THERMODYNAMIC PROPERTIES OF PROPANE IN THE SATURATED STATE

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Equations are obtained and used to calculate a table of propane thermodynamic properties in the saturated state.

Propane is used as a low-boiling point working fluid in cooling equipment and as a raw material in the petrochemical industry. It is a promising fuel for use in internal combustion engines. When propane is used the toxic product content (carbon monoxide, nitrogen oxides, etc.) of combustion products is 5-10 times lower [1] than in gasoline or diesel fuel exhaust.

In calculating thermal machinery cycles and technological processes which employ propane, it is necessary to have access to reliable data on the material's thermodynamic properties.

The present study will systematize and critically evaluate experimental data on saturated vapor pressure, density, specific heat, heat of evaporation, enthalpy and entropy, then use this data to derive equations and a table of propane thermodynamic properties on the boiling and condensation lines.

The fundamental physical constants of propane (C_3H_8) are as follows: mass of a kmole μ= 44.0962 kg/mole; critical parameters: temperature T_{cr} = 369.90°K; pressure P_{cr} = 4.241 MPa; density ρ_{cr} = 220.0 kg/m^3; normal boiling point T_{nbp} = 231.05°K; triple point parameters T_{tr} = 84.45°K [3]; $P_{tr} = 3 \cdot 10^{-10}$ MPa; gas constant R = 188.55 J/(kg•deg).

Saturated vapor pressure was calculated with the equation

$$\lg p = A + B/T + CT + DT^2 + ET^3 + KT^4, \tag{1}$$

which describes the experimental values of [2-5] for propane saturated vapor pressure from 150-370°K with a maximum deviation of ±0.24%. The absolute pressure p is expressed in units of 10^5 Pa, and absolute temperature in °K.

The equation constants were computer-determined, using the least squares and successive approximation techniques: A = 5.143623; B = −1206.7102; C = $0.097372 \cdot 10^{-2}$; D = $-0.839770 \cdot 10^{-4}$; E = $0.203010 \cdot 10^{-6}$; K = $-0.01654584 \cdot 10^{-8}$.

Density of saturated (boiling) liquid. The equation obtained

$$\rho' = \rho_{cr} + \sum_{i=1}^{4} a_i (T_{cr} - T)^{i/3} \tag{2}$$

reproduces the results of [6-9] on density of the boiling liquid ρ' as a function of temperature (ρ', kg/m^3; T, °K) with a maximum relative error of ±0.2%.

The constants of Eq. (2) were computer-determined using the method of least squares: a_1 = 43.3168; a_2 = 9.93606; a_3 = −1.75813; a_4 = 0.15920; T_{cr} = 219.98 kg/m^3.

Density of dry saturated vapor. Since there are no experimental data available on density of the dry saturated vapor up to 283°K, ρ was found from the Clapeyron–Clausius equation

$$r = T\left(\frac{1}{\rho''} - \frac{1}{\rho'}\right)\frac{dp}{dT}. \tag{3}$$

Results of calculating ρ'' then coincided with the reliable data of [4,6] within limits of experimental uncertainty.

The fundamental state parameters on the liquid-vapor equilibrium line are as follows: pressure at the critical point, calculated with Eq. (1) for the saturated vapor, 4.241 MPa;

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TABLE 1. Propane Thermal Properties on Saturation Line

T, °K	p, 10^5 Pa	ρ′	ρ″	h′	h″	r, kJ/kg	s′	s″
		kg/m³		kJ/kg			kJ/(kg • deg K)	
150	0,00286	668,13	0,00991	230,33	738,20	507,87	2,7014	6,0872
155	0,00504	663,03	0,01690	240,55	744,19	503,64	2,7684	6,0177
160	0,00853	657,91	0,02775	250,71	750,05	499,35	2,8329	5,9538
165	0,01393	652,76	0,04404	260,82	755,80	494,98	2,8952	5,8951
170	0,02204	647,58	0,06774	270,94	761,50	490,56	2,9556	5,8412
175	0,03385	642,38	0,1013	281,07	767,13	486,06	3,0143	5,7918
180	0,05062	637,14	0,1476	291,25	772,73	481,48	3,0717	5,7465
185	0,07387	631,86	0,2100	301,48	778,30	476,82	3,1277	5,7052
190	0,1054	626,55	0,2924	311,80	783,88	472,08	3,1827	5,6674
195	0,1473	621,19	0,3992	322,20	789,45	467,25	3,2368	5,6330
200	0,2019	615,80	0,5359	332,71	795,04	462,33	3,2900	5,6016
205	0,2719	610,35	0,7030	343,32	800,63	457,31	3,3424	5,5732
210	0,3604	604,85	0,9135	354,05	806,24	452,19	3,3941	5,5474
215	0,4705	599,30	1,171	364,90	811,87	446,97	3,4452	5,5241
220	0,6059	593,69	1,481	375,88	817,50	441,62	3,4957	5,5030
225	0,7702	588,02	1,581	386,98	823,14	436,16	3,5455	5,4841
230	0,9675	582,28	2,289	398,20	828,78	430,58	3,5949	5,4670
235	1,202	576,46	2,802	409,55	834,40	424,85	3,6437	5,4516
240	1,478	570,57	3,399	421,02	840,00	418,98	3,6920	5,4377
245	1,801	564,58	4,088	432,61	845,57	412,96	3,7400	5,4253
250	2,175	558,50	4,886	444 31	851,08	406,77	3,7871	5,4141
255	2,604	552,32	5,791	456,13	856,54	400,41	3,8339	5,4041
260	3,096	546,03	6,845	468,06	861,92	393,86	3,8802	5,3950
265	3,654	539,61	7,959	480,11	867,22	387,11	3,9261	5,3868
270	4,284	533,06	9,351	492,27	872,40	380,13	3,9716	5,3794
275	4,992	526,35	10,76	504,56	877,47	372,91	4,0165	5,3727
280	5,784	519,49	12,49	506,98	882,42	365,44	4,0614	5,3665
285	6,667	512,44	14,40	529,53	887,21	357,68	4,1058	5,3608
290	7,656	505,19	16,53	542,25	891,86	349,61	4,1500	5,3556
295	8,728	497,70	18,88	555,15	896,35	341,20	4,1941	5,3507
300	9,920	489,97	21,57	568,25	900,66	332,41	4,2382	5,3462
305	11,23	481,94	24,55	581,60	904,78	323,18	4,2822	5,3420
310	12,66	473,58	27,92	595,23	908,70	313,47	4,3266	5,3378
315	14,23	464,84	31,57	609,19	912,41	303,22	4,3713	5,3339
320	15,93	455,64	35,82	623,55	915,88	292,33	4,4165	5,3300
325	17,78	445,93	40,62	638,37	919,08	280,71	4,4624	5,3261
330	19,79	435,57	46,02	653,74	921,25	268,31	4,5093	5,3221
335	21,97	424,45	52,08	669,74	924,40	254,66	4,5574	5,3176
340	24,31	412,35	59,17	686,49	926,30	239,81	4,6071	5,3124
345	26,84	398,99	67,29	704,11	927,40	223,29	4,6585	5,3057
350	29,55	383,93	77,04	729,74	927,25	204,51	4,7121	5,2964
355	32,47	366,38	88,81	742,52	925,05	182,53	4,7682	5,2823
360	35,59	344,78	104,3	763,65	919,03	155,38	4,8272	5,2588
365	38,92	314,93	127,1	786,31	904,14	117,83	4,8897	5,2125
369,9	42,41	219,98	219,98	810,20	810,20	0,00	4,9547	4,9547

critical temperature and density: T_{cr} = 369.90°K and ρ_{cr} = 219.98 kg/m³. At normal physical pressure of p = 0.101325 MPa the boiling point calculated by Eq. (1) is 231.05°K.

Specific Heat of Boiling Liquid. The equation obtained

$$c_b' = \sum_{i=0}^{6} b_i T^i \tag{4}$$

describes the reliable data of [3, 10-12] on specific heat of the saturated liquid in the range 150-360°K with a mean square deviation of 0.09. The constants of Eq. (4) were calculated by an ES-10-60 computer using the method of least squares: $b_0 = 8.573817$; $b_1 = -1.001299 \cdot 10^{-1}$; $b_2 = 11.966324 \times 10^{-4}$; $b_3 = -9.624139 \cdot 10^{-7}$; $b_4 = 2.509253 \cdot 10^{-9}$; $b_5 = -1.224725 \cdot 10^{-11}$; $b_6 = 2.034661 \cdot 10^{-14}$. The heat of evaporation was calculated with the equation

$$r = \sum_{i=1}^{4} c_i (T_{cr} - T)^{i/3}. \tag{5}$$

The constants c_i were determined with data from [11-13] having an experimental uncertainty of ±1%: $c_1 = 53.0733$; $c_2 = -12.2638$; $c_3 = -1.7128$; $c_4 = 0.0886$.

The enthalpy of the boiling liquid is given by

$$h' = h_0' + \int_{273,15}^{T} c_b' \, dT + \int_{273,15}^{T} \frac{1}{\rho'} \left(\frac{dp}{dT} \right) dT. \tag{6}$$

The quantity h'_0 at 273.15°K was taken equal to 500.00 KJ/kg. The entropy of the boiling liquid is given by

$$s' = s'_0 + \int_{273,15}^{T} c'_b dT/T. \quad (7)$$

The quantity $s'_0 = 4.00$ KJ/(kg•deg K), c_b' was calculated with Eq. (4).

The enthalpy h" and entropy s" of the dry saturated vapor are:

$$h'' = h' + r,\ s'' = s' + \frac{r}{T}.$$

NOTATION

T, absolute temperature; p, absolute pressure; ρ, density; h, enthalpy; s, entropy; r, heat of evaporation; c, specific heat; R, ideal gas constant; sub- and superscripts: ', ", liquid and vapor parameters on saturation line; cr and tr, propane states at critical and triple points.

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