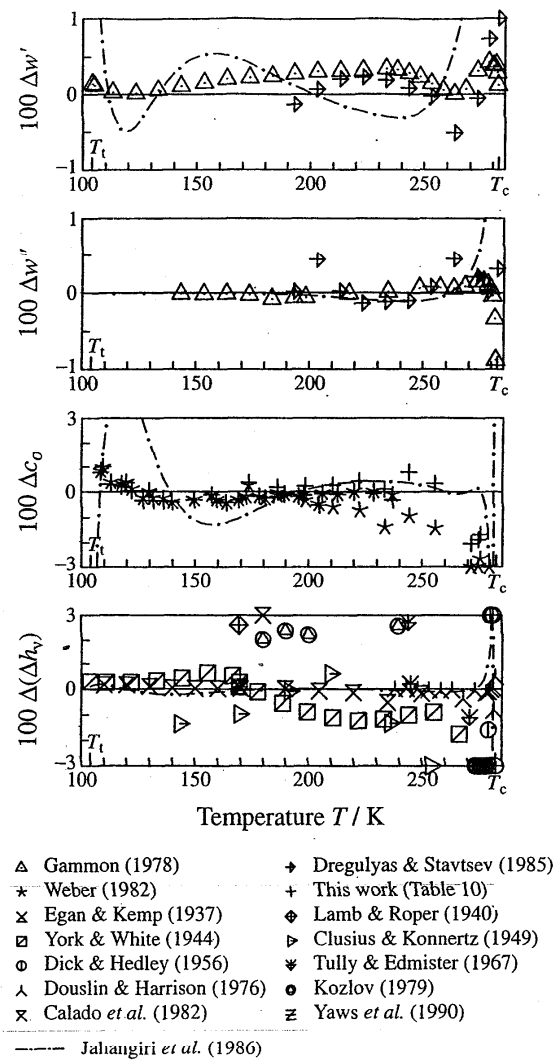

FIG. 12. Percentage deviations $[\Delta y=(y_{exp}-y_{calc})/y_{exp}$ with $y=w',w'',c_\sigma,\Delta h_v]$ of data for the speed of sound on the saturated-liquid and saturated-vapor line, for the heat capacity along the saturated-liquid line, and for the enthalpy of vaporization from values calculated from Eq. (4.1). Values calculated from the IUPAC equation of state are plotted for comparison.

None of the existing equations of state for ethylene are valid on the ITS-90 temperature scale. Therefore, temperatures were reconverted to the IPTS-68 scale again before values were calculated from those equations.

5.1. Liquid–Vapor-Phase Boundary

5.1.1. Thermal Properties

As shown in Sec. 2, the discussion on the representation of thermal properties on the liquid–vapor boundary can be restricted to the data of Nowak *et al.* (1996b). The deviations between these data and values calculated from Eq. (4.1) by using the phase equilibrium conditions [see Eq. (4.2)] are shown in Fig. 11. The additional lines correspond to values calculated from the auxiliary equations given in Sec. 2 and to values calculated from the IUPAC equation of state [Jacobsen *et al.* (1988)]. The upper diagram of Fig. 11 is split up into two parts. On the left side, absolute deviations in the vapor pressure are shown for temperatures below 140 K, while relative deviations are shown on the right side for higher temperatures.

Equation (4.1) represents the selected data far within their uncertainties. The deviations to the vapor-pressure data of Nowak *et al.* (1996b) do not exceed ±0.01% for temperatures above 150 K and ±4 Pa below 150 K. Saturated-liquid densities are represented to within ±0.004% up to a temperature of 279 K. Approaching the critical temperature, the deviations increase up to ±0.1%. The selected saturated-vapor density data are represented to within ±0.1% in the critical region as well. In the range 172 K$\leqslant T\leqslant$282 K, deviations between measured and calculated vapor densities are generally less than ±0.02%. For temperatures below 172 K these deviations increase, reaching up to ±0.1% at temperatures below 120 K. Unambiguously, these deviations result from the increased relative uncertainty in the vapor pressure, which leads to deviations in the same order of magnitude. The IUPAC equation of state is by far not able to represent the selected data within their experimental uncertainties. The auxiliary equations presented in Sec. 2 reproduce the experimental data slightly better than Eq. (4.1) does. Nevertheless, if one is interested in thermodynamically consistent values

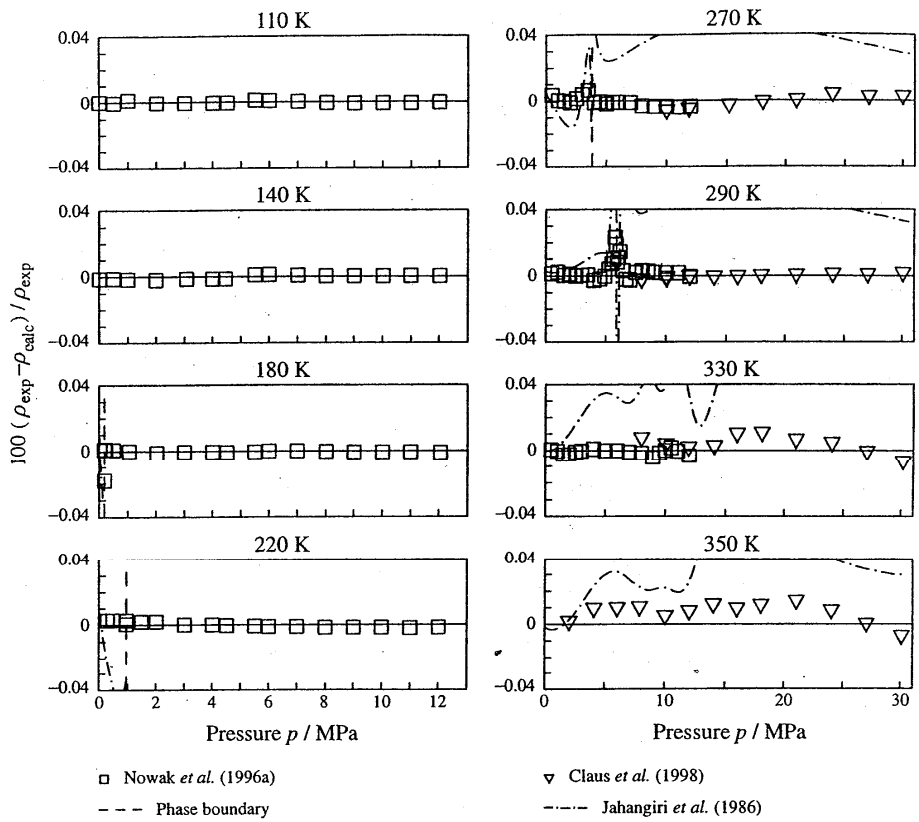

FIG. 13. Percentage density deviations of highly accurate $p\rho T$ data from values calculated from Eq. (4.1). Values calculated from the IUPAC equation of stat are plotted for comparison.

for all properties on the phase boundary, data should be calculated from Eq. (4.1) in combination with Eq. (4.2).

5.1.2. Caloric Properties

Figure 12 gives a comparison between selected data providing information on caloric properties on the phase boundary of ethylene and values calculated from Eq. (4.1). All data are represented by Eq. (4.1) to within their experimental uncertainties.

The data for the speed of sound data in the saturated liquid measured by Gammon (1978) are reproduced to within ±0.43%, while the experimental results for the speed of sound in the saturated vapor are represented to within ±0.1%. Approaching the critical temperature, the observed deviations increase but they still remain far within the uncertainty of the data. The equation of state by Jahangiri *et al.* (1986) is not able to follow the decreasing values of the speed in the saturated liquid and vapor for temperatures above 260 and 270 K, respectively.

The group 1 data for the heat capacity along the saturated-liquid line are represented by Eq. (4.1) to within ±1%. Three points at temperatures above 270 K show larger deviations which probably result from increased uncertainties of the original c_v data of Weber (1982), see also Sec. 2.8.

Data for the enthalpy of vaporization have not been use to establish the new equation of state. They are represente within their rather large experimental uncertainties, both b Eq. (4.1) and by the IUPAC equation of state by Jahangi *et al.* (1986).

5.2. Single-Phase Region

5.2.1. $p\rho T$ Data

Figure 13 shows comparisons between highly accurat $p\rho T$ data assigned to group 1 and values calculated from Ec (4.1). The plotted pressure and temperature range corre sponds to the region covered by state-of-the-art measure ments of Nowak *et al.* (1996a, 1996b), Guo *et al.* (1992) and Claus *et al.* (1998). The data of Nowak *et al.* for pres sures up to 12 MPa and at temperatures up to 340 K ar supplemented by the data of Claus *et al.* extending the rang covered by highly accurate measurements to 30 MPa an 350 K. By these data, the $p\rho T$ surface is described with a uncertainty of approximately ±0.02% in density. In the ex tended critical region the experimental uncertainty is abou ±0.015% in pressure. Equation (4.1) represents the data c Nowak *et al.*, Guo *et al.*, and Claus *et al.* far within thes uncertainties. The IUPAC equation of state, which of cours

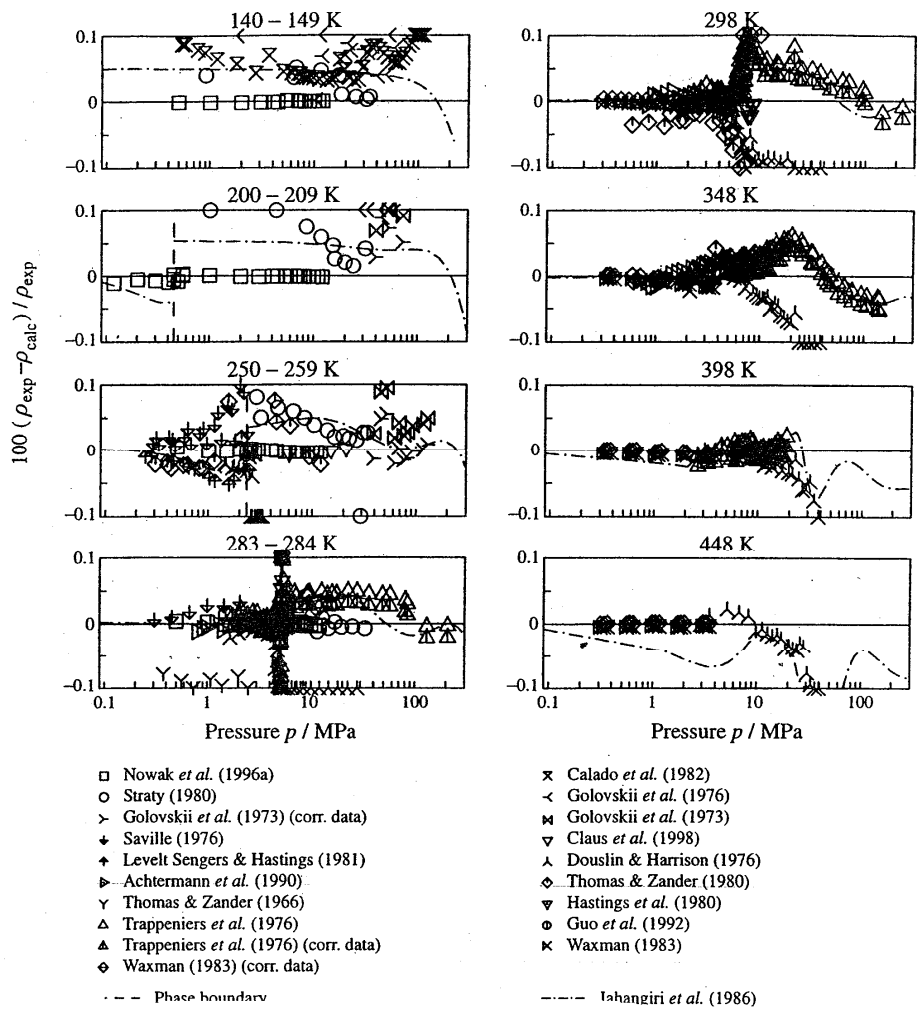

FIG. 14. Percentage density deviations of $p\rho T$ data assigned to groups 1 and 2 from values calculated from Eq. (4.1). Values calculated from the IUPAC equation of state are plotted for comparison.

had no access to recent $p\rho T$ data, is not able to represent the reference data to within their experimental uncertainty by far.

Figure 14 shows a representative set of group 1 and 2 data for pressures up to 300 MPa. With ±0.1%, the scale chosen in Fig. 14 corresponds to the typical experimental uncertainty of group 2 data. Data sets were assigned to group 2, if they agree with group 1 data within this limit. Partly enlarged deviations in the order of ±(0.1%–0.2%) were tolerated if the corresponding data sets play an important role in defining the $p\rho T$ surface. The data set of Straty (1980) was selected for the development of the new equation of state only in the range 105 K$\leq T \leq$230 K at pressures 12 MPa$\leq p \leq$40 MPa and 230 K$< T \leq$270 K at 30 MPa$< p \leq$40 MPa, which was not covered by other reliable experimental data. Outside of this region, the data of Straty deviate systematically from other group 1 data. When these data were considered in the development of preliminary equations of state, they caused unreasonable behavior in the representation of the liquid region. The described deviations become obvious for the isotherms at 140–149 and 200–209 K.

At temperatures above 273 K and pressures above 30 MPa, the data set of Trappeniers *et al.* (1976), corrected according to Eq. (3.2), was used to establish the new equation of state. The isotherm at 348 K shows a characteristic problem with this data set. While the course of Eq. (4.1) is in agreement with the reference data of Claus *et al.* (1998) at 350 K (see Fig. 13), systematic deviations from the data set of Trappeniers *et al.* (from +0.04% at 20 MPa to −0.05% at 143 MPa) are observed in Fig. 14. Obviously, Jahangiri *et al.* (1986) overfitted this data set.

The data of Douslin and Harrison (1976) are plotted in Fig. 14 to illustrate the systematic deviations between these data, other group 1 data, and values calculated from Eq. (4.1). The observed deviations at high temperatures and pressures are *not* caused by an unreasonable behavior of the new equation of state, but by systematic experimental errors. For

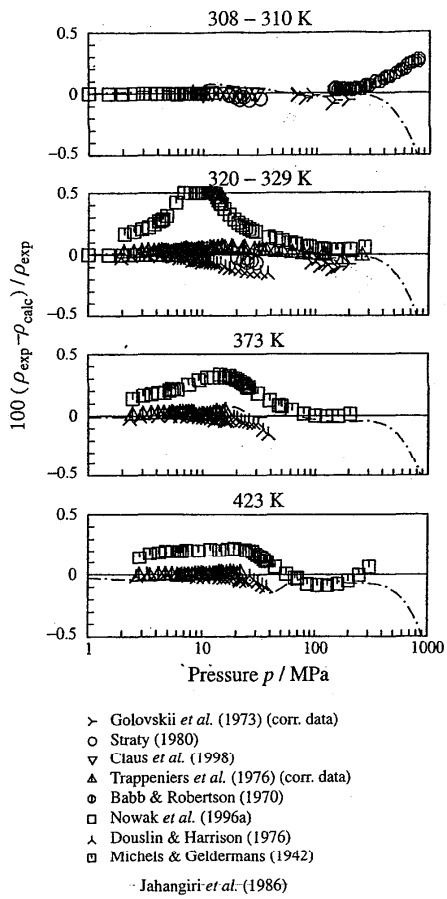

FIG. 15. Percentage density deviations of $p\rho T$ data in the high-pressure range from values calculated from Eq. (4.1). Values calculated from the IUPAC equation of state are plotted for comparison.

temperatures and pressures above 410 K and 4 MPa, respectively, this data set is the only basis of reliable experimental information. Equation (4.1) represents the data to within their experimental uncertainty, whereby an enlarged uncertainty has to be assumed for pressures above about 20 MI

Comparisons with experimental $p\rho T$ data at pressures to 800 MPa are given in Fig. 15. The data set of Babb a Robertson (1970) consists of 26 $p\rho T$ measurements at a te perature of 308 K and at pressures from 145 to 798 MI These data are represented by Eq. (4.1) to within ±0.4 while the IUPAC equation of state is not able to reprodu these data with reasonable deviations. At pressures ≥40 MPa, the experimental results of Michels and Geld mans (1942), which reach up to 320 MPa, are represent both by Eq. (4.1) and by the IUPAC equation with deviatio of less than ±0.2%.

The representation of $p\rho T$ data in the critical region discussed in Sec. 5.3.1.

5.2.2. Virial Coefficients

Deviations between selected data for the second virial c efficient B and values calculated from Eq. (4.1) are shown Fig. 16. The calculated second virial coefficients are in go agreement with the selected data, which are generally repr duced within their uncertainty. At temperatures above 250 the data sets of Douslin and Harrison (1976), Trappenie *et al.* (1976), Waxman and Davis (1979), Achtermann *et* (1990), and Nowak *et al.* (1996a) confirm each other with ±0.4 $cm^3\,mol^{-1}$ and are represented by Eq. (4.1) to with this limit.

In Fig. 17, third virial coefficient C calculated from E (4.1) and from the IUPAC equation of state are plotted t gether with selected data. Near T_c, both equations yield t expected maximum in the third virial coefficient. Compar to Eq. (4.1), the evaluation of the IUPAC equation giv smaller values for C over the whole temperature rang which cannot be justified by comparisons with reliable e perimental data, while Eq. (4.1) is able to reproduce all da sets within their uncertainty.

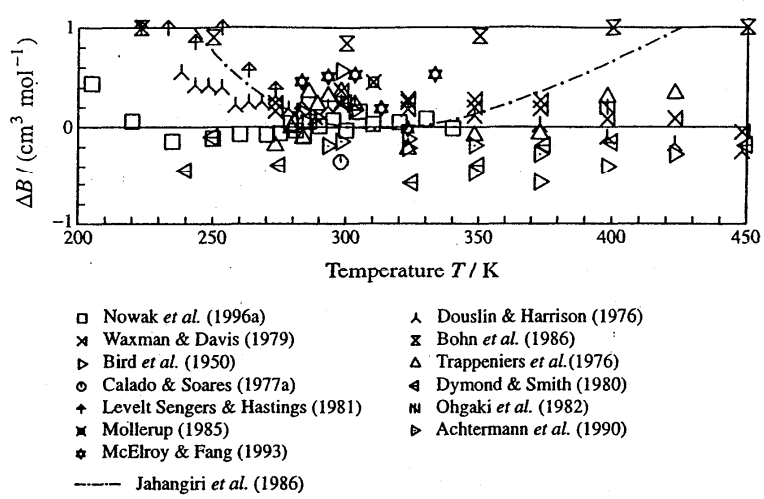

FIG. 16. Absolute deviations ($\Delta B = B_{exp} - B_{calc}$) of the selected data for the second viral coefficient from values calculated from Eq. (4.1). Values calculate from the IUPAC equation of state are plotted for comparison.

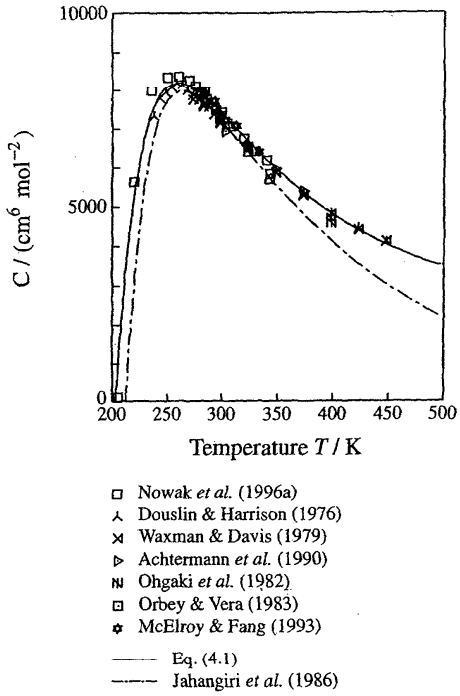

FIG. 17. Representation of the selected data for the third viral coefficient for temperatures up to 500 K. The plotted curves correspond to values calculated from Eq. (4.1) and from the IUPAC equation of state.

5.2.3. Speed of Sound

Figure 18 compares speed of sound data assigned to groups 1 and 2 with values calculated from Eq. (4.1). For ethylene, highly accurate speed of sound data determined by spherical resonator measurements are available only from the experimental work of Mehl and Moldover (1981). Equation (4.1) reproduces this data set within ±0.05%. However, with regard to the development of equations of state, the relevance of this highly accurate data set is rather restricted since it is limited to pressures up to only 1 MPa. At higher pressures the data of Gammon (1978) describe the speed of sound of ethylene with an uncertainty of ±0.1% in the gas phase up to ±2% in the critical region. Those data are represented by Eq. (4.1) to within their experimental uncertainty as well.

With regard to speeds of sound in the liquid region of ethylene, today's knowledge is mainly based on the data of Dregulyas and Stavtsev (1985). However, further work could substantially improve the data situation with regard to caloric properties in the liquid region. The results of Dregulyas and Stavtsev are represented by Eq. (4.1) to within ±0.5%, although they show large scatter and systematic deviations in certain regions. During this work, special attention has been paid to the representation of this data set since reliable experimental information on caloric properties in the liquid region of ethylene is rare. In order to improve the representation of these data, larger values were temporarily used for the corresponding weighting factors, but this approach resulted in unreasonable behavior with regard to the representation of

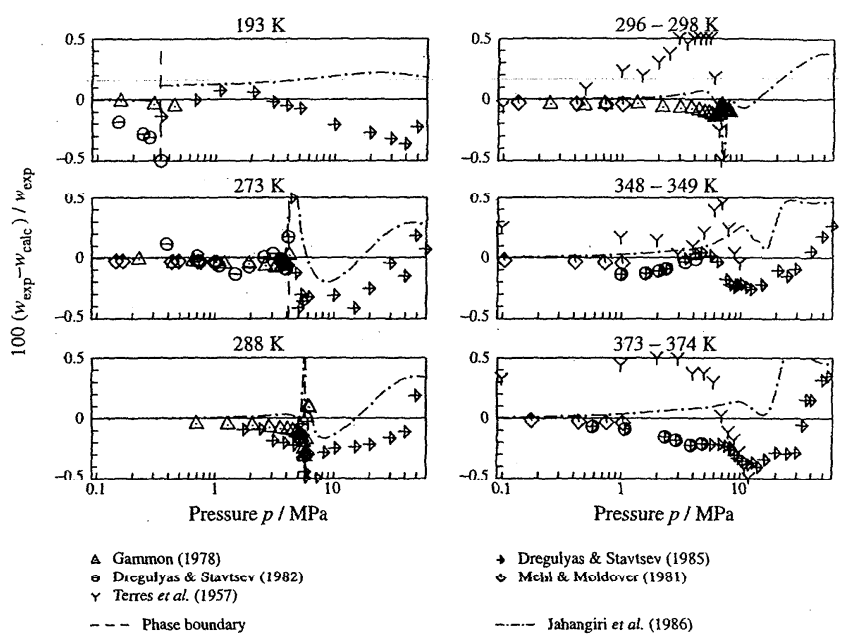

FIG. 18. Percentage deviations of speed of sound data assigned to groups 1 and 2 from values calculated from Eq. (4.1). Values calculated from the IUPAC equation of state are plotted for comparison.

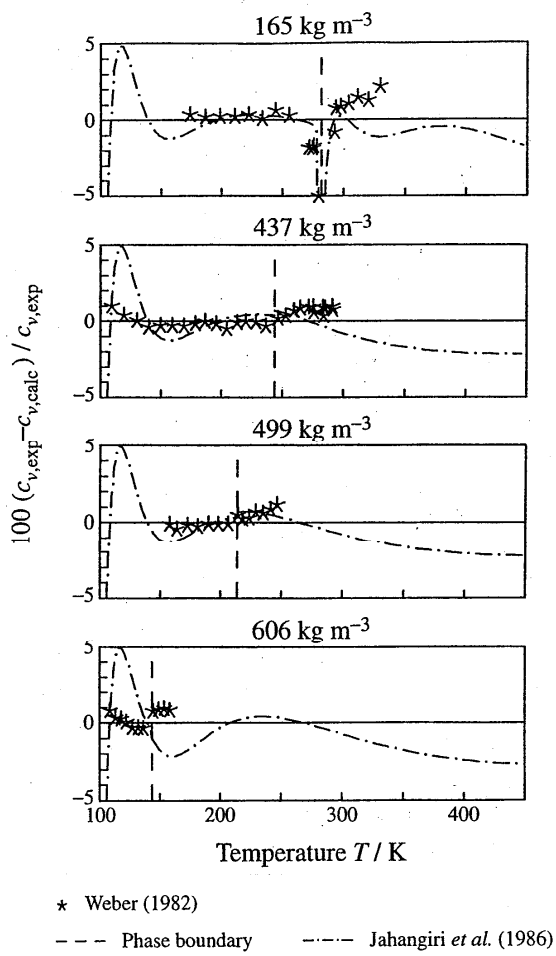

FIG. 19. Percentage deviations of selected isochoric heat capacity data in the homogeneous region and in vapor–liquid equilibrium from values calculated from Eq. (4.1). Values calculated from the IUPAC equation of state are plotted for comparison.

the $p\rho T$ surface, which is precisely known. Thus, we attribute systematic deviations between speed of sound values calculated from Eq. (4.1) and the data of Dregulyas and Stavtsev to experimental uncertainties of the data.

5.2.4. Isochoric Heat Capacity

Deviation plots showing the representation of data for the specific isochoric heat capacity are presented in Fig. 19. In the homogeneous region, the data of Weber (1982) were used to develop the new equation of state; experimental results in the two-phase region left of the line marking the saturation temperature were used only for comparisons. Equation (4.1) represents the data of Weber to within their experimental uncertainty. The IUPAC equation properly reproduces these data only in the homogeneous region for densities below 400 kg m^{-3}. At higher densities and in the two-phase region, the IUPAC equation of state shows an unreasonable behavior. Figure 20 shows the plot of the isochoric heat capacity calculated from Eq. (4.1) and from the

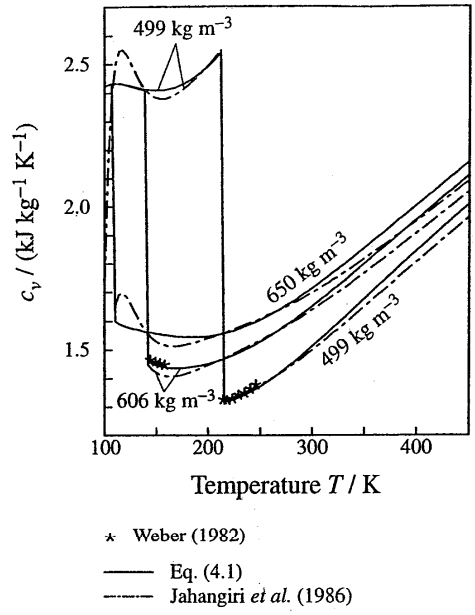

FIG. 20. Representation of the isochoric heat capacity on isochores in t liquid region and in vapor–liquid equilibrium. The plotted curves cor spond to values calculated from Eq. (4.1) and from the IUPAC equati of state.

IUPAC equation of state along three selected isochores in t liquid and in the two-phase region of ethylene. For vapo liquid equilibrium states at densities of 606 and 650 kg m the course of c_v is congruent to that shown for 499 kg m While Eq. (4.1) yields reasonable results for c_v, the IUPA equation of state results in a temperature-dependent oscill tion at temperatures below 200 K.

5.2.5. Isobaric Heat Capacity

Figure 21 shows deviations between group 1 c_p data a values calculated from Eq. (4.1). Equation (4.1) reproduc the data of Bender (1982), corrected according to Table 2 with deviations of less than ±0.11%. The isobar at 2.5 M gives a typical example for the representation of the data Watanabe (1980). Although these data have been adjusted become more consistent with accurate low-pressure data, scatter of about ±1% remains. Equation (4.1) is able to r produce all data sets within their experimental uncertaint The IUPAC equation of state yields very similar results f the isobaric heat capacity in the gas region. In the liqu region, the IUPAC equation shows the same unreasonab behavior as for the isochoric heat capacity. Equation (4. reproduces the only data set for c_p in the liquid regio namely, the one of Egan and Kemp (1937), with deviatio in the order of ±1%, but still far within the experiment uncertainty of the data.

5.2.6. Enthalpy Differences

Absolute deviations between enthalpy differences Δh_{e} calculated from the polynomial equations published by Da

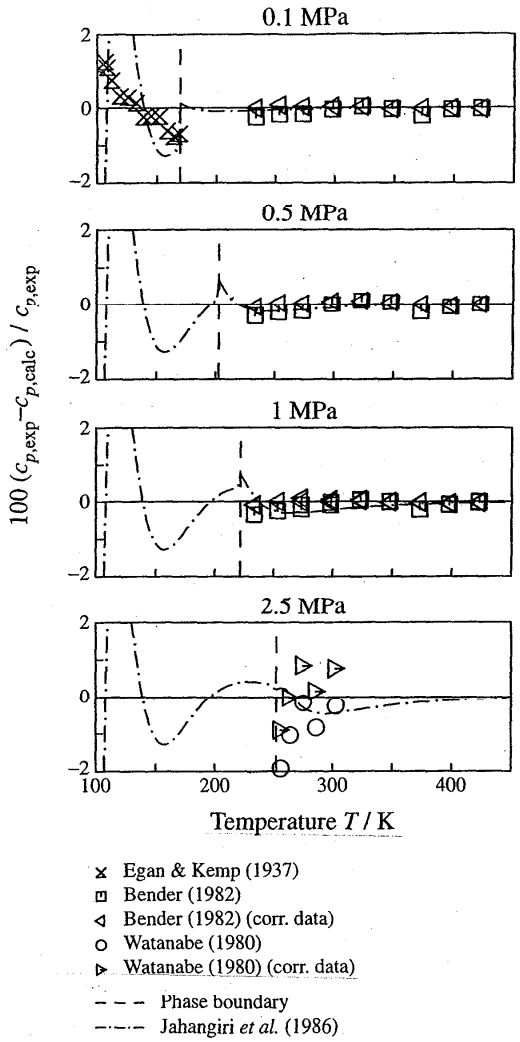

FIG. 21. Percentage deviations of selected isobaric heat capacity data from values calculated from Eq. (4.1). Values calculated from the IUPAC equation of state are plotted for comparison.

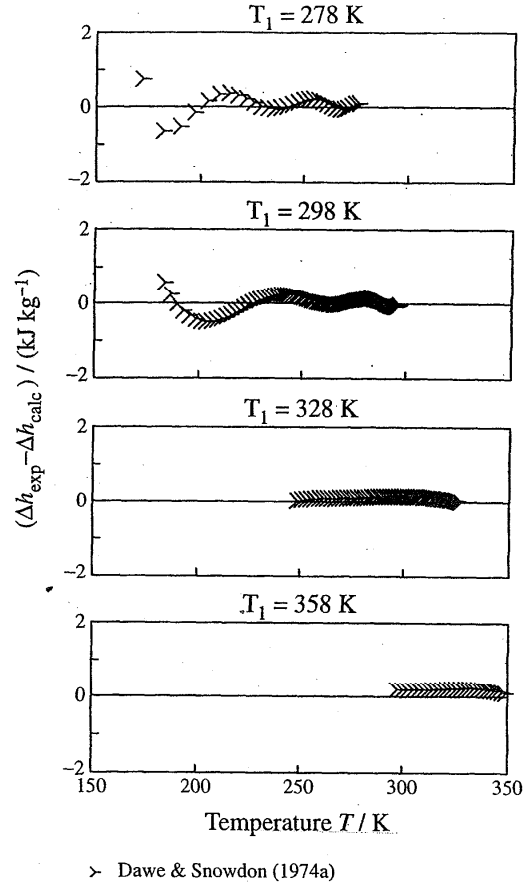

FIG. 22. Absolute deviations of data for differences of enthalpy from values calculated from Eq. (4.1). The data of Dawe and Snowdon (1974a) were calculated from polynomial equations using the corrected values for the coefficients of Dawe and Snowdon (1975).

and Snowdon (1974a), as a representation of their experimental results and values Δh_{calc} determined from Eq. (4.1), are presented in Fig. 22. A separate polynomial equation was published by Dawe and Snowdon for each initial temperature T_1. Those equations yield values for the temperature difference (T_2-T_1) obtained by isenthalpic throttling from p_1 to p_2 with $p_{2,min}$=0.101 325 MPa. In Fig. 22, all data are plotted for the final temperature T_2. Although Δh data were not used in the development of Eq. (4.1), the results of Dawe and Snowdon (1974a, 1974b) are reproduced to within ± 1 kJ kg^{-1}. Likewise, all other data for enthalpy differences are represented by Eq. (4.1) to within their experimental uncertainty.

5.2.7. Throttling Coefficients

Figure 23 shows a comparison between data for the Joule–Thomson coefficient μ and values calculated from Eq. (4.1). Except for two outliers, all data are represented by Eq. (4.1) far within ± 0.1 K MPa^{-1}. In the gas phase, Eq. (4.1) is clearly superior to the IUPAC equation, which shows significant systematic deviations. However, at liquid and liquid-like overcritical states, the deviation between values calculated from both equations is much smaller than the experimental uncertainty of the available data.

No comparisons are given for the isothermal throttling coefficient δ_T since the available experimental data do not allow sound conclusions.

5.3. Critical Region

For an assessment of Eq. (4.1) with regard to the representation of properties close to the critical point, a comparison with results from the revised-and-extended-scaling equation of Levelt Sengers *et al.* (1984) is of special interest. This numerically very complex equation was developed especially for the description of thermodynamic properties in the critical region. In contrast to the values for the critical exponents used in scaled equations of state, analytical equations

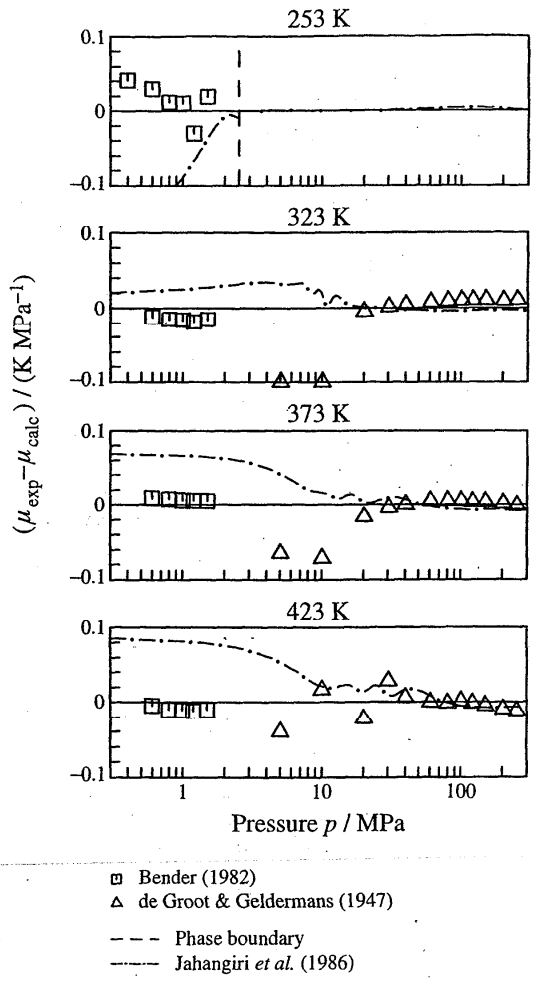

FIG. 23. Absolute deviations of data for the Joule–Thomson coefficient from values calculated from Eq. (4.1). Values calculated from the IUPAC equation of state are plotted for comparison.

of state result in values for the critical exponents, which do not agree with those predicted by the renormalization group theory. From this fact, it is usually concluded that analytical equations of state are not able to describe correctly thermodynamic properties in the critical region. However, it can be shown that this conclusion is wrong for state-of-the-art multiparameter equations of state [see Span and Wagner (1996); Span (2000)]. Based on the data available for ethylene, it will be shown that Eq. (4.1) represents highly accurate data for thermal properties far within their experimental uncertainty even in the immediate vicinity of the critical point.

In order to make fair comparisons between values calculated from Eq. (4.1) and from the revised-and-extended-scaling equation of Levelt Sengers *et al.* possible, the scaled 5equation was transformed to the critical parameters given in Eqs. (2.7)–(2.9) before it was used to generate the figures of this section. In the critical region, the IUPAC tables for ethylene [Jacobsen *et al.* (1988)] are based on the equation by Levelt Sengers *et al.* (1984) instead of the equation by . angiri *et al.* (1986).

5.3.1. Thermal Properties

Figure 24 shows comparisons between group 1 $p\rho T$ c in the critical and extended critical region and values cal lated from Eq. (4.1). Values calculated from the scaled eq tion of Levelt Sengers *et al.* (1984) and from the equatior state of Jahangiri *et al.* (1986) are plotted for comparis Equation (4.1) represents all data to within their experim tal uncertainties. In Fig. 24, the lines which correspond values calculated from the equation of Levelt Sengers *et* end at the limits of its range of validity. In the immedi vicinity of the critical point, values calculated from the n equation of state, Eq. (4.1), and from the adjusted sca equation, agree with each other to within ±0.01% in pr sure. However, at densities above 280 kg m^{-3} the equation Levelt Sengers *et al.* yields pressures which are significan too small. For higher temperatures, the description of $p\rho T$ surface by the scaled equation becomes worse ev though the corresponding states still belong to the extend critical region.

The equation of state of Jahangiri *et al.* (1986) is not al to reproduce the experimental data within their uncertainti

5.3.2. Caloric Properties

At the critical point, the scaled equation of state of Lev Sengers *et al.* (1984) results in a weak divergence of t isochoric heat capacity c_v. As a consequence, the speed sound w becomes zero at the critical point. In contrast to th analytical equations of state yield finite values for c_v a values greater than zero for w. However, for Eq. (4.1) t region in which this completely different behavior affec results for caloric properties is limited to temperatures in t range $|T-T_c| \leq \sim 0.5$ K.

During this work, 303 values for the specific isochor heat capacity which were calculated from the revised-an extended-scaling equation of Levelt Sengers *et al.* (198 with adjusted critical parameters were used in order to in prove the representation of c_v in the critical region. The da were calculated on isochores corresponding to the critic density and to densities 10% and 20% above and below ρ_c The covered temperature range reaches from the respectiv saturation temperature up to a maximum 7 K above satur tion temperature. Figure 25 shows the plot of the isochori heat capacity along the critical isochore and the isochore 257 kg m^{-3} ($1.2\rho_c$), as calculated from Eq. (4.1) and fro the equation of Jahangiri *et al.* The results of the scale equation of state of Levelt Sengers *et al.* are represented b the plotted data points, which illustrate the region in whic "synthetic" data were used to improve the representation o the isochoric heat capacity. Along the critical isochore, Ec (4.1) reproduces the results of the scaled equation of state fo $T-T_c \geq \sim 0.5$ K. However, as a purely analytic equation o state, it yields a finite value for the isochoric heat capacity a the critical point. At densities 20% above ρ_c, there is n

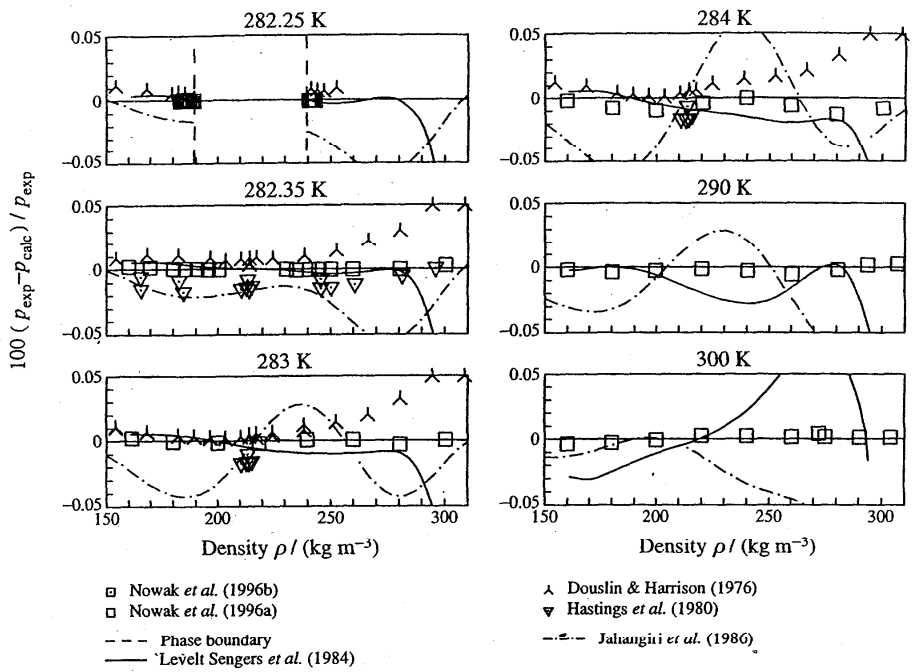

FIG. 24. Percentage pressure deviations of group 1 $p\rho T$ data in the critical and in the extended critical region from values calculated from Eq. (4.1). Values calculated from the revised-and-extended-scaling equation of Levelt Sengers *et al.* (1984) and from the equation of state of Jahangiri *et al.* (1986) are plotted for comparison.

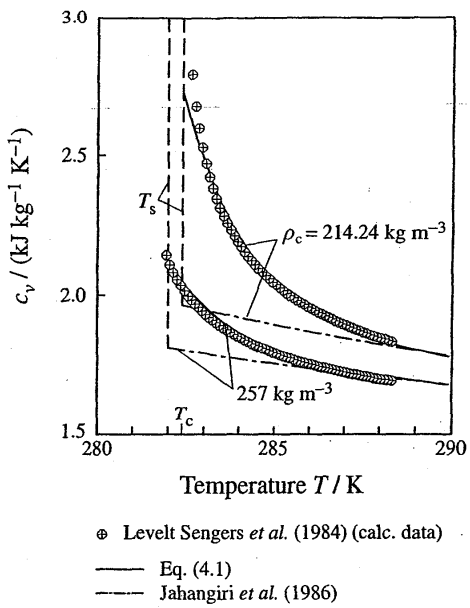

FIG. 25. Representation of the isochoric heat capacity on isochores in the critical and in the extended critical region. The plotted curves correspond to values calculated from Eq. (4.1) and from the equation of state of Jahangiri *et al.* (1986). The data were calculated from the revised-and-extended-scaling equation of Levelt Sengers *et al.* (1984) using the values for the critical parameters given in Sec. 2.

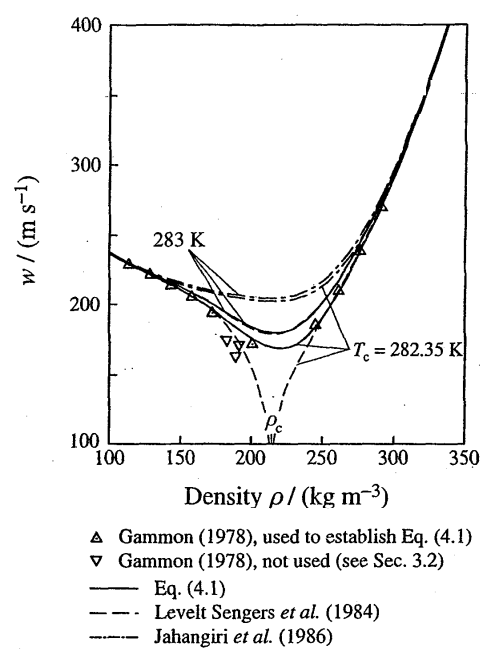

FIG. 26. Representation of the speed of sound on isotherms in the critical region. The plotted curves correspond to values calculated from Eq. (4.1), from the revised-and-extended-scaling equation of Levelt Sengers *et al.* (1984), and from the equation of state of Jahangiri *et al.* (1986).

significant difference between the results of Eq. (4.1) and of the scaled equation of state. In the whole critical region, the equation of Jahangiri *et al.* results in systematically smaller values for the isochoric heat capacity.

In Fig. 26, speeds of sound w calculated from Eq. (4.1) are compared with results from the scaled equation of state of Levelt Sengers *et al.* and from the equation of Jahangiri *et al.* Both Eq. (4.1) and the equation of Levelt Sengers *et al.* are able to reproduce the speed of sound data of Gammon (1978) to within their experimental uncertainties. However, at the critical point Eq. (4.1) does not result in the vanishing speed of sound predicted by the scaled equation of state. At temperatures $T-T_c > \sim 0.5$ K, Eq. (4.1) and the equation of Levelt Sengers *et al.* yield very similar results for the speed of sound. The equation of state of Jahangiri *et al.* (1986) is not able to reproduce the experimental data for the speed of sound in the critical region within their uncertainties.

5.4. Extrapolation Behavior of the New Equation of State

The range of validity of Eq. (4.1) is limited to the region where reliable experimental data exist, and thus to temperatures $T \leqslant 450$ K. This limit results mainly from ethylene's ability to polymerize at elevated temperatures and pressures. Nevertheless, reasonable behavior of the new equation of state has to be guaranteed outside of its range of validity as well, e.g., for its application in state-of-the-art mixture models [see Lemmon and Tillner-Roth (1999)]. This "extrapolation behavior" will be discussed in the following sections.

5.4.1. Extrapolation to High Pressures and Temperatures

Common techniques which are used for other substances to measure thermodynamic properties at very high temperatures and pressures are not applicable for ethylene. To constrain the new equation of state to a reasonable behavior at very high pressures and temperatures, 24 $p\rho T$ data have been calculated from the recent reference equation of state for nitrogen [Span *et al.* (1998)] and have been transferred to ethylene via a simple corresponding states approach. For three selected isotherms, Fig. 27 compares these data with values calculated from Eq. (4.1) and from the IUPAC equation of state. Both equations yield basically reasonable plots. However, pressures calculated from the IUPAC equation seem to be far too large in the high-temperature, high-density region.

5.4.2. "Ideal Curves"

Ideal curves are curves along which one property of a real fluid is equal to the corresponding property of the ideal gas in the same state. The most important ideal curves are derived from the compression factor z and its first derivatives, i.e., the classical ideal curve ($z=1$), the Boyle curve $[(\partial z/\partial p)_T=0]$, the Joule–Thomson inversion curve $[(\partial z/\partial T)_p=0]$, and the Joule inversion curve $[(\partial z/\partial p$ $=0]$. Based on theoretical considerations performed in tl 1960s, the courses of these curves were expected to be un versal for all pure fluids in reduced variables.

Recent investigations [Span and Wagner (1997)] ha shown that the representation of the ideal curves is a usef tool for the assessment of the extrapolation behavior of equ tions of state even though their plot is not as universal as w expected in the 1960s. For ethylene, the range covered b experimental information does not include any of the me tioned ideal curves completely. Thus, an investigation of tl ideal curves calculated from an equation of state for ethyle is not just a consistency test for the selected data set, but can be used to assess the extrapolation behavior of the equ tion.

Preliminary equations established during the work on E (4.1) showed an unreasonable plot of the Joule inversic curve at very high temperatures. In order to force the equ tion to form a maximum in the course of the second viri coefficient and to ensure that the equation of state yields intersection of the Joule inversion curve with the zer pressure line at that temperature, 18 $T\rho$ data were dete mined by graphical extrapolation of the Joule inversic curve, which is almost linear in a ρT plot. At these values T and ρ, the condition of the Joule inversion curve, $\alpha^{r}_{\delta\tau}=$ was introduced into the data set used to establish Eq. (4.1

Figure 28 shows the plot of the ideal curves calculat from Eq. (4.1) and from the IUPAC equation of state. Equ tion (4.1) shows reasonable plots of the ideal curves, indic ing that extrapolation beyond its range of validity is possibl The IUPAC equation of state yields unreasonable plots of tl Joule–Thomson and Joule inversion curve, indicating that extrapolation to high (reduced) temperatures yields mislea ing results.

6. Uncertainty of the New Equation of State

Mainly guided by comparisons with experimental data, e timates for the uncertainty of calculated densities ρ, spee of sound w, and isochoric and isobaric heat capacities c_v a c_p, calculated from Eq. (4.1), have been made. These unce tainties are illustrated in the tolerance diagrams, Figs. 29–3

Using the new equation of state outside its range of vali ity requires a critical assessment of phenomena which mig aid or prevent the polymerization of ethylene. Where pol merization can be neglected, Eq. (4.1) should yield reaso able results outside of its range of validity at least for bas properties like pressure and enthalpy. The calculation of d rived properties such as speeds of sound or specific he capacities is not recommended beyond the given limits validity.

7. Conclusions

Based on a comprehensive study on experimental data f thermodynamic properties of ethylene, a new fundamen

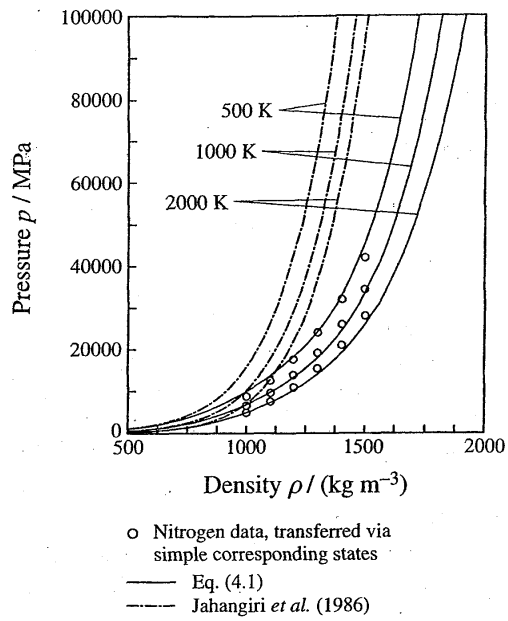

FIG. 27. Representation of data calculated from the reference equation of nitrogen of Span and Wagner (1998) after transformation to ethylene via corresponding-states theory. The plotted curves correspond to values calculated from Eq. (4.1) and from the IUPAC equation of state.

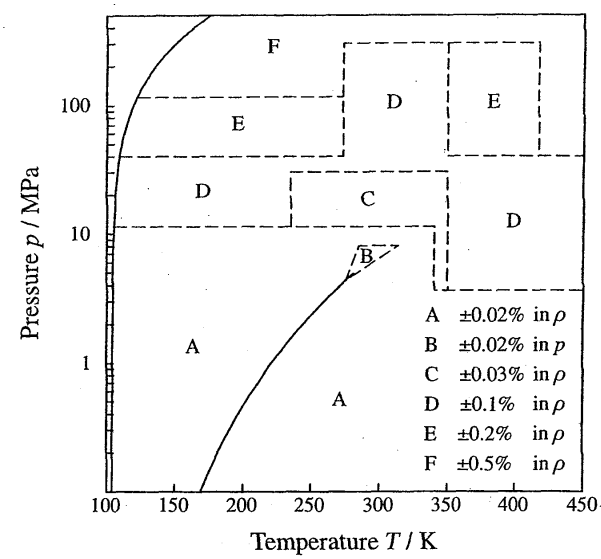

FIG. 29. Tolerance diagram for densities calculated from Eq. (4.1). In region B the uncertainty in pressure is given.

equation explicit in the reduced Helmholtz free energy has been developed. This empirical formulation is valid in the fluid region up to temperatures of 450 K and pressures up to 300 MPa. The equation is able to represent all of the reliable data in the homogeneous region and on the liquid–vapor-phase boundary within their experimental uncertainty. The consideration of new reference data for the thermal properties has resulted in a previously unequaled accuracy for the regions of major technical interest. Intensive work on the consistency of the data set used for the establishment of the new equation of state has led to reasonable results in regions with a poor data situation. Furthermore, the extrapolation behavior of the equation has been tested carefully. For basic

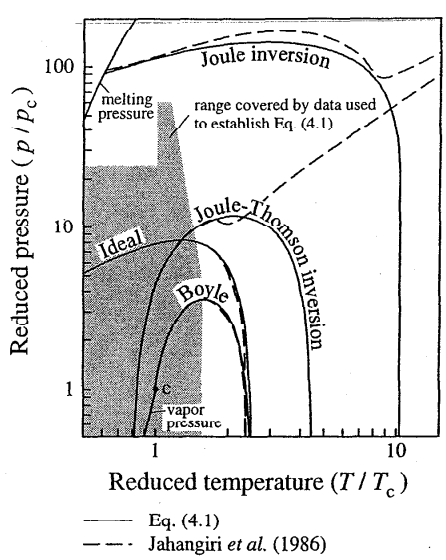

FIG. 28. So-called ideal curves calculated from Eq. (4.1) and from the IUPAC equation of state. The curves are plotted in a double logarithmic p/p_c vs. T/T_c diagram.

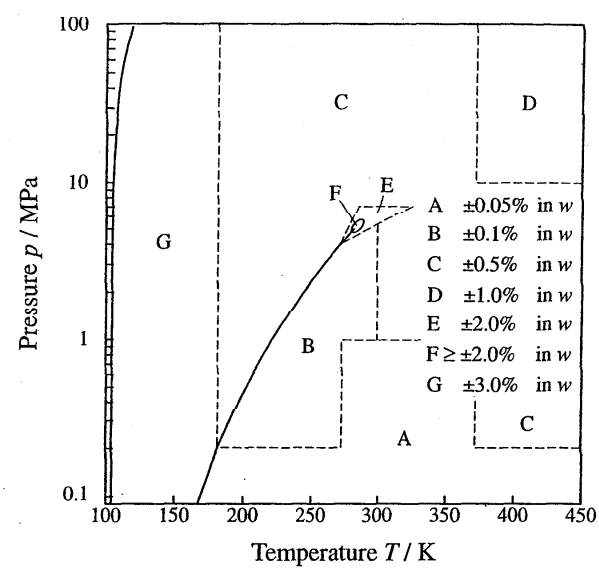

FIG. 30. Tolerance diagram for speed of sound data calculated from Eq. (4.1).

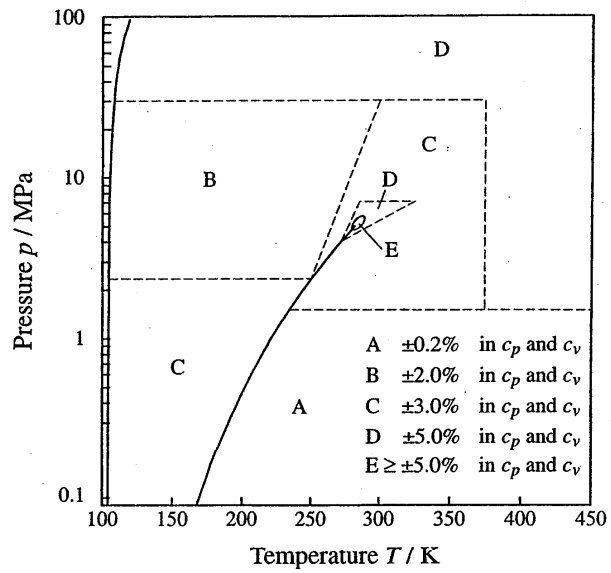

FIG. 31. Tolerance diagram for isobaric and isochoric heat capacity data calculated from Eq. (4.1).

properties such as pressure and enthalpy, the equation yiel reasonable results up to very high temperatures and pr sures.

8. Appendix: Thermodynamic Properties of Ethylene

In order to preserve thermodynamic consistency, all v ues presented in Tables 32 and 33 were calculated direc from the new equation of state, Eq. (4.1). In general, entr in the tables are given with five significant digits, which appropriate with respect to the uncertainties discussed in S 6. However, interpolations between entries in the tables m result in uncertainties, which are significantly larger than t uncertainties of Eq. (4.1). This fact has to be consider especially in the extended critical region. For sophisticat applications, properties should be calculated directly fr the equation of state. Suitable software can be obtained fr the authors.

TABLE 32. Thermodynamic properties of saturated ethylene

Temperature (K)	Pressure (MPa)	Density (kg m^{-3})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
103.989[a]	0.000 122	654.60	−819.13	−4.8014	1.6220	2.4295	1766.6
		0.003 96	−251.60	0.65610	0.890 14	1.1868	202.68
104	0.000 122	654.59	−819.10	−4.8011	1.6219	2.4295	1766.5
		0.003 97	−251.59	0.65565	0.890 14	1.1868	202.69
106	0.000 173	652.06	−814.24	−4.7549	1.6142	2.4313	1753.8
		0.005 51	−249.22	0.57544	0.890 39	1.1872	204.61
108	0.000 241	649.52	−809.38	−4.7094	1.6061	2.4322	1740.8
		0.007 54	−246.86	0.49903	0.890 68	1.1876	206.52
110	0.000 332	646.98	−804.51	−4.6648	1.5976	2.4325	1727.7
		0.010 18	−244.50	0.42621	0.891 01	1.1881	208.41
112	0.000 451	644.43	−799.65	−4.6209	1.5890	2.4322	1714.5
		0.013 58	−242.14	0.35675	0.891 41	1.1886	210.27
114	0.000 605	641.87	−794.78	−4.5779	1.5801	2.4314	1701.1
		0.017 91	−239.78	0.29046	0.891 87	1.1893	212.12
116	0.000 802	639.31	−789.92	−4.5356	1.5711	2.4302	1687.6
		0.023 36	−237.43	0.22717	0.892 40	1.1901	213.94
118	0.001 053	636.74	−785.06	−4.4941	1.5621	2.4288	1674.1
		0.030 14	−235.08	0.16669	0.893 00	1.1910	215.74
120	0.001 368	634.17	−780.21	−4.4533	1.5530	2.4271	1660.4
		0.038 52	−232.74	0.10889	0.893 69	1.1920	217.52
122	0.001 761	631.59	−775.35	−4.4132	1.5439	2.4252	1646.7
		0.048 77	−230.40	0.05359	0.894 46	1.1932	219.27
124	0.002 245	629.00	−770.51	−4.3738	1.5348	2.4232	1632.9
		0.061 21	−228.07	0.00067	0.895 33	1.1946	221.00
126	0.002 838	626.41	−765.66	−4.3350	1.5257	2.4212	1619.1
		0.076 17	−225.74	−0.05000	0.896 30	1.1961	222.71
128	0.003 557	623.81	−760.82	−4.2969	1.5167	2.4191	1605.2
		0.094 03	−223.42	−0.09854	0.897 38	1.1978	224.40
130	0.004 424	621.20	−755.98	−4.2594	1.5079	2.4170	1591.3
		0.115 21	−221.11	−0.14508	0.898 57	1.1997	226.05
132	0.005 462	618.58	−751.15	−4.2225	1.4991	2.4150	1577.3
		0.140 14	−218.81	−0.18971	0.899 89	1.2018	227.69
134	0.006 694	615.95	−746.32	−4.1862	1.4905	2.4131	1563.2
		0.169 32	−216.52	−0.23253	0.901 33	1.2041	229.30
136	0.008 150	613.32	−741.49	−4.1505	1.4820	2.4113	1549.2
		0.203 25	−214.23	−0.27365	0.902 90	1.2066	230.88
138	0.009 857	610.68	−736.67	−4.1153	1.4736	2.4096	1535.1
		0.242 47	−211.96	−0.31315	0.904 60	1.2094	232.43
140	0.011 850	608.02	−731.85	−4.0807	1.4655	2.4081	1520.9
		0.287 58	−209.71	−0.35111	0.906 45	1.2125	233.95
142	0.014 162	605.36	−727.03	−4.0465	1.4525	2.4068	1506.7
		0.339 17	−207.46	−0.38762	0.908 44	1.2158	235.44
144	0.016 829	602.69	722.22	−4.0129	1.4497	2.4057	1492.4
		0.397 90	−205.23	−0.42275	0.910 58	1.2194	236.91
146	0.019 893	600.00	−717.40	−3.9797	1.4421	2.4048	1478.1
		0.464 45	−203.02	−0.45657	0.912 88	1.2233	238.34
148	0.023 394	597.31	−712.59	−3.9470	1.4347	2.4042	1463.8
		0.539 52	−200.82	−0.48914	0.915 33	1.2275	239.73

TABLE 32. Thermodynamic properties of saturated ethylene—Continued

Temperature (K)	Pressure (MPa)	Density (kg m^{-3})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	v (m
150	0.0273 77	594.60	−707.78	−3.9148	1.4275	2.4039	14
		0.623 85	−198.64	−0.520 54	0.917 95	1.2321	241
152	0.0318 89	591.88	−702.97	−3.8829	1.4205	2.4038	143
		0.718 20	−196.48	−0.550 81	0.920 73	1.2369	242
154	0.0369 78	589.15	−698.15	−3.8515	1.4138	2.4041	142
		0.823 38	−194.33	−0.580 02	0.923 68	1.2421	243
156	0.0426 97	586.40	−693.34	−3.8205	1.4072	2.4046	140
		0.940 21	−192.21	−0.608 22	0.926 80	1.2477	244
158	0.0490 97	583.64	−688.52	−3.7899	1.4009	2.4055	139
		1.0695	−190.11	−0.635 46	0.930 09	1.2536	246
160	0.0562 36	580.87	−683.70	−3.7597	1.3948	2.4067	137
		1.2123	−188.03	−0.661 79	0.933 56	1.2599	247
162	0.0641 70	578.08	−678.88	−3.7298	1.3889	2.4083	136
		1.3693	−185.98	−0.687 25	0.937 20	1.2665	248.
164	0.0729 60	575.28	−674.05	−3.7003	1.3833	2.4103	134
		1.5415	−183.95	−0.711 89	0.941 02	1.2736	249.
166	0.0826 67	572.46	−669.22	−3.6711	1.3779	2.4127	133
		1.7299	−181.94	−0.735 74	0.945 03	1.2811	250.
168	0.0933 55	569.62	−664.38	−3.6422	1.3727	2.4154	131
		1.9355	−179.96	−0.758 85	0.949 22	1.2891	251.
170	0.105 09	566.77	−659.53	−3.6137	1.3677	2.4186	130
		2.1593	−178.01	−0.781 26	0.953 59	1.2975	252.
172	0.117 94	563.89	−654.68	−3.5854	1.3630	2.4222	1287
		2.4023	−176.09	−0.802 99	0.958 16	1.3063	253.
174	0.131 96	561.00	−649.82	−3.5575	1.3585	2.4263	1272
		2.6657	−174.20	−0.824 09	0.962 91	1.3157	254.
176	0.147 24	558.09	−644.94	−3.5298	1.3543	2.4308	1257
		2.9504	−172.34	−0.844 58	0.967 85	1.3255	255.
178	0.163 85	555.15	−640.06	−3.5024	1.3503	2.4358	1242
		3.2578	−170.52	−0.864 50	0.972 99	1.3359	256.
180	0.181 85	552.20	−635.17	−3.4752	1.3465	2.4413	1227.
		3.5889	−168.72	−0.883 87	0.978 32	1.3468	256.
182	0.201 31	549.22	−630.26	−3.4483	1.3429	2.4473	1211.
		3.9449	−166.96	−0.902 73	0.983 86	1.3582	257.7
184	0.222 33	546.22	−625.34	−3.4216	1.3396	2.4539	1196.
		4.3271	−165.24	−0.921 10	0.989 59	1.3703	258.3
186	0.244 97	543.19	−620.41	−3.3952	1.3365	2.4610	1180.
		4.7369	−163.55	−0.939 00	0.995 53	1.3830	258.9
188	0.269 30	540.14	−615.46	−3.3689	1.3337	2.4687	1165.
		5.1754	−161.90	−0.956 46	1.0017	1.3963	259.5
190	0.295 42	537.06	−610.49	−3.3429	1.3310	2.4770	1149.
		5.6442	−160.30	−0.973 51	1.0080	1.4103	260.0
192	0.323 39	533.95	−605.50	−3.3171	1.3286	2.4860	1133.
		6.1446	−158.73	−0.990 16	1.0146	1.4251	260.5
194	0.353 31	530.82	−600.50	−3.2914	1.3265	2.4956	1118.
		6.6782	−157.20	−1.0064	1.0214	1.4405	260.9
196	0.385 24	527.65	−595.47	−3.2660	1.3246	2.5059	1102.
		7.2465	−155.72	−1.0224	1.0284	1.4568	261.3

TABLE 32. Thermodynamic properties of saturated ethylene—Continued

Temperature (K)	Pressure (MPa)	Density (kg m^{-3})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
198	0.419 27	524.45	−590.42	−3.2407	1.3229	2.5169	1086.0
		7.8511	−154.28	−1.0380	1.0356	1.4740	261.68
200	0.455 49	521.22	−585.35	−3.2155	1.3214	2.5287	1070.0
		8.4936	−152.89	−1.0533	1.0431	1.4920	261.95
202	0.493 98	517.96	−580.26	−3.1906	1.3202	2.5413	1053.8
		9.1760	−151.55	−1.0683	1.0508	1.5110	262.16
204	0.534 82	514.65	−575.13	−3.1657	1.3192	2.5548	1037.5
		3.9000	−150.26	−1.0830	1.0588	1.5310	262.32
206	0.578 10	511.31	−569.98	−3.1410	1.3184	2.5691	1021.1
		10.668	−149.02	−1.0975	1.0670	1.5521	262.42
208	0.623 91	507.93	−564.80	−3.1164	1.3178	2.5844	1004.6
		11.481	−147.83	−1.1118	1.0754	1.5744	262.47
210	0.672 32	504.50	−559.59	−3.0919	1.3175	2.6007	988.07
		12.342	−146.70	−1.1258	1.0842	1.5980	262.46
212	0.723 44	501.04	−554.35	−3.0676	1.3175	2.6182	971.38
		13.253	−145.63	−1.1397	1.0932	1.6228	262.40
214	0.777 33	497.52	−549.07	−3.0433	1.3177	2.6367	954.58
		14.217	−144.62	−1.1533	1.1024	1.6492	262.27
216	0.834 11	493.96	−543.75	−3.0191	1.3181	2.6565	937.67
		15.237	−143.67	−1.1669	1.1120	1.6771	262.09
218	0.893 85	490.34	−538.40	−2.9950	1.3187	2.6777	920.65
		16.314	−142.78	−1.1802	1.1219	1.7067	261.84
220	0.956 64	486.67	−533.00	−2.9709	1.3196	2.7003	903.50
		17.452	−141.96	−1.1935	1.1320	1.7383	261.54
222	1.022 6	482.94	−527.56	−2.9469	1.3208	2.7245	886.23
		18.655	−141.21	−1.2066	1.1425	1.7718	261.17
224	1.091 7	479.15	522.08	2.9230	1.3222	2.7503	868.83
		19.926	−140.54	−1.2197	1.1534	1.8076	260.74
226	1.164 3	475.30	−516.54	−2.8990	1.3239	2.7780	851.30
		21.268	−139.94	−1.2327	1.1645	1.8459	260.25
228	1.240 2	471.37	−510.96	−2.8751	1.3258	2.8078	833.63
		22.685	−139.42	−1.2456	1.1761	1.8869	259.69
230	1.319 6	467.38	−505.32	−2.8513	1.3280	2.8398	815.82
		24.183	−138.99	−1.2586	1.1880	1.9309	259.06
232	1.402 7	463.30	−499.62	−2.8274	1.3305	2.8742	797.86
		25.766	−138.65	−1.2715	1.2003	1.9783	258.37
234	1.489 5	459.15	−493.85	−2.8034	1.3333	2.9114	779.75
		27.440	−138.40	−1.2844	1.2130	2.0295	257.60
236	1.580 0	454.90	−488.03	−2.7795	1.3364	2.9517	761.47
		29.210	−138.26	−1.2974	1.2262	2.0850	256.77
238	1.674 5	450.56	−482.13	−2.7555	1.3398	2.9954	743.03
		31.083	−138.21	1.3105	1.2398	2.1453	255.86
240	1.773 1	446.11	−476.16	−2.7314	1.3435	3.0431	724.40
		33.066	−138.29	−1.3236	1.2540	2.2112	254.88
242	1.875 7	441.56	−470.10	−2.7072	1.3476	3.0951	705.59
		35.168	−138.48	−1.3369	1.2687	2.2835	253.83
244	1.982 5	436.88	−463.96	−2.6830	1.3521	3.1522	686.56
		37.398	−138.80	−1.3504	1.2840	2.3632	252.69

TABLE 32. Thermodynamic properties of saturated ethylene—Continued

Temperature (K)	Pressure (MPa)	Density (kg m^{-3})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s
246	2.0937	432.07	−457.73	−2.6586	1.3569	3.2152	667
		39.767	−139.26	−1.3640	1.3000	2.4516	251
248	2.2094	427.13	−451.39	−2.6340	1.3622	3.2851	647
		42.286	−139.87	−1.3779	1.3168	2.5502	250
250	2.3296	422.02	−444.95	−2.6093	1.3680	3.3630	628
		44.970	−140.64	−1.3921	1.3344	2.6609	248
252	2.4545	416.74	−438.38	−2.5843	1.3743	3.4504	608
		47.835	−141.59	−1.4066	1.3529	2.7861	247
254	2.5842	411.27	−431.68	−2.5590	1.3812	3.5494	587
		50.900	−142.74	−1.4215	1.3725	2.9290	245
256	2.7189	405.59	−424.84	−2.5335	1.3888	3.6625	566
		54.187	−144.10	−1.4369	1.3932	3.0936	244
258	2.8586	399.67	−417.83	−2.5076	1.3973	3.7931	545
		57.723	−145.70	−1.4528	1.4152	3.2854	242
260	3.0036	393.47	−410.63	−2.4812	1.4069	3.9458	524
		61.542	−147.57	−1.4695	1.4388	3.5116	240
262	3.1539	386.95	−403.23	−2.4543	1.4177	4.1269	501
		65.684	−149.75	−1.4869	1.4641	3.7828	238
264	3.3098	380.07	−395.59	−2.4268	1.4303	4.3457	478
		70.201	−152.29	−1.5052	1.4915	4.1138	236
266	3.4714	372.74	−387.66	−2.3985	1.4450	4.6158	455
		75.160	−155.23	−1.5247	1.5214	4.5272	234
268	3.6389	364.89	−379.40	−2.3693	1.4626	4.9584	430
		80.651	−158.67	−1.5457	1.5545	5.0583	231
270	3.8125	356.39	−370.74	−2.3389	1.4840	5.4087	405
		86.795	−162.71	−1.5684	1.5918	5.7660	229
272	3.9926	347.06	−361.55	−2.3069	1.5105	6.0293	378
		93.774	−167.51	−1.5935	1.6347	6.7558	226
274	4.1793	336.61	−351.68	−2.2727	1.5446	6.9439	349
		101.86	−173.32	−1.6218	1.6859	8.2377	223
276	4.3730	324.59	−340.86	−2.2355	1.5904	8.4376	319
		111.53	−180.53	−1.6546	1.7500	10.696	219
278	4.5743	310.07	−328.52	−2.1933	1.6577	11.345	285
		123.70	−189.95	−1.6948	1.8377	15.541	215
280	4.7836	290.70	−313.28	−2.1411	1.7785	19.563	246
		140.70	−203.54	−1.7492	1.9809	29.261	208
282	5.0023	253.12	−287.09	−2.0508	2.2089	146.97	188
		175.80	−232.15	−1.8560	2.3981	225.24	191
282.350[b]	5.0418	214.24	−261.60	−1.9611			

[a]Triple-point temperature.
[b]Critical temperature.

TABLE 33. Thermodynamic properties of ethylene

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			0.1 MPa isobar				
104.003[a]	654.63	−819.13	−818.97	−4.801 4	1.621 9	2.4293	1767.1
105	653.37	−816.70	−816.55	−4.778 2	1.618 1	2.4303	1760.7
110	647.03	−804.55	−804.39	−4.665 1	1.597 7	2.4323	1728.3
115	640.65	−792.39	−792.23	−4.557 0	1.575 7	2.4307	1694.9
120	634.23	−780.25	−780.09	−4.453 6	1.553 0	2.4269	1661.0
125	627.76	−768.13	−767.97	−4.354 6	1.530 3	2.4220	1626.6
130	621.26	−756.03	−755.87	−4.259 7	1.507 9	2.4168	1591.8
135	614.70	−743.96	−743.80	−4.168 6	1.486 3	2.4119	1556.8
140	608.08	−731.91	−731.75	−4.081 0	1.465 6	2.4078	1521.5
145	601.41	−719.88	−719.72	−3.996 5	1.446 0	2.4049	1485.8
150	594.66	−707.87	−707.70	−3.915 0	1.427 6	2.4036	1449.9
155	587.83	−695.85	−695.68	−3.836 2	1.410 5	2.4040	1413.7
160	580.91	−683.83	−683.65	−3.759 9	1.394 8	2.4065	1377.1
165	573.89	−671.79	−671.61	−3.685 7	1.380 6	2.4113	1340.1
169.155[b]	567.97	−661.76	−661.58	−3.625 7	1.369 8	2.4172	1309.0
169.155[b]	2.062 5	−227.32	−178.83	−0.771 88	0.951 72	1.2939	252.31
170	2.051 1	−226.50	−177.74	−0.765 43	0.951 87	1.2931	252.99
175	1.986 5	−221.62	−171.28	−0.728 00	0.953 51	1.2899	256.95
180	1.926 2	−216.75	−164.84	−0.691 68	0.956 36	1.2886	260.79
185	1.869 9	−211.88	−158.40	−0.656 37	0.960 33	1.2891	264.52
190	1.816 9	−206.98	−151.95	−0.621 97	0.965 34	1.2911	268.15
195	1.767 1	−202.07	−145.48	−0.588 40	0.971 32	1.2944	271.67
200	1.720 2	−197.13	−139.00	−0.555 57	0.978 18	1.2990	275.11
205	1.675 8	−192.16	−132.49	−0.523 42	0.985 88	1.3047	278.45
210	1.633 8	−187.16	−125.95	−0.491 91	0.994 38	1.3115	281.72
215	1.593 9	−182.11	−119.37	−0.460 96	1.003 6	1.3191	284.91
220	1.556 0	−177.02	−112.76	−0.430 54	1.013 5	1.3277	288.03
225	1.520 0	−171.89	−106.10	−0.400 60	1.024 1	1.3370	291.07
230	1.485 6	−166.70	−99.386	−0.371 10	1.035 3	1.3471	294.06
235	1.452 8	−161.45	−92.623	−0.342 02	1.047 1	1.3579	296.98
240	1.421 5	−156.15	−85.805	−0.313 31	1.059 5	1.3694	299.85
245	1.391 6	−150.79	−78.929	−0.284 95	1.072 4	1.3814	302.66
250	1.362 9	−145.36	−71.991	−0.256 92	1.085 7	1.3940	305.42
255	1.335 4	−139.87	−64.988	−0.229 18	1.099 5	1.4071	308.14
260	1.309 0	−134.31	−57.918	−0.201 73	1.113 8	1.4208	310.81
265	1.283 7	−128.68	−50.780	−0.174 53	1.128 4	1.4348	313.43
270	1.259 3	−122.98	−43.569	−0.147 58	1.143 4	1.4493	316.02
275	1.235 9	−117.20	−36.286	−0.120 85	1.158 8	1.4642	318.57
280	1.213 4	−111.34	−28.927	−0.094 33	1.174 5	1.4794	321.08
285	1.191 6	−105.41	−21.491	−0.068 01	1.190 5	1.4950	323.56
290	1.170 7	−99.397	−13.977	−0.041 87	1.206 7	1.5108	326.01
295	1.150 5	−93.303	−6.3825	−0.015 91	1.223 2	1.5269	328.43
300	1.131 0	−87.128	1.2931	0.009 89	1.239 9	1.5433	330.83
305	1.112 1	−80.869	9.0510	0.035 54	1.256 8	1.5599	333.19
310	1.093 9	−74.526	16.892	0.061 04	1.273 9	1.5767	335.53
315	1.076 2	−68.097	24.818	0.086 40	1.291 1	1.5937	337.85
320	1.059 2	−61.583	32.829	0.111 63	1.308 5	1.6108	340.14
330	1.026 6	−48.295	49.110	0.161 73	1.343 6	1.6454	344.66
340	0.996 07	−34.655	65.739	0.211 37	1.379 1	1.6805	349.11
350	0.967 28	−20.662	82.721	0.260 59	1.414 8	1.7158	353.49
360	0.940 13	−6.3119	100.06	0.009 43	1.450 6	1.7513	357.80
370	0.914 47	8.3946	117.75	0.357 90	1.486 5	1.7869	362.05
380	0.890 18	23.458	135.79	0.406 02	1.522 3	1.8224	366.25

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s
			0.1 MPa isobar—Continued				
390	0.867 16	38.878	154.20	0.453 82	1.5580	1.8579	370.4
400	0.845 31	54.652	172.95	0.501 30	1.5934	1.8931	374.5
410	0.824 54	70.778	192.06	0.548 48	1.6286	1.9281	378.5
420	0.804 78	87.255	211.51	0.595 36	1.6636	1.9629	382.5
430	0.785 94	104.08	231.31	0.641 95	1.6982	1.9973	386.5
440	0.767 97	121.24	251.46	0.688 26	1.7324	2.0314	390.4
450	0.750 81	138.75	271.94	0.734 28	1.7662	2.0650	394.3
			0.5 MPa isobar				
104.059 [a]	654.75	−819.11	−818.35	−4.801 2	1.6218	2.4288	1768
105	653.56	−816.83	−816.06	−4.779 4	1.6182	2.4297	1762
110	647.23	−804.68	−803.91	−4.666 3	1.5978	2.4316	1730
115	640.86	−792.53	−791.75	−4.558 2	1.5759	2.4299	1697
120	634.45	−780.40	−779.61	−4.454 9	1.5533	2.4261	1663
125	628.00	−768.29	−767.49	−4.355 9	1.5306	2.4211	1628
130	621.51	−756.21	−755.40	−4.261 1	1.5083	2.4158	1594
135	614.97	−744.15	−743.34	−4.170 0	1.4866	2.4108	1559
140	608.37	−732.12	−731.29	−4.082 4	1.4659	2.4066	1524
145	601.71	−720.10	−719.27	−3.998 0	1.4464	2.4035	1488
150	594.98	−708.10	−707.26	−3.916 6	1.4280	2.4020	1452
155	588.17	−696.10	−695.25	−3.837 8	1.4109	2.4022	1416
160	581.27	−684.09	−683.23	−3.761 5	1.3953	2.4045	1380
165	574.28	−672.07	−671.20	−3.687 5	1.3810	2.4090	1343
170	567.18	−660.02	−659.14	−3.615 4	1.3682	2.4160	1306
175	559.95	−647.92	−647.03	−3.545 3	1.3568	2.4258	1268
180	552.58	−635.78	−634.87	−3.476 8	1.3468	2.4386	1230
185	545.05	−623.56	−622.64	−3.409 7	1.3383	2.4548	1191
190	537.35	−611.25	−610.32	−3.344 0	1.3312	2.4747	1151
195	529.44	−598.83	−597.89	−3.279 4	1.3256	2.4989	1111
200	521.30	−586.28	−585.32	−3.215 8	1.3214	2.5280	1070
202.302 [b]	517.46	−580.45	−579.48	−3.186 8	1.3200	2.5433	1051
202.302 [b]	9.2827	−205.22	−151.35	−1.070 5	1.0520	1.5140	262.1
205	9.1138	−202.15	−147.29	−1.050 6	1.0511	1.5025	264.5
210	8.8211	−196.50	−139.82	−1.014 6	1.0514	1.4859	268.8
215	8.5515	−190.89	−132.42	−0.979 74	1.0538	1.4743	272.9
220	8.3019	−185.30	−125.07	−0.945 94	1.0580	1.4667	276.8
225	8.0695	−179.71	−117.75	−0.913 04	1.0637	1.4622	280.6
230	7.8524	−174.12	−110.44	−0.880 92	1.0706	1.4606	284.2
235	7.6489	−168.51	−103.14	−0.849 51	1.0788	1.4612	287.7
240	7.4574	−162.87	−95.826	−0.818 72	1.0880	1.4638	291.1
245	7.2767	−157.21	88.497	0.788 50	1.0981	1.4681	294.4
250	7.1059	−151.51	−81.143	−0.758 79	1.1091	1.4738	297.6
255	6.9440	−145.76	−73.756	−0.729 53	1.1208	1.4809	300.7
260	6.7903	−139.97	−66.332	−0.700 70	1.1332	1.4892	303.8
265	6.6440	−134.12	−58.863	−0.672 24	1.1462	1.4985	306.8
270	6.5046	−128.21	−51.345	−0.644 14	1.1597	1.5087	309.7
275	6.3716	−122.25	−43.775	−0.616 36	1.1738	1.5197	312.6
280	6.2444	−116.22	−36.147	−0.588 87	1.1883	1.5314	315.4
285	6.1226	−110.12	−28.460	−0.561 66	1.2032	1.5438	318.1
290	6.0060	−103.96	−20.708	−0.534 70	1.2185	1.5568	320.8
295	5.8940	−97.723	−12.891	−0.507 97	1.2342	1.5703	323.5
300	5.7865	−91.413	−5.0048	−0.481 43	1.2501	1.5842	326.1
305	5.6831	−85.027	2.9522	−0.455 16	1.2663	1.5986	328.7

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			0.5 MPa isobar—Continued				
310	5.5837	−78.565	10.982	−0.429 04	1.2828	1.6134	331.25
315	5.4878	−72.024	19.087	−0.403 11	1.2995	1.6285	333.75
320	5.3955	−65.402	27.268	−0.377 34	1.3164	1.6439	336.22
330	5.2203	−51.916	43.864	−0.326 28	1.3506	1.6755	341.08
340	5.0567	−38.098	60.780	−0.275 78	1.3853	1.7079	345.83
350	4.9036	−23.941	78.024	−0.225 80	1.4204	1.7409	350.48
360	4.7599	−9.4430	95.601	−0.176 28	1.4556	1.7744	355.04
370	4.6248	5.3998	113.51	−0.127 21	1.4910	1.8082	359.52
380	4.4974	20.589	131.76	−0.078 54	1.5264	1.8421	363.92
390	4.3771	36.125	150.36	−0.030 25	1.5617	1.8762	368.26
400	4.2632	52.006	169.29	0.017 68	1.5969	1.9102	372.53
410	4.1554	68.233	188.56	0.065 27	1.6319	1.9441	376.75
420	4.0530	84.803	208.17	0.112 52	1.6666	1.9778	380.91
430	3.9557	101.71	228.11	0.159 45	1.7009	2.0113	385.02
440	3.8631	118.96	248.39	0.206 07	1.7350	2.0445	389.08
450	3.7748	136.54	269.00	0.252 38	1.7686	2.0774	393.09
			1.0 MPa isobar				
104.130[a]	654.90	−819.09	−817.57	−4.801 1	1.6215	2.4281	1771.2
105	653.81	−816.98	−815.45	−4.780 8	1.6182	2.4289	1765.7
110	647.49	−804.85	−803.30	−4.667 8	1.5980	2.4308	1733.3
115	641.13	−792.71	−791.15	−4.559 8	1.5762	2.4290	1700.0
120	634.73	−780.59	−779.02	−4.456 5	1.5536	2.4250	1666.1
125	628.30	−768.49	−766.90	−4.357 6	1.5310	2.4199	1631.9
130	621.82	−756.42	−754.82	−4.262 8	1.5087	2.4145	1597.3
135	615.30	−744.38	−742.76	−4.171 7	1.4871	2.4097	1562.4
140	608.72	−732.36	−730.72	−4.084 2	1.4664	2.4050	1527.3
145	602.08	−720.37	−718.71	−3.999 9	1.4469	2.4018	1491.9
150	595.37	−708.38	−706.70	−3.918 5	1.4285	2.4000	1456.3
155	588.59	−696.40	−694.70	−3.839 8	1.4115	2.4000	1420.3
160	581.72	−684.42	−682.70	−3.763 6	1.3958	2.4020	1384.0
165	574.76	−672.42	−670.68	−3.689 6	1.3815	2.4062	1347.4
170	567.69	−660.39	−658.63	−3.617 7	1.3687	2.4128	1310.3
175	560.50	−648.33	−646.55	−3.547 6	1.3573	2.4222	1272.9
180	553.18	−636.21	−634.40	−3.479 2	1.3473	2.4344	1234.9
185	545.70	−624.03	−622.20	−3.412 3	1.3388	2.4499	1196.3
190	538.05	−611.76	−609.90	−3.346 7	1.3317	2.4691	1157.2
195	530.20	−599.38	−597.50	−3.282 3	1.3260	2.4924	1117.4
200	522.13	−586.88	−584.97	−3.218 8	1.3218	2.5203	1076.8
205	513.79	−574.23	−572.29	−3.156 2	1.3190	2.5537	1035.3
210	505.16	−561.40	−559.42	−3.094 2	1.3177	2.5936	992.84
215	496.18	−548.35	−546.34	−3.032 6	1.3179	2.6413	949.23
220	486.78	−535.05	−532.99	−2.971 3	1.3196	2.6989	904.25
221.326[b]	484.20	−531.47	−529.40	−2.955 0	1.3204	2.7161	892.06
221.326[b]	18.242	−196.27	−141.46	−1.202 2	1.1390	1.7603	261.30
225	17.731	−191.46	−135.06	−1.173 6	1.1335	1.7216	265.11
230	17.100	−185.04	−126.56	−1.136 2	1.1303	1.6825	269.98
235	16.530	−178.72	−118.22	−1.100 3	1.1306	1.6541	274.57
240	16.010	−172.47	−110.01	−1.065 7	1.1334	1.6336	278.91
245	15.533	−166.26	−101.88	−1.032 2	1.1382	1.6189	283.05
250	15.092	−160.07	−93.808	−0.999 60	1.1447	1.6089	287.00
255	14.682	−153.89	−85.781	−0.967 80	1.1527	1.6028	290.80
260	14.299	−147.71	−77.776	−0.936 71	1.1618	1.5997	294.46

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s
			1.0 MPa isobar—Continued				
265	13.941	−141.51	−69.779	−0.906 25	1.1720	1.5992	297
270	13.605	−135.28	−61.780	−0.876 35	1.1831	1.6010	301
275	13.287	−129.03	−53.767	−0.846 94	1.1951	1.6046	304
280	12.988	−122.73	−45.731	−0.817 98	1.2077	1.6098	307
285	12.703	−116.39	−37.666	−0.789 43	1.2210	1.6165	311
290	12.434	−109.99	−29.565	−0.761 25	1.2349	1.6244	314
295	12.177	−103.54	−21.421	−0.733 41	1.2492	1.6333	317
300	11.932	−97.036	−13.230	−0.705 88	1.2640	1.6432	320
305	11.699	−90.466	−4.9875	−0.678 63	1.2792	1.6539	322
310	11.476	−83.831	3.3104	−0.651 64	1.2948	1.6654	325
315	11.262	−77.129	11.667	−0.624 90	1.3106	1.6774	328
320	11.057	−70.356	20.086	−0.598 39	1.3267	1.6901	331
330	10.671	−56.592	37.119	−0.545 98	1.3597	1.7169	336
340	10.314	−42.525	54.428	−0.494 30	1.3933	1.7452	341
350	9.9828	−28.145	72.027	−0.443 29	1.4275	1.7748	346
360	9.6738	−13.445	89.927	−0.392 87	1.4620	1.8053	351
370	9.3850	1.5817	108.13	−0.342 98	1.4968	1.8365	356
380	9.1142	16.939	126.66	−0.293 59	1.5317	1.8682	361
390	8.8597	32.629	145.50	−0.244 65	1.5665	1.9002	365
400	8.6200	48.653	164.66	−0.196 13	1.6013	1.9324	370
410	8.3938	65.012	184.15	−0.148 02	1.6359	1.9648	374
420	8.1797	81.704	203.96	−0.100 29	1.6703	1.9971	378
430	7.9770	98.729	224.09	−0.052 92	1.7044	2.0293	383
440	7.7845	116.08	244.54	−0.005 89	1.7382	2.0614	387
450	7.6016	133.77	265.32	−0.040 79	1.7717	2.0933	391
			1.5 MPa isobar				
104.200[a]	655.05	−819.08	−816.79	−4.8009	1.6213	2.4274	177
105	654.05	−817.14	−814.84	−4.7823	1.6183	2.4281	176
110	647.74	−804.01	−802.70	−4.6693	1.5982	2.4300	173
115	641.39	−792.89	−790.55	−4.5613	1.5764	2.4281	170
120	635.02	−780.78	−778.42	−4.4581	1.5540	2.4240	166
125	628.60	−768.70	−766.31	−4.3592	1.5314	2.4188	163
130	622.14	−756.64	−754.23	−4.2644	1.5091	2.4133	160
135	615.63	−744.61	−742.18	−4.1735	1.4876	2.4080	156
140	609.07	−732.61	−730.15	−4.0860	1.4669	2.4035	153
145	602.45	−720.63	−718.14	−4.0017	1.4474	2.4001	149
150	595.77	−708.66	−706.15	−3.9204	1.4291	2.3981	145
155	589.01	−696.70	−694.16	−3.8418	1.4120	2.3979	142
160	582.17	−684.74	−682.16	−3.7656	1.3964	2.3996	138
165	575.24	−672.77	−670.16	−3.6917	1.3821	2.4035	135
170	568.20	−660.77	−658.13	−3.6199	1.3693	2.4097	131
175	561.05	−648.73	−646.06	−3.5499	1.3578	2.4186	127
180	553.76	−636.64	−633.93	−3.4816	1.3479	2.4303	123
185	546.33	−624.49	−621.75	−3.4148	1.3393	2.4453	120
190	538.73	−612.26	−609.48	−3.3494	1.3322	2.4637	116
195	530.95	−599.93	−597.10	−3.2851	1.3265	2.4860	112
200	522.94	−587.48	−584.61	−3.2218	1.3222	2.5129	108
205	514.69	−574.88	−571.97	−3.1594	1.3193	2.5449	104
210	506.15	−562.11	−559.15	−3.0976	1.3179	2.5830	100
215	497.28	−549.14	−546.12	−3.0363	1.3179	2.6284	957.
220	488.01	−535.92	−532.85	−2.9753	1.3195	2.6829	912.
225	478.27	−522.41	−519.28	−2.9143	1.3228	2.7490	867.

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			1.5 MPa isobar—Continued				
230	467.95	−508.54	−505.34	−2.853 0	1.3278	2.8305	819.60
234.237[b]	458.65	−496.44	−493.17	−2.800 6	1.3337	2.9160	777.59
234.237[b]	27.645	−192.64	−138.38	−1.286 0	1.2146	2.0358	257.51
235	27.449	−191.48	−136.83	−1.279 4	1.2116	2.0178	258.47
240	26.271	−184.09	−127.00	−1.237 9	1.1984	1.9240	264.42
245	25.245	−176.96	−117.55	−1.199 0	1.1924	1.8594	269.86
250	24.335	−170.01	−108.37	−1.161 9	1.1910	1.8129	274.91
255	23.516	−163.18	−99.398	−1.126 4	1.1927	1.7788	279.65
260	22.773	−156.44	−90.570	−1.092 1	1.1969	1.7537	284.13
265	22.093	−149.74	−81.850	−1.058 9	1.2030	1.7354	288.38
270	21.466	−143.08	−73.207	−1.026 5	1.2108	1.7224	292.44
275	20.886	−136.44	−64.618	−0.995 03	1.2198	1.7138	296.33
280	20.345	−129.79	−56.064	−0.964 20	1.2300	1.7087	300.07
285	19.839	−123.13	−47.527	−0.933 98	1.2411	1.7064	303.68
290	19.365	−116.46	−38.995	−0.904 30	1.2532	1.7067	307.18
295	18.918	−109.75	−30.457	−0.875 11	1.2659	1.7090	310.56
300	18.497	−103.00	−21.903	−0.846 36	1.2793	1.7130	313.85
305	18.097	−96.209	−13.324	−0.818 00	1.2932	1.7186	317.06
310	17.719	−89.370	−4.7146	−0.790 00	1.3077	1.7255	320.18
315	17.359	−82.479	3.9325	−0.762 33	1.3226	1.7335	323.23
320	17.016	−75.530	12.622	−0.734 96	1.3378	1.7426	326.21
330	16.376	−61.448	30.148	−0.681 03	1.3693	1.7631	332.00
340	15.790	−47.101	47.894	−0.628 06	1.4017	1.7864	337.57
350	15.251	−32.473	65.883	−0.575 91	1.4349	1.8117	342.96
360	14.752	−17.550	84.133	−0.524 50	1.4686	1.8386	348.18
370	14.288	−2.3233	102.66	−0.473 75	1.5027	1.8667	353.26
380	13.856	13.216	121.47	−0.423 58	1.5370	1.8958	358.21
390	13.452	29.071	140.58	−0.373 95	1.5714	1.9256	363.04
400	13.073	45.248	159.98	−0.324 82	1.6057	1.9558	367.77
410	12.717	61.746	179.69	−0.276 15	1.6400	1.9864	372.40
420	12.382	78.567	199.71	−0.227 91	1.6740	2.0172	376.95
430	12.065	95.711	220.04	−0.180 09	1.7079	2.0480	381.41
440	11.765	113.18	240.67	−0.132 65	1.7414	2.0789	385.80
450	11.481	130.96	261.62	−0.085 59	1.7747	2.1097	390.11
			2.0 MPa isobar				
104.270[a]	655.20	−819.06	−816.00	−4.8007	1.6212	2.4267	1775.8
105	654.29	−817.29	−814.23	−4.7838	1.6184	2.4274	1771.2
110	647.99	−805.18	−802.09	−4.6708	1.5984	2.4291	1738.8
115	641.66	−793.06	−789.95	−4.5629	1.5767	2.4272	1705.6
120	635.29	−780.97	−777.82	−4.4596	1.5543	2.4231	1671.8
125	628.89	−768.90	−765.72	−4.3608	1.5318	2.4177	1637.7
130	622.45	−756.86	−753.64	−4.2661	1.5096	2.4121	1603.3
135	615.96	−744.85	−741.60	−4.1752	1.4880	2.4067	1568.6
140	609.42	−732.86	−729.58	−4.0878	1.4674	2.4020	1533.7
145	602.82	−720.89	−717.58	−4.0035	1.4479	2.3984	1498.6
150	596.16	−708.95	−705.59	−3.9223	1.4296	2.3962	1463.2
155	589.43	−697.00	−693.61	−3.8437	1.4126	2.3958	1427.6
160	582.62	−685.06	−681.63	−3.7676	1.3969	2.3972	1391.6
165	575.71	−673.11	−669.64	−3.6938	1.3827	2.4008	1355.4
170	568.71	−661.14	−657.62	−3.6221	1.3698	2.4067	1318.8
175	561.59	−649.13	−645.57	−3.5522	1.3584	2.4151	1281.7
180	554.35	−637.07	−633.46	−3.4840	1.3484	2.4264	1244.3

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			2.0 MPa isobar—Continued				
185	546.96	−624.95	−622.30	−3.4173	1.3398	2.4407	120
190	539.41	−612.76	−609.05	−3.3529	1.3327	2.4564	116
195	531.68	−600.47	−596.71	−3.2879	1.3260	2.4799	112
200	523.75	−588.06	−584.24	−3.2248	1.3226	2.5087	108
205	515.57	−575.52	−571.64	−3.1625	1.3196	2.5364	104
210	507.12	−562.82	−558.87	−3.1010	1.3183	2.5728	100
215	498.39	−549.93	−545.90	−3.0401	1.3181	2.6191	984
220	489.22	−536.78	−532.70	−2.979 2	1.3195	2.6678	931
225	479.64	−523.38	−519.23	−2.918 6	1.3225	2.7300	876
230	468.51	−509.63	−505.37	−2.857 8	1.3272	2.8061	829
235	458.72	−495.47	−491.11	−2.796 5	1.3339	2.9010	781
240	447.08	−480.79	−476.32	−2.734 2	1.3428	3.0231	730
244.318[a]	436.12	−467.58	−462.87	−2.679 1	1.3528	3.1619	683
244.318[b]	37.767	−191.82	−178.86	−1.352 3	1.2865	2.3787	252
245	37.479	−190.62	−177.26	−1.346 0	1.2820	2.3459	253
250	35.991	−182.10	−169.99	−1.309 4	1.2587	2.1749	260
255	34.604	−174.22	−163.41	−1.258 5	1.2471	2.0641	266
260	32.613	−166.58	−105.29	−1.210 2	1.2422	1.9874	272
265	31.426	−159.14	−95.409	−1.161 9	1.2416	1.9018	277
270	30.346	−151.85	−85.948	−1.146 2	1.2442	1.8907	282
275	29.371	−144.67	−76.575	−1.111 8	1.2491	1.8501	287
280	28.481	−137.56	−67.234	−1.078 5	1.2559	1.8274	291
285	27.664	−130.49	−58.191	−1.046 1	1.2642	1.8208	295
290	26.910	−123.44	−49.318	−1.014 6	1.2738	1.8091	299
295	26.209	−116.40	−40.093	−0.983 72	1.2845	1.8014	303
300	25.555	−109.36	−31.098	−0.953 40	1.2961	1.7970	307
305	24.942	−102.30	−22.118	−0.923 80	1.3086	1.7955	310
310	24.367	−95.220	−13.141	−0.894 61	1.3217	1.7959	314
315	23.824	−88.105	−4.1357	−0.865 86	1.3354	1.7984	317
320	23.311	−80.950	4.9464	−0.837 50	1.3496	1.8026	321
330	22.363	−66.502	22.931	−0.781 89	1.3794	1.8151	327
340	21.505	−51.838	41.164	−0.727 42	1.4105	1.8320	333
350	20.722	−36.933	59.582	−0.674 04	1.4426	1.8521	339
360	20.004	−21.795	78.213	−0.621 55	1.4754	1.8747	344
370	19.342	−6.3190	97.081	−0.569 86	1.5088	1.8982	350
380	18.729	9.4165	116.20	−0.518 87	1.5424	1.9232	355
390	18.159	25.450	135.59	−0.468 51	1.5763	1.9524	360
400	17.627	41.788	155.23	−0.418 73	1.6102	1.9804	365
410	17.128	58.454	175.20	−0.369 48	1.6440	2.0090	370
420	16.661	75.392	195.41	−0.320 72	1.6778	2.0381	375
430	16.221	92.661	215.96	−0.272 42	1.7113	2.0674	379
440	15.805	110.24	236.78	−0.224 55	1.7446	2.0969	384
450	15.413	128.14	257.90	−0.177 10	1.7777	2.1265	388
			3.0 MPa isobar				
104.405[a]	655.59	−819.02	−814.44	−4.8004	1.6268	2.4253	178
105	654.76	−817.89	−813.61	−4.7867	1.6186	2.4259	177
110	648.49	−805.50	−800.68	−4.6738	1.5948	2.4275	174
115	642.19	−793.42	−788.74	−4.5659	1.5773	2.4254	171
120	635.85	−781.34	−776.63	−4.4624	1.5650	2.4211	167
125	629.48	−769.30	−764.53	−4.3631	1.5526	2.4156	164
130	623.07	−757.29	−752.47	−4.2684	1.5105	2.4097	160
135	616.61	−745.30	−740.44	−4.1786	1.4690	2.4040	157

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			3.0 MPa isobar—Continued				
140	610.11	−733.35	−728.43	−4.091 3	1.4684	2.3990	1540.0
145	603.56	−721.42	−716.45	−4.007 2	1.4490	2.3951	1505.1
150	596.94	−709.50	−704.48	−3.926 0	1.4307	2.3925	1470.0
155	590.26	−697.60	−692.52	−3.847 6	1.4137	2.3916	1434.7
160	583.50	−685.70	−680.56	−3.771 6	1.3981	2.3925	1399.1
165	576.65	−673.79	−668.59	−3.698 0	1.3838	2.3955	1363.2
170	569.71	−661.86	−656.60	−3.626 4	1.3710	2.4007	1327.0
175	562.67	−649.91	−644.58	−3.556 7	1.3595	2.4084	1290.4
180	555.50	−637.91	−632.51	−3.488 7	1.3495	2.4187	1253.5
185	548.20	−625.86	−620.39	−3.422 3	1.3409	2.4319	1216.1
190	540.75	−613.73	−608.19	−3.357 2	1.3337	2.4483	1178.2
195	533.13	−601.52	−595.90	−3.293 4	1.3279	2.4682	1139.7
200	525.32	−589.21	−583.50	−3.230 6	1.3235	2.4920	1100.7
205	517.29	−576.77	−570.97	−3.168 7	1.3204	2.5203	1061.0
210	509.01	−564.18	−558.29	−3.107 6	1.3187	2.5537	1020.6
215	500.45	−551.42	−545.42	−3.047 0	1.3184	2.5932	979.40
220	491.55	538.45	532.34	−2.986 9	1.3196	2.6399	937.21
225	482.25	−525.23	−519.01	−2.927 0	1.3222	2.6954	893.91
230	472.49	−511.72	−505.37	−2.867 0	1.3264	2.7622	849.30
235	462.16	−497.85	−491.36	−2.806 8	1.3323	2.8439	803.12
240	451.11	−483.55	−476.90	−2.745 9	1.3401	2.9458	755.00
245	439.16	−468.69	−461.85	−2.683 9	1.3502	3.0774	704.37
250	425.99	−453.09	−446.05	−2.620 0	1.3634	3.2553	650.36
255	411.09	−436.46	−429.17	−2.553 1	1.3810	3.5150	591.37
259.952[b]	393.62	−418.43	−410.81	−2.481 9	1.4066	3.9418	524.66
259.952[b]	61.446	−196.35	−147.53	−1.469	1.4382	3.5057	240.52
260	61.392	−196.22	−147.36	−1.468 4	1.4372	3.4966	240.63
265	56.748	−184.48	−131.62	−1.408 4	1.3740	2.8848	250.84
270	53.307	−174.30	−118.03	−1.357 6	1.3452	2.5797	259.12
275	50.551	−164.97	−105.63	−1.312 1	1.3307	2.3940	266.29
280	48.246	−156.17	−93.987	−1.270 1	1.3242	2.2692	272.70
285	46.264	−147.72	−82.875	−1.230 8	1.3227	2.1804	278.56
290	44.526	−139.52	−72.144	−1.193 5	1.3246	2.1151	283.97
295	42.978	−131.50	−61.697	−1.157 8	1.3292	2.0661	289.03
300	41.585	−123.60	−51.464	−1.123 4	1.3358	2.0290	293.80
305	40.319	−115.80	−41.393	−1.090 1	1.3440	2.0008	298.31
310	39.159	−108.05	−31.444	−1.057 7	1.3536	1.9797	302.62
315	38.090	−100.35	−21.578	−1.026 2	1.3643	1.9640	306.74
320	37.100	−92.659	−11.796	−0.995 34	1.3759	1.9529	310.69
330	35.314	−77.288	7.6631	−0.935 46	1.4014	1.9410	318.19
340	33.743	−61.851	27.057	−0.877 56	1.4292	1.9393	325.22
350	32.342	−46.285	46.474	−0.821 28	1.4588	1.9450	331.86
360	31.081	−30.546	65.976	−0.766 34	1.4896	1.9562	338.19
370	29.937	−14.599	85.612	−0.712 54	1.5212	1.9715	344.24
380	28.891	1.5798	105.42	−0.659 72	1.5535	1.9899	350.06
390	27.931	18.009	125.42	−0.607 77	1.5863	2.0107	355.68
400	27.044	34.703	145.64	−0.556 59	1.6192	2.0332	361.11
410	26.220	51.672	166.09	−0.506 09	1.6523	2.0572	366.38
420	25.454	68.924	186.78	−0.456 21	1.6853	2.0823	371.50
430	24.738	86.463	207.74	−0.406 91	1.7183	2.1082	376.49
440	24.066	104.29	228.95	−0.358 15	1.7511	2.1346	381.37
450	23.435	122.42	250.43	−0.309 88	1.7836	2.1615	386.13

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	(m
			4.0 MPa isobar				
104.550[a]	655.80	−818.98	−812.88	−4.800 0	1.6205	2.4240	17
105	655.24	−817.90	−811.79	−4.789 6	1.6188	2.4244	17
110	648.99	−805.83	−799.66	−4.676 8	1.5992	2.4259	17
115	642.71	−793.76	−787.54	−4.569 0	1.5779	2.4237	17
120	636.40	−781.72	−775.43	−4.465 9	1.5557	2.4192	16
125	630.06	−769.70	−763.35	−4.367 3	1.5334	2.4135	16
130	623.68	−757.71	−751.30	−4.272 7	1.5114	2.4074	16
135	617.26	−745.75	−739.27	−4.182 0	1.4900	2.4014	15
140	610.80	−733.83	−727.28	−4.094 8	1.4695	2.3961	15
145	604.28	−721.93	−715.31	−4.010 8	1.4500	2.3919	15
150	597.71	−710.05	−703.36	−3.929 7	1.4318	2.3890	14
155	591.07	−698.19	−691.42	−3.851 4	1.4148	2.3876	14
160	584.37	−686.33	−679.48	−3.775 6	1.3992	2.3880	14
165	577.58	−674.46	−667.54	−3.702 1	1.3850	2.3905	13
170	570.70	−662.58	−655.57	−3.630 7	1.3721	2.3950	13
175	563.72	−650.68	−643.58	−3.561 2	1.3607	2.4019	12
180	556.63	−638.74	−631.55	−3.493 4	1.3507	2.4114	12
185	549.42	−626.74	−619.46	−3.427 1	1.3420	2.4235	12
190	542.06	−614.69	−607.31	−3.362 3	1.3348	2.4387	11
195	534.55	−602.55	−595.07	−3.298 7	1.3289	2.4571	11
200	526.86	−590.32	−582.73	−3.236 3	1.3244	2.4792	11
205	518.96	−577.98	−570.27	−3.174 7	1.3213	2.5054	10
210	510.84	−565.50	−557.67	−3.114 0	1.3194	2.5361	10
215	502.46	−552.86	−544.90	−3.053 9	1.3190	2.5722	99
220	493.78	−540.04	−531.94	−2.994 3	1.3199	2.6146	95
225	484.74	−527.00	−518.74	−2.935 0	1.3222	2.6645	91
230	475.30	−513.69	−505.28	−2.875 8	1.3259	2.7238	86
235	465.36	−500.08	−491.49	−2.816 5	1.3312	2.7950	82
240	454.82	−486.10	−477.30	−2.756 8	1.3382	2.8819	77
245	443.53	−471.65	−462.63	−2.696 3	1.3472	2.9904	73
250	431.29	−456.62	−447.34	−2.634 5	1.3584	3.1304	68
255	417.77	−440.82	−431.25	−2.570 8	1.3727	3.3199	62
260	402.42	−423.94	−414.00	−2.503 8	1.3917	3.5966	56
265	384.16	−405.40	−394.99	−2.431 4	1.4191	4.0557	50
270	360.27	−383.71	−372.61	−2.347 7	1.4691	5.0602	42
272.081[b]	346.66	−372.70	−361.16	−2.305 5	1.5118	6.0594	37
272.081[b]	94.077	−210.25	−167.73	−1.594 6	1.6366	6.8042	22
275	85.983	−198.11	−151.59	−1.535 6	1.5220	4.6845	23
280	77.638	−183.11	−131.59	−1.463 5	1.4470	3.5169	24
285	72.012	−170.94	−115.40	−1.406 1	1.4136	3.0151	25
290	67.728	−160.15	−101.09	−1.356 4	1.3968	2.7300	26
295	64.262	−150.18	−87.932	−1.311 4	1.3889	2.5458	27
300	61.351	−140.74	−75.541	−1.269 7	1.3865	2.4177	27
305	58.843	−131.68	−63.697	−1.230 6	1.3878	2.3246	28
310	56.641	−122.88	−52.256	−1.193 3	1.3919	2.2550	29
315	54.682	−114.27	−41.120	−1.157 7	1.3982	2.2020	29
320	52.918	−105.80	−30.216	−1.123 4	1.4062	2.1613	30
330	49.848	−89.148	−8.9037	−1.057 8	1.4260	2.1059	30
340	47.243	−72.687	11.981	−0.995 43	1.4497	2.0741	31
350	44.988	−56.282	32.630	−0.935 57	1.4761	2.0579	32
360	43.005	−39.838	53.174	−0.877 70	1.5044	2.0525	33
370	41.239	−23.290	73.706	−0.821 44	1.5342	2.0550	33
380	39.650	−6.5906	94.293	−0.766 54	1.5650	2.0631	34

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			4.0 MPa isobar—Continued				
390	38.209	10.296	114.98	−0.712 80	1.5964	2.0756	351.20
400	36.893	27.394	135.82	−0.660 05	1.6283	2.0914	357.10
410	35.684	44.725	156.82	−0.608 19	1.6605	2.1097	362.79
420	34.568	62.302	178.02	−0.557 11	1.6929	2.1299	368.29
430	33.532	80.136	199.42	−0.506 74	1.7252	2.1517	373.63
440	32.568	98.236	221.05	−0.457 02	1.7575	2.1746	378.82
450	31.668	116.61	242.92	−0.407 88	1.7896	2.1984	383.87
			5.0 MPa isobar				
104.690[a]	656.09	−818.94	−811.32	−4.7997	1.6202	2.4227	1789.2
105	655.71	−818.20	−810.57	−4.7925	1.6191	2.4229	1787.2
110	649.48	−806.15	−798.45	−4.6798	1.5996	2.4243	1754.8
115	643.23	−794.11	−786.33	−4.5720	1.5785	2.4220	1721.8
120	636.95	−782.08	−774.23	−4.4690	1.5565	2.4173	1688.4
125	630.64	−770.09	−762.16	−4.3705	1.5342	2.4114	1654.6
130	624.29	−758.13	−750.12	−4.2760	1.5123	2.4051	1620.7
135	617.90	−746.20	−738.11	−4.1854	1.4910	2.3989	1586.6
140	611.48	−734.31	−726.13	−4.0982	1.4705	2.3933	1552.4
145	605.00	−722.44	−714.17	−4.0143	1.4511	2.3888	1518.0
150	598.47	−710.59	−702.24	−3.9334	1.4329	2.3855	1483.4
155	591.88	−698.77	−690.32	−3.8552	1.4160	2.3837	1448.7
160	585.22	−686.94	−678.40	−3.7795	1.4004	2.3837	1413.7
165	578.49	−675.12	−666.48	−3.7062	1.3862	2.3856	1378.5
170	571.67	−663.29	−654.54	−3.6349	1.3733	2.3895	1343.1
175	564.76	−651.43	−642.58	−3.5656	1.3619	2.3957	1307.3
180	557.74	−639.54	−630.58	−3.4979	1.3519	2.4043	1271.3
185	550.61	−627.61	−618.53	−3.4319	1.3432	2.4156	1234.9
190	543.34	−615.62	−606.42	−3.3673	1.3359	2.4296	1198.1
195	535.93	−603.56	−594.23	−3.3040	1.3300	2.4467	1160.9
200	528.35	−591.41	−581.95	−3.2418	1.3254	2.4672	1123.2
205	520.59	−579.16	−569.55	−3.1806	1.3222	2.4914	1085.1
210	512.61	−566.78	−557.03	−3.1202	1.3203	2.5198	1046.4
215	504.40	−554.26	−544.35	−3.0606	1.3196	2.5529	1007.2
220	495.92	−541.57	−531.49	−3.0014	1.3204	2.5916	967.20
225	487.12	−528.68	−518.42	−2.9427	1.3224	2.6368	926.50
230	477.95	−515.57	−505.11	−2.8842	1.3258	2.6899	884.94
235	468.36	−502.18	−491.50	−2.8257	1.3306	2.7527	842.38
240	458.25	−488.47	−477.56	−2.7670	1.3370	2.8279	798.66
245	447.52	−474.37	−463.20	−2.7078	1.3450	2.9194	753.55
250	436.01	−459.80	−448.33	−2.6477	1.3549	3.0335	706.72
255	423.51	−444.62	−432.81	−2.5862	1.3672	3.1804	657.71
260	409.69	−428.64	−416.44	−2.5226	1.3825	3.3785	605.80
265	393.98	−411.57	−398.88	−2.4558	1.4023	3.6651	549.75
270	375.35	−392.82	−379.50	−2.3833	1.4301	4.1313	487.24
275	351.28	−371.04	−356.80	−2.3001	1.4762	5.0846	413.00
280	311.34	−340.71	−324.65	−2.1843	1.5996	9.1274	306.79
281.979[b]	253.91	−307.29	−287.60	−2.0526	2.1965	137.69	189.80
281.979[b]	175.04	−260.10	−231.54	−1.8538	2.3874	211.65	191.78
285	122.65	−214.01	−173.25	−1.6477	1.6466	8.1763	229.04
290	104.49	−191.31	−143.46	−1.5440	1.5252	4.6878	244.34
295	94.610	−175.73	−122.88	−1.4736	1.4782	3.6857	254.99
300	87.741	−162.78	−105.80	−1.4162	1.4552	3.1938	263.71
305	82.468	−151.25	−90.621	−1.3660	1.4436	2.8993	271.28

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s
			5.0 MPa isobar—Continued				
310	78.193	−140.59	−76.644	−1.320 6	1.4387	2.7036	278
315	74.604	−130.51	−63.490	−1.278 5	1.4383	2.5653	284
320	71.515	−120.85	−50.930	−1.238 9	1.4411	2.4635	289
330	66.402	−102.33	−27.035	−1.165 4	1.4534	2.3274	300
340	62.277	−84.491	−4.2043	−1.097 2	1.4718	2.2455	309
350	58.833	−67.006	17.980	−1.302 9	1.4945	2.1957	318
360	55.886	−49.691	39.777	−0.971 51	1.5200	2.1664	326
370	53.319	−32.420	61.356	−0.912 38	1.5476	2.1512	333
380	51.050	−15.109	82.834	−0.855 10	1.5766	2.1459	340
390	49.022	2.3021	104.30	−0.799 35	1.6067	2.1478	347
400	47.192	19.859	125.81	−0.744 89	1.6375	2.1551	353
410	45.529	37.593	147.41	−0.691 54	1.6688	2.1665	359
420	44.006	55.529	169.15	−0.639 17	1.7004	2.1810	365
430	42.605	73.686	191.04	−0.587 65	1.7321	2.1979	371
440	41.310	92.077	213.11	−0.536 91	1.7638	2.2167	376
450	40.106	110.71	235.38	−0.486 87	1.7954	2.2369	381
			6.0 MPa isobar				
104.830[a]	656.38	−818.90	−809.76	−4.7993	1.6200	2.4214	179
105	656.17	−818.49	−809.35	−4.7954	1.6194	2.4215	179
110	649.97	−806.47	−797.24	−4.6827	1.6001	2.4228	176
115	643.75	−794.45	−785.13	−4.5751	1.5791	2.4203	172
120	637.49	−782.45	−773.04	−4.4721	1.5572	2.4155	169
125	631.21	−770.48	−760.97	−4.3737	1.5351	2.4094	166
130	624.89	−758.54	−748.94	−4.2793	1.5132	2.4029	162
135	618.54	−746.64	−736.94	−4.1887	1.4920	2.3965	159
140	612.15	−734.78	−724.98	−4.1017	1.4716	2.3906	155
145	605.71	−722.94	−713.04	−4.0179	1.4522	2.3858	152
150	599.22	−711.13	−701.12	−3.9371	1.4341	2.3821	148
155	592.68	−699.34	−689.21	−3.8590	1.4172	2.3800	145
160	586.07	−687.55	−677.31	−3.7834	1.4016	2.3795	142
165	579.39	−675.77	−665.41	−3.7102	1.3874	2.3809	138
170	572.63	−663.98	−653.50	−3.6391	1.3746	2.3842	135
175	565.78	−652.17	−641.57	−3.5699	1.3631	2.3898	131
180	558.83	−640.34	−629.60	−3.5025	1.3531	2.3976	127
185	551.77	−628.46	−617.59	−3.4366	1.3444	2.4079	124
190	544.59	−616.53	−605.52	−3.3723	1.3371	2.4209	120
195	537.28	−604.54	−593.37	−3.3092	1.3311	2.4368	117
200	529.81	−592.47	−581.14	−3.2472	1.3265	2.4558	113
205	522.17	−580.30	−568.81	−3.1863	1.3232	2.4783	109
210	514.33	−568.02	−556.35	−3.1263	1.3212	2.5045	105
215	506.28	−555.61	−543.76	−3.0670	1.3204	2.5351	102
220	497.98	−543.04	−531.00	−3.0083	1.3210	2.5705	981
225	489.39	−530.30	−518.04	−2.9501	1.3228	2.6117	941
230	480.48	−517.36	−504.87	−2.8922	1.3259	2.6595	901
235	471.19	−504.17	−491.43	−2.8344	1.3304	2.7154	860
240	461.46	−490.70	−477.70	−2.7766	1.3362	2.7814	818
245	451.20	−476.90	−463.60	−2.7185	1.3436	2.8601	775
250	440.29	−462.70	−449.07	−2.6598	1.3525	2.9555	730
255	428.59	−448.01	−434.01	−2.6001	1.3634	3.0740	685
260	415.87	−432.70	−418.27	−2.5390	1.3764	3.2255	637
265	401.82	−416.60	−401.67	−2.4758	1.3925	3.4279	587
270	385.89	−399.40	−383.85	−2.4092	1.4127	3.7156	533

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			6.0 MPa isobar—Continued				
275	367.13	−380.59	−364.24	−2.337 2	1.4400	4.1664	475.03
280	343.50	−359.04	−341.58	−2.255 5	1.4809	5.0024	408.88
285	309.02	−331.54	−312.12	−2.151 4	1.5576	7.2292	329.04
290	231.16	−279.61	−253.65	−1.948 3	1.7533	19.330	235.92
295	153.11	−220.67	−181.48	−1.701 2	1.6441	8.6768	236.94
300	128.88	−194.96	−148.40	−1.589 9	15569	5.2836	248.89
305	115.55	−177.24	−125.32	−1.513 6	1.5167	4.1072	258.53
310	106.44	−162.78	−106.40	−1.452 1	1.4959	3.5140	266.80
315	99.553	−150.06	−89.792	−1.398 9	1.4852	3.1574	274.14
320	94.044	−138.43	−74.634	−1.351 2	1.4807	2.9205	280.82
330	85.563	−117.15	−47.029	−1.266 2	1.4832	2.6299	292.69
340	79.167	−97.417	−21.628	−1.190 4	1.4954	2.4646	303.13
350	74.062	−78.539	2.4739	−1.120 5	1.5137	2.3637	312.55
360	69.836	−60.144	25.771	−1.054 8	1.5361	2.3007	321.19
370	66.243	−42.008	48.567	−0.992 39	1.5612	2.2617	329.22
380	63.130	−23.984	71.058	−0.932 41	1.5884	2.2389	336.74
390	60.391	−5.9709	93.382	−0.874 42	1.6171	2.2275	343.84
400	57.951	12.101	115.64	−0.818 08	1.6467	2.2245	350.59
410	55.757	30.283	137.89	−0.763 13	1.6770	2.2276	357.04
420	53.768	48.613	160.20	−0.709 36	1.7078	2.2353	363.22
430	51.952	67.120	182.61	−0.656 63	1.7389	2.2467	369.17
440	50.284	85.824	205.15	−0.604 82	1.7700	2.2608	374.91
450	48.744	104.74	227.83	−0.553 84	1.8012	2.2771	380.47
			7.0 MPa isobar				
104.969[a]	656.67	−818.86	−808.20	−4.7990	1.6198	2.4201	1797.7
105	656.64	−818.79	−808.13	−4.7983	1.6197	2.4201	1797.5
110	650.46	−806.78	−796.02	−4.6856	1.6006	2.4213	1765.2
115	644.26	−794.78	−783.92	−4.5781	1.5798	2.4187	1732.3
120	638.03	−782.81	−771.84	−4.4752	1.5580	2.4137	1699.1
125	631.77	−770.86	−759.78	−4.3768	1.5360	2.4075	1665.6
130	625.49	−758.95	−747.76	−4.2825	1.5142	2.4007	1632.0
135	619.17	−747.08	−735.78	−4.1920	1.4930	2.3941	1598.2
140	612.81	−735.24	−723.82	−4.1051	1.4727	2.3880	1564.4
145	606.42	−723.44	−711.89	−4.0214	1.4534	2.3828	1530.4
150	599.97	−711.66	−699.99	−3.9407	1.4352	2.3789	1496.4
155	593.47	−699.90	−688.10	−3.8627	1.4184	2.3763	1462.2
160	586.90	−688.15	−676.22	−3.7873	1.4028	2.3754	1727.8
165	580.28	−676.41	−664.35	−3.7142	1.3886	2.3763	1393.3
170	573.57	−664.66	−652.46	−3.6432	1.3758	2.3791	1358.5
175	566.78	−652.90	−640.55	−3.5742	1.3644	2.3840	1323.6
180	559.90	−641.12	−628.61	−3.5069	1.3543	2.3912	1288.3
185	552.92	−629.30	−616.64	−3.4413	1.3456	2.4007	1252.8
190	545.82	−617.43	−604.60	−3.3771	1.3383	2.4127	1217.1
195	538.60	−605.50	−592.50	−3.3142	1.3323	2.4274	1181.0
200	531.23	−593.50	−580.32	−3.2526	1.3276	2.4451	1144.5
205	523.70	−581.41	−568.05	−3.1919	1.3242	2.4660	1107.7
210	216.00	−569.22	−555.66	−3.1322	1.3221	2.4903	1070.5
215	508.09	−556.92	−543.14	−3.0733	1.3213	2.5186	1032.9
220	499.96	−544.47	−530.47	−3.0151	1.3217	2.5512	994.82
225	491.57	−531.86	−517.62	−2.9573	1.3233	2.5888	956.22
230	482.90	−519.06	−504.57	−2.8999	1.3262	2.6322	917.05
235	473.88	−506.06	−491.29	−2.8428	1.3304	2.6824	877.26

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			7.0 MPa isobar—Continued				
240	464.48	−492.80	−477.73	−2.785 7	1.3358	2.7409	836.76
245	454.62	−479.26	−463.86	−2.728 5	1.3426	2.8095	795.46
250	444.22	−465.37	−449.61	−2.671 0	1.3509	2.8910	753.24
255	433.16	−451.08	−434.92	−2.612 8	1.3607	2.9893	709.93
260	421.30	−436.30	−419.68	−2.553 6	1.3723	3.1104	665.33
265	408.43	−420.90	−403.76	−2.493 0	1.3860	3.2639	619.16
270	394.23	−404.72	−386.97	−2.430 2	1.4025	3.4655	571.03
275	378.23	−387.49	−368.98	−2.364 2	1.4228	3.7446	520.40
280	359.62	−368.76	−349.30	−2.293 3	1.4487	4.1598	466.55
285	336.91	−347.72	−326.94	−2.214 1	1.4840	4.8475	408.57
290	306.90	−322.59	−299.79	−2.119 7	1.5360	6.1773	345.97
295	262.67	−289.36	−262.72	−1.993 1	1.6113	8.9100	284.69
300	206.13	−247.59	−213.63	−1.828 1	1.6433	9.6272	253.67
305	167.83	−214.68	−172.97	−1.693 6	1.5979	6.7253	253.96
310	146.24	−191.94	−144.07	−1.599 6	1.5594	5.0296	260.51
315	132.26	−174.29	−121.36	−1.526 9	1.5362	4.1408	267.63
320	122.16	−159.37	−102.07	−1.4661	1.5230	3.6165	274.47
330	108.05	−133.92	−69.131	−1.364 7	1.5145	3.0409	286.99
340	98.260	−111.60	−40.361	−1.278 8	1.5198	2.7417	298.12
350	90.857	−90.937	−13.893	−1.202 1	1.5333	2.5663	308.16
360	84.949	−71.221	11.181	−1.131 4	1.5523	2.4569	317.33
370	80.062	−52.058	35.374	−1.065 1	1.5749	2.3868	325.83
380	75.914	−33.208	59.001	−1.002 1	1.6002	2.3421	333.77
390	72.324	−14.513	82.273	−0.941 58	1.6274	2.3146	341.24
400	69.170	4.1330	105.33	−0.883 29	1.6558	2.2992	348.32
410	66.364	22.808	128.29	−0.826 61	1.6852	2.2926	355.06
420	63.844	41.566	151.21	−0.771 38	1.7151	2.2927	361.51
430	61.562	60.450	174.16	−0.717 38	1.7455	2.2978	367.71
440	59.480	79.489	197.18	−0.664 46	1.7761	2.3067	373.67
450	57.569	98.708	220.30	−0.612 49	1.8068	2.3187	379.44
			8.0 MPa isobar				
105.108[a]	656.96	−818.82	−806.64	−4.7986	1.6197	2.4188	1802.0
110	650.94	−807.09	−794.80	−4.6886	1.6012	2.4198	1770.4
115	644.77	−795.12	−782.71	−4.5810	1.5805	2.4171	1737.5
120	638.56	−783.16	−770.64	−4.4783	1.5588	2.4120	1704.4
125	632.34	−771.24	−758.59	−4.3799	1.5369	2.4056	1671.0
130	626.08	−759.36	−746.58	−4.2857	1.5152	2.3986	1637.5
135	619.80	−747.51	−734.61	−4.1953	1.4941	2.3917	1603.9
140	613.47	−735.70	−722.66	−4.1085	1.4738	2.3854	1570.3
145	607.11	−723.93	−910.75	−4.0249	1.4545	2.3799	1536.6
150	600.70	−712.18	−698.86	−3.9442	1.4364	2.3757	1502.7
155	594.25	−700.45	−686.99	−3.8664	1.4196	2.3728	1468.8
160	587.73	−688.74	−675.13	−3.7911	1.4040	2.3715	1434.7
165	581.15	−677.04	−663.27	−3.7181	1.3899	2.3719	1400.5
170	574.50	−665.33	−651.41	−3.6473	1.3771	2.3742	1366.1
175	567.7 7	−653.62	−639.53	−3.5784	1.3656	2.3785	1331.4
180	560.96	−641.88	−627.62	−3.5113	1.3556	2.3850	1296.6
185	554.05	−630.11	−615.67	−3.4458	1.3469	2.3937	1261.6
190	547.03	−618.30	−603.68	−3.3819	1.3395	2.4048	1226.2
195	539.89	−606.44	−591.62	−3.3192	1.3335	2.4185	1190.7
200	532.62	−594.51	−579.49	−3.2578	1.3288	2.4350	1154.8
205	525.20	−582.50	−567.27	−3.1974	1.3253	2.4544	1118.6

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			8.0 MPa isobar—Continued				
210	517.62	−570.40	−554.94	−3.138 0	1.3232	2.4770	1082.0
215	509.85	−558.18	−542.49	−3.079 4	1.3222	2.5032	1045.1
220	501.88	−545.84	−529.90	−3.021 6	1.3225	2.5333	1007.9
225	493.67	−533.36	−517.15	−2.964 3	1.3240	2.5678	970.18
230	485.21	−520.70	−504.22	−2.907 4	1.3267	2.6074	932.04
235	476.44	−507.86	−491.07	−2.850 8	1.3306	2.6528	893.40
240	467.33	−494.79	−477.68	−2.794 5	1.3357	2.7051	854.22
245	457.82	−481.48	−464.00	−2.738 1	1.3421	2.7657	814.43
250	447.85	−467.86	−450.00	−2.681 5	1.3498	2.8364	773.97
255	437.34	−453.91	−435.62	−2.624 5	1.3589	2.9199	732.73
260	426.17	−439.55	−420.78	−2.566 9	1.3694	3.0198	690.62
265	414.19	−424.70	−405.38	−2.508 3	1.3817	3.1416	647.50
270	401.23	−409.25	−389.31	−2.448 2	1.3959	3.2938	603.19
275	387.00	−393.05	−372.37	−2.386 0	1.4126	3.4894	557.50
280	371.08	−375.86	−354.31	−2.320 9	1.4324	3.7508	510.25
285	352.88	−357.36	−334.69	−2.251 5	1.4565	4.1167	461.31
290	331.39	−336.99	−312.85	−2.175 6	1.4865	4.6564	410.89
295	305.06	−313.88	−287.65	−2.089 4	1.5236	5.4818	360.33
300	272.08	−286.89	−257.49	−1.988 0	1.5651	6.6093	314.55
305	234.00	−256.49	−222.30	−1.871 8	1.5935	7.2584	283.70
310	199.74	−227.46	−187.40	−1.758 2	1.5913	6.5179	271.99
315	174.82	−203.49	−157.72	−1.663 2	1.5747	5.3805	271.40
320	157.28	−183.95	−133.09	−1.585 6	1.5595	4.5283	274.93
330	134.44	−152.75	−93.246	−1.463 0	1.5438	3.5611	285.12
340	119.82	−127.07	−60.304	−1.364 6	1.5432	3.0769	295.70
350	109.33	−104.20	−31.025	−1.279 7	1.5524	2.8024	305.70
360	101.27	−82.901	−3.9074	−1.203 3	1.5681	2.6339	315.02
370	94.790	−62.546	21.852	−1.132 7	1.5884	2.5256	323.72
380	89.400	−42.758	46.728	−1.066 4	1.6117	2.4546	331.88
390	84.811	−23.303	71.024	−1.003 2	1.6374	2.4081	339.58
400	80.833	−4.0241	94.946	−0.942 67	1.6647	2.3785	346.88
410	77.333	15.186	118.64	−0.884 18	1.6931	2.3611	353.83
420	74.217	34.406	142.20	−0.827 40	1.7223	2.3526	360.48
430	71.417	53.691	165.71	−0.772 07	1.7520	2.3508	366.85
440	68.880	73.085	189.23	−0.718 00	1.7820	2.3540	372.99
450	66.565	92.620	212.80	−0.665 03	1.8123	2.3613	378.91
			10.0 MPa isobar				
105.386[a]	657.54	−818.73	−803.52	−4.7979	1.6195	2.4163	1810.2
110	651.90	−807.71	−792.37	−4.6943	1.6023	2.4170	1780.4
115	645.77	−795.78	−780.29	−4.5870	1.5819	2.4140	1747.7
120	639.62	−783.87	−768.23	−4.4843	1.5605	2.4086	1714.7
125	633.45	−771.99	−756.21	−4.3861	1.5387	2.4019	1681.6
130	627.25	−760.16	−744.22	−4.2921	1.5172	2.3945	1648.4
135	621.03	−748.36	−732.26	−4.2018	1.4962	2.3872	1615.1
140	614.77	−736.61	−720.34	−4.1152	1.4760	2.3804	1581.9
145	608.48	−724.89	−708.46	−4.0317	1.4568	2.3745	1548.5
150	602.15	−713.20	−696.60	−3.9513	1.4388	2.3696	1515.2
155	595.78	−701.54	−684.76	−3.8737	1.4220	2.3660	1481.7
160	589.35	−689.90	−672.93	−3.7986	1.4065	2.3640	1448.2
165	582.87	−678.27	−661.12	−3.7259	1.3924	2.3636	1414.5
170	576.33	−666.65	−649.30	−3.6553	1.3796	2.3649	1380.7
175	569.71	−655.02	−637.46	−3.5867	1.3682	2.3681	1346.8

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			10.0 MPa isobar—Continued				
180	563.02	−643.37	−625.61	−35.199	1.3581	2.3734	1312.7
185	556.24	−631.70	−613.73	−3.4548	1.3494	2.3807	1278.5
190	549.37	−620.00	−601.80	−3.3912	1.3421	2.3902	1244.0
195	542.40	−608.26	−589.82	−3.3289	1.3360	2.4020	1209.4
200	535.31	−596.46	−577.78	−3.2680	1.3312	2.4163	1174.5
205	528.09	−584.59	−565.65	−3.2081	1.3277	2.4331	1139.4
210	520.73	−572.64	−553.44	−3.1492	1.3254	2.4528	1104.1
215	513.22	−560.61	−541.12	−3.0913	1.3243	2.4754	1068.5
220	505.53	−548.46	−528.68	−3.0341	1.3244	2.5013	1032.7
225	497.65	−536.20	−516.10	−2.9775	1.3257	2.5308	996.59
230	489.56	−523.79	−503.37	−2.9215	1.3281	2.5642	960.22
235	481.22	−511.23	−490.45	−2.8660	1.3316	2.6020	923.56
240	472.61	−498.50	−477.34	−2.8108	1.3363	2.6447	886.59
245	463.70	−485.56	−464.00	−2.7558	1.3420	2.6933	849.30
250	454.43	−472.40	−450.40	−2.7008	1.3489	2.7485	811.66
255	444.77	−458.98	−436.50	−2.6458	1.3569	2.8117	773.66
260	434.65	−445.27	−422.26	−2.5905	1.3661	2.8843	735.29
265	423.99	−431.22	−407.64	−2.5348	1.3766	2.9686	696.52
270	412.70	−416.78	−392.55	−2.4784	1.3883	3.0672	657.34
275	400.67	−401.89	−376.93	−2.4211	1.4015	3.1841	617.78
280	387.76	−386.46	−360.67	−2.3625	1.4162	3.3241	577.88
285	373.77	−370.40	−343.64	−2.3022	1.4326	3.4941	537.77
290	358.48	−353.57	−325.67	−2.2397	1.4509	3.7022	497.70
295	341.62	−335.82	−306.54	−2.1743	1.4712	3.9569	458.16
300	322.89	−316.99	−286.02	−2.1053	1.4932	4.2620	420.01
305	302.13	−296.96	−263.86	−2.0311	1.5162	4.6027	384.64
310	279.52	−275.80	−240.02	−1.9546	1.5380	4.9192	354.13
315	255.98	−253.97	−214.91	−1.8742	1.5558	5.0934	330.67
320	233.21	−232.38	−189.50	−1.7942	1.5672	5.0282	315.19
330	195.49	−193.22	−142.06	−1.6481	1.5747	4.4015	303.11
340	169.20	−160.54	−101.44	−1.5268	1.5771	3.7544	304.14
350	150.78	−132.60	−66.284	−1.4249	1.5837	3.3084	309.85
360	137.21	−107.64	−34.756	−1.3360	1.5957	3.0176	317.09
370	126.70	−84.532	−5.6062	−1.2562	1.6124	2.8253	324.75
380	118.25	−62.608	21.957	−1.1827	1.6328	2.6955	332.38
390	111.26	−41.443	48.440	−1.1139	1.6560	2.6066	339.84
400	105.33	−20.762	74.182	−1.0487	1.6812	2.5455	347.06
410	100.21	−0.37711	99.416	−0.98637	1.7079	2.5040	354.02
420	95.725	19.843	124.31	−0.92638	1.7357	2.4766	360.74
430	91.752	39.994	148.98	−0.86832	1.7642	2.4598	367.23
440	88.194	60.144	173.53	−0.81189	1.7933	2.4508	373.49
450	84.982	80.348	198.02	−0.75685	1.8227	2.4480	379.56
			15.0 MPa isobar				
106.077[a]	658.95	−818.50	−795.73	−4.7961	1.6195	2.4104	1830.0
110	654.24	−809.21	−786.28	−4.7086	1.6054	2.4103	1804.7
115	648.23	−797.37	−774.23	−4.6015	1.5857	2.4068	1772.2
120	642.20	−785.57	−762.21	−4.4992	1.5649	2.4008	1739.6
125	636.16	−773.81	−750.23	−4.4013	1.5436	2.3933	1707.1
130	630.10	−762.09	−738.28	−4.3076	1.5224	2.3851	1674.5
135	624.03	−750.41	−726.38	−4.2177	1.5017	2.3769	1642.0
140	617.93	−738.79	−714.51	−4.1314	1.4818	2.3690	1609.6
145	611.80	−727.20	−702.69	−4.0484	1.4628	2.3619	1577.2

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			15.0 MPa isobar—Continued				
150	605.65	−715.66	−690.89	−3.968 5	1.4450	2.3557	1544.9
155	599.47	−704.15	−679.13	−3.891 3	1.4284	2.3508	1512.6
160	593.25	−692.67	−667.38	−3.816 7	1.4130	2.3471	1480.2
165	586.99	−681.21	−655.65	−3.744 6	1.3989	2.3449	1447.9
170	580.68	−669.76	−643.93	−3.674 6	1.3862	2.3442	1415.5
175	574.32	−658.33	−632.21	−3.606 6	1.3749	2.3452	1383.1
180	567.91	−646.89	−620.48	−3.540 5	1.3648	2.3479	1350.6
185	561.43	−635.44	−608.73	−3.476 1	1.3561	2.3523	1318.1
190	554.89	−623.98	−596.95	−3.413 3	1.3487	2.3586	1285.5
195	548.27	612.50	585.14	3.351 9	1.3426	2.3667	1252.8
200	541.57	−600.98	−573.28	−3.291 9	1.3378	2.3768	1220.1
205	534.78	−589.41	−561.37	−3.233 1	1.3341	2.3889	1187.3
210	527.89	−577.80	−549.39	−3.175 3	1.3317	2.4030	1154.4
215	520.90	−566.13	−537.33	−3.118 6	1.3304	2.4193	1121.5
220	513.80	−554.38	−525.19	−3.062 8	1.3303	2.4378	1088.5
225	506.56	−542.56	−512.95	−3.007 8	1.3312	2.4586	1055.5
230	499.19	−530.65	−500.60	−2.953 5	1.3332	2.4818	1022.5
235	491.67	−518.64	−488.13	−2.899 8	1.3362	2.5076	989.49
240	483.99	−506.51	−475.52	−2.846 7	1.3402	2.5360	956.48
245	476.13	−494.27	−462.76	−2.794 1	1.3451	2.5674	923.50
250	468.07	−481.89	−449.84	−2.741 9	1.3510	2.6017	890.58
255	459.81	−469.36	−436.74	−2.690 0	1.3578	2.6393	857.75
260	451.31	−456.68	−423.44	−2.638 4	1.3655	2.6805	825.04
265	442.57	−443.82	−409.93	−2.586 9	1.3740	2.7254	792.49
270	433.54	−430.78	−396.18	−2.535 5	1.3833	2.7743	760.16
275	424.22	−417.54	−382.18	−2.484 1	1.3935	2.8276	728.11
280	414.58	−404.08	−367.90	−2.432 7	1.4045	2.8855	696.40
285	404.59	−390.39	−353.31	−2.381 1	1.4162	2.9483	665.15
290	394.22	−376.45	−338.41	−2.329 2	1.4286	3.0160	634.46
295	383.46	−362.26	−323.15	−2.277 0	1.4418	3.0885	604.50
300	372.28	−347.80	−307.51	−2.224 5	1.4555	3.1654	575.42
305	360.68	−333.07	−291.49	−2.171 5	1.4698	3.2454	547.46
310	348.67	−318.08	−275.06	−2.118 1	1.4844	3.3265	520.86
315	336.27	−302.83	−258.22	−2.064 2	1.4994	3.4055	495.90
320	323.56	−287.37	−241.01	−2.010 0	1.5144	3.4783	472.86
330	297.60	−256.04	−205.64	−1.901 2	1.5439	3.5854	433.49
340	271.97	−224.73	−169.57	−1.793 5	1.5714	3.6123	404.06
350	248.03	−194.18	−133.70	−1.689 5	1.5963	3.5475	384.47
360	226.78	−164.98	−98.841	−1.591 3	1.6191	3.4179	373.10
370	208.55	−137.35	−65.420	−1.499 7	1.6410	3.2656	367.68
380	193.13	−111.17	−33.503	−1.414 6	1.6632	3.1206	366.21
390	180.10	−86.225	−2.9386	−1.335 2	1.6862	2.9961	367.28
400	169.03	−62.245	26.497	−1.260 7	1.7104	2.8949	369.95
410	159.53	−38.996	55.032	−1.190 2	1.7356	2.8153	373.62
420	151.29	−16.284	82.863	−1.123 1	1.7618	2.7539	377.93
430	144.07	6.0454	110.16	−1.058 9	1.7888	2.7075	382.61
440	137.69	28.115	137.05	−0.997 07	1.8164	2.6732	387.52
450	132.00	50.020	163.66	−0.937 29	1.8444	2.6487	392.55
			20.0 MPa isobar				
106.764[a]	660.33	−818.24	−787.96	−4.7942	1.6203	2.4048	1848.6
110	656.51	−810.64	−780.17	−4.7224	1.6090	2.4043	1827.8
115	650.61	−798.90	−768.16	−4.6156	1.5900	2.4003	1795.5

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s
			20.0. MPa isobar—Continued				
120	644.69	−787.20	−756.18	−4.5136	1.5696	2.3937	176
125	638.77	−775.54	−744.23	−4.4160	1.5488	2.3856	173
130	632.84	−763.92	−732.32	−4.3227	1.5279	2.3767	169
135	626.90	−752.36	−720.46	−4.2331	1.5075	2.3677	166
140	620.95	−740.85	−708.64	−4.1472	1.4878	2.3590	163
145	614.98	−729.39	−696.87	−4.0645	1.4691	2.3509	160
150	608.99	−717.97	−685.13	−3.9850	1.4514	2.3436	157
155	602.98	−706.60	−673.43	−3.9082	1.4349	2.3375	154
160	596.94	−695.26	−661.76	−3.8341	1.4196	2.3325	151
165	590.88	−683.95	−650.10	−3.7624	1.4057	2.3288	147
170	584.78	−672.67	−638.47	−3.6929	1.3931	2.3266	144
175	578.64	−661.40	−626.83	−3.6255	1.3818	2.3258	141
180	572.47	−650.14	−615.20	−3.5599	1.3718	2.3266	138
185	566.25	−638.89	−603.57	−3.4962	1.3631	2.3288	135
190	559.98	−627.63	−591.91	−3.4340	1.3557	2.3327	132
195	553.66	−616.36	−580.24	−3.3733	1.3496	2.3382	129
200	547.29	−605.07	−568.53	−3.3141	1.3448	2.3453	126
205	540.84	−593.76	−556.78	−3.2560	1.3411	2.3540	123
210	534.34	−582.42	−544.99	−3.1992	1.3386	2.3644	119
215	527.76	−571.03	−533.13	−3.1434	1.3372	2.3765	116
220	521.10	−559.60	−521.22	−3.0886	1.3369	2.3903	113
225	514.35	−548.11	−509.23	−3.0348	1.3377	2.4057	110
230	507.52	−536.56	−497.16	−2.9817	1.3395	2.4229	107
235	500.59	−524.95	−485.00	−2.9294	1.3423	2.4418	104
240	493.55	−513.26	−472.74	−2.8778	1.3460	2.4625	101
245	486.40	−501.49	−460.37	−2.8268	1.3506	2.4849	985.
250	479.14	−489.63	−447.88	−2.7763	1.3561	2.5091	955.
255	471.75	−477.67	−435.27	−2.7264	1.3624	2.5351	925.
260	464.23	−465.61	−422.53	−2.6769	1.3695	2.5629	896.
265	456.57	−453.45	−409.64	−2.6278	1.3773	2.5925	867.
270	448.76	−441.17	−396.60	−2.5790	1.3859	2.6239	838.
275	440.80	−428.77	−383.40	−2.5306	1.3951	2.6570	810.
280	432.68	−416.25	−370.03	−2.4824	1.4051	2.6919	782.
285	424.39	−403.60	−356.48	−2.4344	1.4156	2.7283	755.
290	415.93	−390.83	−342.74	−2.3867	1.4267	2.7662	728.
295	407.30	−377.92	−328.81	−2.3390	1.4383	2.8053	702.
300	398.50	−364.88	−314.69	−2.2916	1.4504	2.8454	677.
305	389.53	−351.70	−300.36	−2.2442	1.4630	2.8860	652.
310	380.40	−338.40	−285.83	−2.1969	1.4759	2.9268	629.
315	371.12	−324.98	−271.09	−2.1498	1.4892	2.9670	606.
320	361.71	−311.45	−256.16	−2.1027	1.5028	3.0059	585.
330	342.61	−284.12	−225.74	−2.0092	1.5305	3.0757	546.
340	323.37	−256.55	−194.70	−1.9165	1.5586	3.1282	513.
350	304.38	−228.96	−163.26	−1.8253	1.5867	3.1571	485.
360	286.03	−201.57	−131.65	−1.7363	1.6144	3.1598	463.
370	268.70	−174.58	−100.14	−1.6500	1.6417	3.1380	446.
380	252.65	−148.11	−68.954	−1.5668	1.6687	3.0973	434.
390	238.01	−122.26	−38.236	−1.4870	1.6955	3.0452	426.
400	224.81	−97.027	−8.0631	−1.4106	1.7224	2.9892	421.
410	212.96	−72.358	21.555	−1.3375	1.7493	2.9350	418.
420	202.36	−48.183	50.653	−1.2674	1.7765	2.8858	417.
430	192.85	−24.415	79.293	−1.2000	1.8040	2.8433	418.
440	184.31	−0.97080	107.54	−1.1350	1.8317	2.8079	419.

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			20.0 MPa isobar—Continued				
450	176.61	22.228	135.47	−1.0722	1.8596	2.7794	421.75
			25.0 MPa isobar				
107.446[a]	661.68	−817.97	−780.19	−4.7923	1.6216	2.3996	1866.1
110	658.72	−812.01	−774.06	−4.7360	1.6130	2.3988	1849.7
115	652.91	−800.37	−762.08	−4.6294	1.5945	2.3945	1817.7
120	647.11	−788.75	−750.12	−4.5276	1.5746	2.3874	1785.9
125	641.30	−777.19	−738.20	−4.4304	1.5542	2.3787	1754.2
130	635.49	−765.67	−726.33	−4.3373	1.5336	2.3692	1722.8
135	629.68	−754.22	−714.51	−4.2480	1.5135	2.3595	1691.6
140	623.86	−742.81	−702.74	−4.1624	1.4940	2.3500	1660.7
145	618.03	−731.46	−691.01	−4.0801	1.4754	2.3411	1629.9
150	612.19	−720.16	−679.33	−4.0008	1.4579	2.3329	1599.3
155	606.33	−708.91	−667.68	−3.9245	1.4415	2.3258	1568.8
160	600.46	−697.70	−656.07	−3.8507	1.4264	2.3198	1538.5
165	594.57	−686.53	−644.48	−3.7794	1.4125	2.3149	1508.3
170	588.66	−675.38	−632.92	−3.7104	1.4000	2.3114	1478.2
175	582.72	−664.27	−621.36	−3.6434	1.3888	2.3092	1448.1
180	576.76	−653.17	−609.82	−3.5784	1.3788	2.3085	1418.2
185	570.76	−642.08	−598.28	−3.5151	1.3702	2.3091	1388.3
190	564.73	−631.00	−586.73	−3.4535	1.3629	2.3111	1358.5
195	558.67	−619.91	−575.16	−3.3934	1.3538	2.3146	1328.8
200	552.56	−608.82	−563.58	−3.3348	1.3519	2.3195	1299.2
205	546.41	−597.72	−551.97	−3.2774	1.3482	2.3258	1269.7
210	540.22	−586.60	−540.32	−3.2213	1.3457	2.3336	1240.3
215	533.97	−575.45	−528.63	−3.1663	1.3443	2.3427	1211.0
220	527.67	−564.27	−516.89	−3.1123	1.3440	2.3532	1181.8
225	521.32	−553.05	−505.09	−3.0593	1.3447	2.3651	1152.8
230	514.90	−541.79	−493.24	−3.0072	1.3464	2.3784	1124.0
235	508.42	−530.48	−481.31	−2.9559	1.3491	2.3930	1095.4
240	501.87	−519.12	−469.30	−2.9053	1.3527	2.4089	1067.1
245	495.25	−507.70	−457.22	−2.8555	1.3571	2.4260	1039.0
250	488.56	−496.21	−445.04	−2.8063	1.3624	2.4444	1011.2
255	481.78	−484.66	−432.77	−2.7577	1.3685	2.4640	983.65
260	474.93	−473.04	−420.40	−2.7096	1.3754	2.4848	956.50
265	468.00	−461.34	−407.92	−2.6621	1.3829	2.5067	929.73
270	460.98	−449.56	−395.33	−2.6150	1.3912	2.5295	903.38
275	453.87	−437.71	−382.62	−2.5684	1.4000	2.5534	877.48
280	446.67	−425.76	−369.80	−2.5222	1.4095	2.5781	852.07
285	439.38	−413.74	−356.84	−2.4763	1.4196	2.6037	827.20
290	432.01	401.63	−343.76	−2.4308	1.4302	2.6298	802.90
295	424.55	−389.43	−330.54	−2.3856	1.4413	2.6565	779.23
300	417.00	−377.14	−317.19	−2.3407	1.4528	2.6835	756.22
305	409.37	−364.78	−303.71	−2.2962	1.4648	2.7107	733.92
310	401.66	−352.33	−290.09	−2.2519	1.4772	2.7378	712.37
315	393.89	−339.80	−276.33	−2.2078	1.4899	2.7646	691.63
320	386.06	−327.20	−262.44	−2.1641	1.5029	2.7908	671.73
330	370.27	−301.80	−234.28	−2.0775	1.5297	2.8403	634.62
340	354.42	−276.19	−205.66	−1.9920	1.5573	2.8835	601.37
350	338.65	−250.46	−176.64	−1.9079	1.5854	2.9177	572.18
360	323.15	224.70	−147.34	−1.8253	1.6138	2.9412	547.12
370	308.09	−199.00	−117.85	−1.7446	1.6424	2.9533	526.08
380	293.63	−173.45	−88.306	−1.6658	1.6709	2.9547	508.82

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	κ (m s
			25.0 MPa isobar—Continued				
390	279.91	−148.10	−58.791	−1.5891	1.6995	2.9469	495
400	267.02	−123.02	−29.391	−1.5147	1.7280	2.9321	484
410	255.00	−98.204	−0.16397	−1.4425	1.7564	2.9127	476
420	243.85	−73.666	28.855	−1.3726	1.7849	2.8910	470
430	233.56	−49.383	57.655	−1.3048	1.8133	2.8690	466
440	224.08	−25.325	86.240	−1.2391	1.8417	2.8484	463
450	215.36	−1.4561	114.63	−1.1753	1.8701	2.8299	462
			50. MPa isobar				
111.384[a]	667.42	−815.00	−740.08	−4.7696	1.6322	2.3766	193
115	663.54	−806.85	−731.49	−4.6937	1.6203	2.3721	191
120	658.19	−795.62	−719.65	−4.5929	1.6022	2.3633	188
125	652.86	−784.45	−707.86	−4.4967	1.5832	2.3527	185
130	647.55	−773.34	−696.13	−4.4046	1.5638	2.3411	182
135	642.25	−762.30	−684.45	−4.3165	1.5446	2.3292	179
140	636.97	−751.33	−672.84	−4.2320	1.5259	2.3172	176
145	631.71	−740.43	−661.28	−4.1509	1.5080	2.3056	174
150	626.46	−729.59	−649.78	−4.0729	1.4911	2.2946	171
155	621.22	−718.82	−638.33	−3.9978	1.4752	2.2844	168
160	615.99	−708.11	−626.93	−3.9255	1.4604	2.2751	166
165	610.77	−697.44	−615.58	−3.8556	1.4469	2.2668	163
170	605.56	−686.83	−604.27	−3.7880	1.4347	2.2595	160
175	600.35	−676.27	−592.98	−3.7226	1.4237	2.2533	158
180	595.16	−665.74	−581.73	−3.6592	1.4140	2.2482	155
185	589.97	−655.25	−570.50	−3.5977	1.4055	2.2443	153
190	584.78	−644.79	−559.29	−3.5379	1.3984	2.2414	150
195	579.60	−634.35	−548.08	−3.4797	1.3924	2.2397	147
200	574.43	−623.93	−536.89	−3.4230	1.3876	2.2390	145
205	569.25	−613.53	−525.69	−3.3677	1.3840	2.2395	142
210	564.08	−603.13	−514.49	−3.3137	1.3816	2.2409	140
215	558.91	−592.74	−503.28	−3.2609	1.3802	2.2433	138
220	553.74	−582.35	−492.06	−3.2093	1.3799	2.2467	135
225	548.58	−571.96	−480.81	−3.1588	1.3806	2.2510	133
230	543.41	−561.56	−469.54	−3.1093	1.3822	2.2561	130
235	538.25	−551.14	−458.25	−3.0607	1.3848	2.2621	128
240	533.08	−540.72	−446.92	−3.0130	1.3883	2.2689	126
245	527.92	−530.27	−435.56	−2.9661	1.3926	2.2765	124
250	522.75	−519.80	−424.16	−2.9201	1.3977	2.2847	121
255	517.59	−509.31	−412.71	−2.8747	1.4036	2.2936	119
260	512.43	−498.79	−401.22	−2.8301	1.4102	2.3030	117
265	507.27	−488.25	−389.68	−2.7861	1.4175	2.3131	115
270	502.11	−477.67	−378.09	−2.7428	1.4254	2.3236	113
275	496.95	−467.06	−366.44	−2.7001	1.4339	2.3346	111
280	491.80	−456.41	−354.74	−2.6579	1.4430	2.3460	109
285	486.65	−445.73	−342.98	−2.6163	1.4526	2.3578	107
290	481.51	−435.00	−331.16	−2.5752	1.4628	2.3699	105
295	479.37	−424.24	−319.28	−2.5345	1.4734	2.3822	103
300	471.25	−413.44	−307.34	−2.4944	1.4844	2.3948	101
305	466.13	−402.60	−295.33	−2.4547	1.4958	2.4076	100
310	461.03	−391.72	−283.26	−2.4155	1.5076	2.4205	98
315	455.93	−380.79	−271.13	−2.3766	1.5198	2.4336	96
320	450.86	−369.83	−258.93	−2.3382	1.5322	2.4467	95
330	440.46	−347.77	−234.33	−2.2625	1.5580	2.4729	91

TABLE 33. *Thermodynamic properties of ethylene—Continued*

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			50.0 MPa isobar—Continued				
340	430.74	−325.55	−209.47	−2.1883	1.5848	2.4991	889.85
350	420.83	−303.16	−184.35	−2.1155	1.6123	2.5248	862.70
360	411.03	−280.62	−158.98	−2.0440	1.6405	2.5499	837.49
370	401.38	−257.92	−133.36	−1.9738	1.6692	2.5742	814.18
380	391.89	−235.08	−107.50	−1.9048	1.6983	2.5976	792.72
390	382.58	−212.10	−81.407	−1.8371	1.7276	2.6200	773.05
400	373.46	−188.98	−55.100	−1.7705	1.7571	2.6413	755.12
410	364.55	−165.74	−28.584	−1.7050	1.7867	2.6616	738.83
420	355.87	−142.37	−1.8720	−1.6406	1.8163	2.6807	724.11
430	347.42	−118.89	25.027	−1.5773	1.8458	2.6989	710.88
440	339.23	−95.293	52.102	−1.5151	1.8752	2.7160	699.03
450	331.28	−71.586	79.344	−1.4539	1.9045	2.7323	688.47
			75.0 MPa isobar				
119.283[a]	668.71	−802.82	−690.67	−4.6656	1.6340	2.3496	1973.0
120	667.99	−801.26	−688.98	−4.6515	1.6314	2.3481	1968.9
125	663.03	−790.39	−677.27	−4.5559	1.6132	2.3364	1940.7
130	658.10	−779.59	−665.62	−4.4645	1.5945	2.3237	1913.2
135	653.20	−768.86	−654.04	−4.3770	1.5759	2.3104	1886.4
140	648.32	−758.20	−642.52	−4.2932	1.5576	2.2972	1860.2
145	643.47	−747.62	−631.06	−4.2129	1.5400	2.2842	1834.6
150	638.65	−737.11	−619.67	−4.1356	1.5233	2.2718	1809.4
155	633.84	−726.67	−608.34	−4.0613	1.5076	2.2600	1784.7
160	629.06	−716.30	597.07	3.9898	1.4930	2.2491	1760.4
165	624.31	−705.99	−585.85	−3.9207	1.4796	2.2392	1736.4
170	619.57	−695.73	−574.68	−3.8540	1.4674	2.2302	1712.7
175	614.86	−685.53	−563.55	−3.7895	1.4565	2.2223	1689.3
180	610.17	−675.37	−552.45	−3.7270	1.4469	2.2154	1666.2
185	605.50	−665.26	−541.39	−3.6663	1.4385	2.2095	1643.3
190	600.85	−655.18	−530.36	−3.6075	1.4313	2.2047	1620.7
195	596.21	−645.14	−519.34	−3.5503	1.4253	2.2010	1598.3
200	591.60	−635.12	−508.35	−3.4946	1.4206	2.1982	1576.2
205	587.01	−625.13	−497.36	−3.4403	1.4170	2.1965	1554.3
210	582.43	−615.15	−486.38	−3.3874	1.4145	2.1957	1532.6
215	577.88	−605.19	−475.40	−3.3357	1.4131	2.1959	1511.2
220	573.34	−595.23	−464.42	−3.2852	1.4128	2.1969	1490.0
225	568.82	−585.28	−453.43	−3.2359	1.4134	2.1988	1469.1
230	564.31	−575.33	−442.43	−3.1875	1.4150	2.2016	1448.5
235	559.83	−565.38	−431.41	−3.1401	1.4176	2.2051	1428.1
240	555.36	−555.42	−420.38	−3.0936	1.4210	2.2094	1408.0
245	550.92	−545.46	−409.32	−3.0480	1.4252	2.2144	1388.2
250	546.49	−535.47	−398.23	−3.0032	1.4303	2.2201	1368.7
255	542.07	−525.47	−387.12	−2.9592	1.4361	2.2264	1349.5
260	537.68	−515.46	−375.97	−2.9159	1.4526	2.2333	1330.6
265	533.31	−505.41	−364.78	−2.8733	1.4498	2.2407	1312.1
270	528.95	−495.35	−353.56	−2.8314	1.4576	2.2487	1293.9
275	524.61	−485.26	−342.29	−2.7900	1.4660	2.2571	1276.0
280	520.30	−475.13	−330.99	−2.7493	1.4750	2.2660	1258.4
285	516.00	−464.98	−319.63	−2.7091	1.4846	2.2753	1241.3
290	511.73	−454.80	−308.23	−2.6694	1.4946	2.2849	1224.4
295	507.47	−444.58	−296.78	−2.6303	1.5050	2.2949	1208.0
300	503.24	−434.32	−285.28	−2.5916	1.5159	2.3052	1191.9
305	499.03	−424.02	−273.73	−2.5534	1.5272	2.3158	1176.2

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s
			75.0 MPa isobar—Continued				
310	494.84	−413.69	−262.13	−2.5157	1.5389	2.3266	116
315	490.67	−403.32	−250.46	−2.4784	1.5509	2.3377	114
320	486.53	−392.90	−238.75	−2.4415	1.5632	2.3489	113
330	478.32	−371.94	−215.15	−2.3688	1.5887	2.3718	110
340	470.21	−350.81	−191.31	−2.2977	1.6152	2.3952	107
350	462.21	−329.50	−167.24	−2.2279	1.6424	2.4190	105
360	454.32	−308.01	−142.93	−2.1594	1.6704	2.4429	102
370	446.55	−286.34	−118.38	−2.0922	1.6988	2.4668	100
380	438.90	−264.48	−93.593	−2.0261	1.7275	2.4907	984.
390	431.37	−242.43	−68.567	−1.9611	1.7566	2.5145	964.
400	423.98	−220.20	−43.304	−1.8971	1.7858	2.5380	946.
410	416.73	−197.78	−17.807	−1.8341	1.8152	2.5613	929.
420	409.62	−175.18	7.9215	−1.7722	1.8445	2.5843	913.
430	402.64	−152.39	33.877	−1.7111	1.8738	2.6069	898.
440	395.82	−129.42	60.057	−1.6509	1.9030	2.6291	884.
450	389.14	−106.28	86.458	−1.5916	1.9321	2.6509	872.
			100.0 MPa isobar				
127.136[a]	670.20	−790.79	−641.58	−4.5702	1.6350	2.3203	200
130	667.56	−784.74	−634.95	−4.5186	1.6244	2.3124	198
135	662.97	−774.25	−623.42	−4.4316	1.6059	2.2985	196
140	658.41	−763.84	−611.96	−4.3483	1.5878	2.2844	193
145	653.88	−753.51	−600.57	−4.2683	1.5702	2.2707	191
150	649.39	−743.25	−589.25	−4.1916	1.5535	2.2574	189
155	644.92	−733.06	−578.00	−4.1178	1.5378	2.2449	186
160	640.48	−722.94	−566.80	−4.0467	1.5232	2.2331	184
165	636.07	−712.88	−555.67	−3.9781	1.5098	2.2223	182
170	631.69	−702.88	−544.58	−3.9119	1.4976	2.2124	180
175	627.34	−692.94	−533.54	−3.8479	1.4866	2.2036	178
180	623.01	−683.05	−522.54	−3.7860	1.4769	2.1958	176
185	618.71	−673.21	−511.58	−3.7259	1.4684	2.1890	173
190	614.44	−663.40	−500.65	−3.6676	1.4611	2.1832	171
195	610.19	−653.63	−489.75	−3.6110	1.4551	2.1785	169
200	605.97	−643.89	−478.86	−3.5559	1.4502	2.1748	167
205	601.78	−634.17	−468.00	−3.5022	1.4465	2.1721	165
210	597.61	−624.48	−457.14	−3.4499	1.4440	2.1703	163
215	593.46	−614.79	−446.29	−3.3988	14425	2.1695	161
220	589.34	−605.13	−435.44	−3.3489	1.4420	2.1695	160
225	585.24	−595.46	−424.59	−3.3002	1.4425	2.1705	158
230	581.17	−585.80	−413.74	−3.2525	1.4441	2.1722	156
235	577.13	−576.14	−402.87	−3.2057	1.4465	2.1748	154
240	573.10	−566.48	−391.99	−3.1599	1.4498	2.1781	152
245	569.10	−556.80	−381.09	−3.1149	1.4539	2.1821	150
250	565.13	−547.12	−370.17	−3.0708	1.4588	2.1868	148
255	561.18	−537.42	−359.22	−3.0275	1.4645	2.1921	147
260	557.25	−527.70	−348.25	−2.9848	1.4709	2.1980	145
265	553.35	−517.96	−337.24	−2.9429	1.4780	2.2045	143
270	549.47	−508.19	−326.20	−2.9016	1.4857	2.2116	142
275	545.62	−498.40	−315.12	−2.8610	1.4940	2.2191	140
280	541.79	−488.58	−304.01	−2.8209	1.5029	2.2271	138
285	537.99	−478.73	−292.85	−2.7814	1.5123	2.2356	137
290	534.21	−468.84	−281.65	−2.7425	1.5221	2.2444	135
295	530.45	−458.92	−270.41	−2.7040	1.5325	2.2536	134

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			100.0 MPa isobar—Continued				
300	526.72	−448.97	−259.11	−2.6661	1.5433	2.2632	1328.5
305	523.01	−438.97	−247.77	−2.6286	1.5544	2.2731	1314.0
310	519.33	−428.94	−236.38	−2.5915	1.5659	2.2833	1299.8
315	515.67	−418.86	−224.94	−2.5549	1.5778	2.2937	1286.0
320	512.04	−408.74	−213.45	−2.5187	1.5900	2.3043	1272.4
330	504.86	−388.37	−190.29	−2.4475	1.6152	2.3263	1246.3
340	497.77	−367.81	−166.92	−2.3777	1.6414	2.3489	1221.4
350	490.79	−347.07	−143.31	−2.3093	1.6684	2.3721	1197.7
360	483.91	−326.12	−119.47	−2.2421	1.6960	2.3957	1175.2
370	477.15	−304.98	−95.398	−2.1762	1.7241	2.4195	1153.9
380	470.48	−283.63	−71.083	−2.1113	1.7526	2.4435	1133.7
390	463.93	−262.08	−46.527	−2.0475	1.7814	2.4676	1114.6
400	457.49	−240.32	−21.730	−1.9848	1.8103	2.4917	1096.6
410	451.16	−218.35	3.3070	−1.9229	1.8394	2.5157	1079.6
420	444.93	−196.17	28.584	−1.8620	1.8685	2.5396	1063.5
430	438.82	−173.78	54.099	−1.8020	1.8975	2.5634	1048.4
440	432.83	−151.19	79.851	−1.7428	1.9265	2.5869	1034.2
450	426.94	−128.39	105.84	−1.6844	1.9553	2.6102	1020.9
			200.0 MPa isobar				
158.146[a]	677.67	−743.50	−448.37	−4.2546	1.6279	2.2141	2120.0
160	676.34	−739.98	−444.27	−4.2289	1.6224	2.2094	2113.6
165	672.78	−730.53	−433.25	−4.1611	1.6081	2.1975	2096.7
170	669.25	−721.14	−422.29	−4.0956	1.5951	2.1866	2080.1
175	665.75	−711.80	−411.39	−4.0324	1.5833	2.1767	2063.8
180	662.28	−702.51	−400.52	−3.9712	1.5728	2.1679	2047.7
185	658.85	−693.27	−389.71	−3.9119	1.5636	2.1601	2031.9
190	655.44	−684.06	−378.92	−3.8544	1.5556	2.1533	2016.3
195	652.06	−674.89	−368.17	−3.7985	1.5488	2.1476	2000.9
200	648.72	−665.75	−357.44	−3.7442	1.5432	2.1429	1985.6
205	645.40	−656.65	−346.74	−3.6914	1.5388	2.1392	1970.6
210	642.11	−647.52	−336.05	−3.6398	1.5355	2.1365	1955.7
215	638.85	−638.44	−325.37	−3.5896	1.5333	2.1347	1940.9
220	635.61	−629.36	−314.70	−3.5405	1.5322	2.1338	1926.3
225	632.41	−620.29	−304.03	−3.4926	1.5321	2.1338	1911.8
230	629.23	−611.21	−293.36	−3.4457	1.5329	2.1347	1897.5
235	626.08	−602.13	−282.69	−3.3997	1.5347	2.1363	1883.4
240	622.95	−593.05	−272.00	−3.3547	1.5374	2.1387	1869.4
245	619.86	−583.95	−261.30	−3.3106	1.5409	2.1419	1855.5
250	616.78	−574.84	−250.58	−3.2673	1.5453	2.1458	1841.8
255	613.74	−565.71	−239.84	−3.2248	1.5503	2.1503	1828.3
260	610.72	−556.56	−229.07	−3.1830	15561	2.1555	1814.9
265	607.73	−547.38	−218.28	−3.1419	1.5626	2.1612	1801.7
270	604.76	−538.17	−207.46	−3.1014	1.5698	2.1676	1788.7
275	601.81	−528.93	−196.61	−3.0616	1.5775	2.1744	1775.8
280	598.90	−519.66	−185.72	−3.0223	1.5858	2.1818	1763.2
285	596.00	−510.36	−174.79	−2.9836	1.5946	2.1896	1750.7
290	593.13	−501.01	−163.82	−2.9455	1.6039	2.1979	1738.4
295	590.29	−491.63	−152.81	−2.9078	1.6137	2.2065	1726.3
300	587.46	−482.20	−141.75	−2.8707	1.6240	2.2156	1714.4
305	584.66	−472.73	−130.65	−2.8340	1.6346	2.2250	1702.6
310	581.89	−463.21	−119.50	−2.7977	1.6456	2.2347	1691.1
315	579.14	−453.65	−108.30	−2.7619	1.6569	2.2447	1679.8

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s
			200.0 MPa isobar—Continued				
320	576.41	−444.03	−97.055	−2.7265	1.6686	2.2550	166
330	571.02	−424.65	−74.398	−2.6567	1.6928	2.2764	164
340	565.71	−405.06	−51.524	−2.5885	1.7179	2.2986	162
350	560.50	−385.25	−28.423	−2.5215	1.7439	2.3216	160
360	555.37	−365.21	−5.0906	−2.4558	1.7705	2.3451	158
370	55032	−344.95	18.479	−2.3912	1.7977	2.3690	156
380	545.35	−324.44	42.290	−2.3277	1.8252	2.3933	155
390	540.47	−303.70	66.345	−2.2652	1.8530	2.4178	153
400	535.66	−282.72	91.646	−2.2037	1.8811	2.4424	151
410	530.93	−261.50	115.19	−2.1431	1.9092	2.4672	150
420	526.28	−240.04	139.99	−2.0833	1.9374	2.4920	148
430	521.70	−218.33	165.03	−2.0244	1.9656	2.5167	147
440	517.20	−196.38	190.32	−1.9662	1.9936	2.5413	145
450	512.76	−174.18	215.86	−1.9089	2.0216	2.5659	144
			300.0 MPa isobar				
188.621[a]	686.14	−696.66	−259.43	−4.0100	1.6255	2.1524	223
190	685.33	−694.21	−256.46	−3.9944	1.6232	2.1506	223
195	682.40	−685.35	−245.72	−3.9386	1.6157	2.1450	222
200	679.50	−676.51	−235.01	−3.8843	1.6094	2.1404	221
205	676.63	−667.69	−224.32	−3.8315	1.6044	2.1368	219
210	673.78	−658.89	−213.64	−3.7801	1.6005	2.1342	218
215	670.96	−650.10	−202.97	−3.7299	1.5977	2.1325	217
220	668.16	−641.31	−192.31	−3.6808	1.5959	2.1317	216
225	665.39	−632.52	−181.66	−3.6329	1.5952	2.1318	215
230	662.64	−623.73	−170.99	−3.5861	1.5955	2.1328	213
235	659.91	−614.93	−160.33	−3.5402	1.5968	2.1345	212
240	657.21	−606.12	−149.65	−3.4952	1.5989	2.1371	211
245	654.54	−597.29	−138.95	−3.4511	1.6019	2.1403	210
250	651.88	−588.45	−128.24	−3.4079	1.6057	2.1443	209
255	649.25	579.58	−117.51	−3.3653	1.6103	2.1489	208
260	646.65	−570.68	−106.75	−3.3236	1.6156	2.1541	207
265	644.06	−561.76	−95.968	−3.2825	1.6216	2.1600	205
270	641.50	−552.80	−85.152	−3.2420	1.6283	2.1664	204
275	638.96	−543.81	−74.303	−3.2022	1.6355	2.1733	203
280	636.45	−534.78	−63.418	−3.1630	1.6434	2.1808	202
285	633.95	−525.72	−52.494	−3.1243	1.6518	2.1887	20
290	631.48	−516.61	−41.530	−3.0862	1.6607	2.1970	200
295	629.03	−507.45	−30.523	−3.0486	1.6700	2.2058	199
300	626.60	−498.25	−19.472	−3.0114	1.6798	2.2149	19
305	624.18	−489.00	−8.3735	−2.9747	1.6900	2.2244	19
310	621.79	−479.70	2.7729	−2.9385	1.7006	2.2342	19
315	619.42	−470.35	13.969	−2.9027	1.7115	2.2443	19
320	617.07	−460.95	25.217	−2.8672	1.7228	2.2547	19
330	612.43	−441.98	47.871	−2.7975	1.7462	2.2762	19
340	607.87	−422.78	70.744	−2.7292	1.7706	2.2986	19
350	603.38	−403.35	93.846	−2.6623	1.7925	2.3217	18
360	598.97	−383.68	117.18	−2.5965	1.8217	2.3454	18
370	594.62	−363.76	140.76	−2.5320	1.8482	2.3695	18
380	590.35	−343.60	164.57	−2.4684	1.8750	2.3940	18
390	586.15	−323.18	188.64	−2.4059	1.9022	2.4187	18
400	582.01	−302.51	212.95	−2.3444	1.9296	2.4436	18
410	577.93	−281.58	237.51	−2.2837	1.9571	2.4685	17

TABLE 33. Thermodynamic properties of ethylene—Continued

Temperature (K)	Density (kg m^{-3})	Internal energy (kJ kg^{-1})	Enthalpy (kJ kg^{-1})	Entropy (kJ kg^{-1} K^{-1})	c_v (kJ kg^{-1} K^{-1})	c_p (kJ kg^{-1} K^{-1})	w (m s^{-1})
			300.0 MPa isobar—Continued				
420	573.92	−260.40	262.32	−2.2240	1.9846	2.4935	1779.8
430	569.98	−238.96	287.38	−2.1650	2.0122	2.5185	1766.3
440	566.09	−217.26	312.69	−2.1068	2.0397	2.5433	1753.2
450	562.26	−195.31	338.25	−2.0494	2.0671	2.5681	1740.6

[a]Melting temperature.
[b]Saturation temperature.

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