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Simplified Equations for Saturated Steam Properties for Simulation Purpose

Marwan Affandi[a],*, Normahira Mamat[a], Siti Nurul Aqmariah Mohd Kanafiah[a], Nurul Syahirah Khalid[a]

[a]School of Mechatronic Engineering
Universiti Malaysia Perlis
Perlis, Malaysia.

Abstract

Steam is a very important fluid in industries and its thermodynamic properties have been tabulated. Graphs showing various relationships of steam thermodynamics have also been developed. However, the use of tables or graphs has a particular drawback: interpolation is often necessary. For simulation purpose or real time system which often needs hundreds or even thousands of data, interpolation will become very tedious and time consuming. Formulas for thermodynamic properties of steam are available and can then be programmed in a computer, which will then compute the thermodynamic properties quickly. Unfortunately, formulas for thermodynamic properties of steam are quite complicated so programming them for a simple simulation purpose is quite difficult and is therefore inconvenient. This paper shows the results from simplified equations for saturated steam properties. The equations which are developed in this paper are for saturated pressure and temperature, and for enthalpy, entropy, and specific volume in saturated liquid and saturated vapour states. The equations are developed from data given in the International Steam Tables. The accuracy for each equation is fairly small, less than 2% except for saturated liquid entropy which is 3.22%, which is good enough for most applications. Since the number of parameter used for each equation is just five, those equations developed can be conveniently used for simulation purpose.

1. Introduction

Steam is a very important fluid in industries and its thermodynamic properties have been tabulated. Graphs showing various relationships of steam thermodynamics have also been developed. However, the use of tables or graphs has a particular drawback: interpolation is often necessary. Linear interpolation is usually accurate for most applications while quadratic interpolation or other techniques may be necessary for higher accuracy. A property with two independent variables may need double interpolation. For simulation purpose or real time system which often needs hundreds or even thousands of data, interpolation will become very tedious and time consuming. Formulas for thermodynamic properties of steam are available; see for example [1]-[7]. Those formulas can then be programmed in a computer, which will then compute the thermodynamic properties quickly. As an example, International Steam Tables published by IAWPS are generated from [1]. Unfortunately, formulas for thermodynamic properties of steam are quite complicated. In the International Steam Tables,

* Corresponding author. *E-mail address:* marwan@unimap.edu.my

there are five basic equations assigned to their corresponding regions. The basic equations are in the form of Gibbs free energy or Helmholtz free energy. As an example, the basic equation for region 2 has 43 parameters while the basic equation for region 4 has 10 parameters. The saturated line is a quadratic equation in terms of which can be solved directly with regard to both saturation pressure and saturation temperatures. There are 10 parameters for this equation. Equations for other thermodynamic properties are derived from basic equations for the saturated line. This makes the calculation for those properties are quite difficult. The use of those formulas for a simple simulation is therefore inconvenient. This paper shows the results from simplified equations for saturated steam properties. The equations which are developed in this paper are for saturated pressure and temperature, and for specific enthalpy, specific entropy, and specific volume in saturated liquid and saturated vapour states. The equations are developed from data given in the International Steam Tables [1]. All properties have a range from 0 to 370ºC except for entropy which is from 5 to 370ºC.

2. Saturated Pressure

Saturated pressure depends on saturated temperature. Various equations of saturation pressure of water are available in the literature [1]-[7]. However, those equations are not simple and have at least six parameters. After fitting the data, it is found that the saturated pressure can be represented satisfactorily using Eq. (1) which is developed from a modified equation suggested by [8].

$$\ln(P) = a + b \ln(T_r) + c[(\ln T_r)]^2 + d[(\ln T_r)]^4 + eT_r^5 \quad (1)$$

T_r is the reduced temperature which is defined as T/T_{cr}. T_{cr} is critical temperature; for steam it is 647.096 K [1]. Values of a to e are given in Table 1.

Table 1.

a	b	c	d	e
9,56756	5,39806	-6,16183	1,49572	0,43300

Maximum error = 0.12% (25.09 kPa), average error = 0.05% (2.17 kPa). Actually the average error of 2.17 kPa which is calculated in term of absolute value is not quite correct since the pressure spans a wide range (from 0.61 to 22038.91 kPa). If we consider the relative error which is quite small, the percentage is a better value compared to the absolute value. Maximum error occurs at the critical temperature.

3. Saturated Temperature

Saturated temperature depends on saturated pressure. Given the saturated pressure, the saturated temperature can be calculated numerically from Eq. (1). However, it is more convenient if we have a separate equation for temperature. After fitting the data, it is found that the saturated temperature can be represented satisfactorily using Eq. (2) which is developed following [7].

$$\ln(T) = [a + bP_r + cP_r^2 + dP_r^3 + eP_r^4]^{-0.4} \quad (2)$$

P_r is the reduced pressure which is defined as P/P_{cr}. Pcr is critical pressure; for steam it is 22.064 MPa [1]. Values of a to e are given in Table 2.

Table 2.

a	b	c	d	e
9.37817 E-03	4.98951 E-04	1.11049 E-05	3.34995 E-07	3.44102 E-08

Maximum error = 0.92% (0.76ºC), average error = 0.09% (0.14ºC). Although the maximum error is almost 1%, the actual absolute value is just 0.76ºC, which less than one degree centigrade. This happens at the critical pressure.

4. Specific Enthalpy

4.1 Specific Enthalpy of Saturated Vapor

Specific enthalpy of saturated vapor depends on saturated temperature; this can be calculated using the equation of Wagner and Prauss containing 22 constants [7]. Popiel and Wojtkowiak [9] mentioned an equation in the form polynomial of five degree. Modifying the equation suggested by [8], it is found that the specific enthalpy of saturated vapor can be represented satisfactorily using a simpler equation as follows

$$\ln(h_g) = \sqrt{a + b\,[\ln(1/T_r)]^{0.35} + c/T_r^2 + d/T_r^3 + e/T_r^4} \tag{3}$$

Values of a to e are given in Table 3

Table 3

a	b	c	d	e
64.87678	11.76476	-11.94431	6.29015	-0.99893

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Maximum error = 0.26% (6.5 kJ/kg), average error = 0.05% (1.3 kJ/kg), which occurs at 0ºC. If we take a range of temperature from 5 to 370ºC, the maximum error reduces to just 0.13% (3.2 kJ/kg) while the average error almost remains the same.

4.2 Specific Enthalpy of Vaporization

Specific enthalpy of vaporization depends on saturated temperature. Popiel and Wojtkowiak gave a simple equation which has an estimated uncertainty of 0.09% [9]. After fitting the data, it is found that the enthalpy of vaporization can be represented satisfactorily using Eq. (4) which is developed following [8].

$$\ln(h_{fg}) = \sqrt{a + b\,[\ln(1/T_r)]^{0.1} + c/T_r^2 + d/T_r^3 + e/T_r^4} \tag{4}$$

Values of a to e are given in Table 4.

Table 4

a	b	c	d	e
4.38230	77.88524	9.76781	5.34311	-0.86975

Maximum error = 0.24% (5.9 kJ/kg), average error = 0.05% (1.0 kJ/kg), which occurs at 0ºC. If we take range of temperature from 5 to 370ºC, the maximum error reduces to just 0.12% (2.8 kJ/kg) while the average error almost remains the same.

A. Specific Enthalpy of Saturated Liquid

Specific enthalpy of saturated liquid is just the difference between saturated vapor enthalpy and enthalpy of vaporization. For the range from 5 to 370ºC, the maximum error is 1.68% (1.2 kJ/kg) and the average error is 0.11% (0.4 kJ/kg).

5. Specific Volume

5.1 Specific Volume of Saturated Vapor

Specific volume of saturated vapor depends on temperature. Wagner and Pruss gave an equation to calculate specific

volume of saturated vapor; it has six constants with the highest exponent is 71/6 [7].After fitting the data, it is found that the saturated vapor volume can be represented satisfactorily using Eq. (5) which is developed from a modified equation suggested by [8].

$$\ln(v_g) = a + b\,[\ln(1/T_r)]^{0.4} + c/T_r^2 + d/T_r^4 + e/T_r^5 \tag{5}$$

Values of a to e are given in Table 5.

Table 5

a	b	c	d	e
-7.75883	3.23753	2.05755	-0.06052	0.00529

Maximum error = 0.19% occurs at critical temperature while average error = 0.03%. However, maximum error of absolute value does not occur at the critical point but at 0ºC, which is 0,0611 m³/kg.

5.2 Specific Volume of Saturated Liquid

Specific volume of saturated liquid depends on temperature. After fitting the data, it is found that the saturated liquid volume can be represented satisfactorily using Eq. (6)

$$\ln(v_f) = a + b\,[\ln(1/T_r)]^{0.25} + c/T_r^2 + d/T_r^3 + e/T_r^4 \tag{6}$$

Values of a to e are given in Table 6.

Table 6

a	b	c	d	e
1.07853	-1.56881	2.05755	-0.12860	0.02074

Maximum error = 0.05% occurs at 360ºC critical temperature while average error = 0.01%. However, maximum error of absolute value occurs at the critical point, which is 0,00093 m³/kg.

5.3 Specific Volume of Vaporization

Specific volume of vaporization is the difference between specific volume of saturated vapor and specific volume of saturated liquid. Maximum error is 0.37% and average error is 0.04%.

6. Specific Entropy

6.1 Specific Entropy of Saturated Vapor

Specific entropy of saturated vapor depends on saturated temperature. After fitting the data, it is found that the saturated vapor entropy can be represented satisfactorily using Eq. (7) from a modified equation suggested by [7].

$$\ln(s_g) = a + b\,[\ln(1/T_r)]^{0.35} + c/T_r^2 + d/T_r^4 + e/T_r^5 \tag{7}$$

Values of a to e are given in Table 7.

Table 7

a	b	c	d	e
1.47735	0.53242	-0.01923	0.02974	-0.-00802

Average error is 0.04% (0.00234 kJ/kg) while maximum error is 3,22% (0.00607 kJ/kg.K), which occurs at 5ºC. If we take range of temperature from 5 to 370ºC, the maximum error reduces to just 0.10% (0.00567 kJ/kg.K) while the average error is 0.04% (0.00288 kJ/kg.K.

6.2 Specific Entropy of Saturated Liquid

Specific entropy of saturated liquid can be simply calculated from:

$$s_f = s_g - \frac{h_{fg}}{T} \tag{8}$$

Eq. (8) is given in many thermodynamic text books.

Average error is 0.39% (0.00304 kJ/kg) while maximum error is 0.11% (0.00104 kJ/kg.K), which occurs at 5ºC. If we take a range of temperature from 5 to 370ºC, the maximum error reduces to just 0.10% (0.00567 kJ/kg.K) while the average error is 0.04% (0.00288 kJ/kg.K. The applicable range for entropy is from 5 to 370ºC.

7. Conclusions

It can be seen that accuracy for each equation is fairly small, less than 2% except for saturated liquid entropy which is 3.22%,, which is good enough for most applications. Since the number of parameter used for each equation is small (just five), those equations developed can be conveniently used for simulation purpose.

Acknowledgment

References

[1] W. Wagner and H. J. Kretzschmar, International Steam tables, 2ed., Springer-Verlag: Berlin, 2008.

[2] J.M.H. Levelt Sengers, "Thermodynamic Properties of Steam in the Critical Region,"J. Phys. Chem. Ref. Data, vol. 12(1), pp. 1-28, 1983.

[3] A. Saul and W. Wagner, "International Equations for the Saturation Properties of Ordinary Water Substance," J. Phys. Chem. Ref. Data, vol. 16(4), pp. 893-901, 1987.

[4] H. Sato, M. Uematsu, K. Watanabe, A. Saul and W. Wagner, "New International Skeleton tables for Equations for the Thermodynamic Properties of Ordinary Water Substance," J. Phys. Chem. Ref. Data, vol. 17(4), pp. 1439-1540, 1988.

[5] A. Saul and W. Wagner, "A Fundamental Equation for Water Covering the Range from the Melting Line to 1273 K at Pressures up to 25000 MPa," J. Phys. Chem. Ref. Data, vol. 18(4), pp. 1537-1564, 1989.

[6] P.G. Hill, "A Unified Fundamental Equation for The Thermodynamic properties of H2O," J. Phys. Chem. Ref. Data. vol. 19(5), pp. 1233-1274, 1990.

[7] W. Wagner and A. Pruss, "International Equations for the Saturation Properties of Ordinary Water Substance. Revised according to the International Tempearture Scale of 1990," J. Phys. Chem. Ref. Data. vol. 22(3), pp. 783-787, 1993.

[8] R. Martin-Dominguez and T. W. McDonald, "Correlations for Some Saturated Thermodynamics and Transport Properties of Refrigerant R-22," ASHRAE Transactions, vol. 96(2), pp. 344-348, 1990.

[9] C.O. Popiel and J. Wojtkowiak, "Simple Formulas for Thermophysical Properties of Liquid Water for Heat Transfer Calculations (from 0℃ to 150℃)," Heat Transfer Engineering, vol. 19(3), pp. 87-101, 1998.