DETERMINATION THERMODYNAMIC PROPERTIES OF WATER AND STEAM

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Abstract

This work presents functions of thermodynamic parameters developed in MATLAB. There are functions to determine: saturation pressure on the temperature and conversely, enthalpy on the temperature and pressure, entropy on the temperature and pressure. All functions based on formulation IAPWS-IF97. Functions for saturation pressure and temperature are a simple functions with one variable. Determination enthalpy and entropy to the temperature and pressure required solution of equation with differentials.

1   Theoretical basis

The Industrial Formulation IAPWS-IF97 consist from set of equations for different regions. At the Figure 1 shows diagram state of water and steam. Region 1 is a liquid phase; region 2 is a vapor phase; region 3 is a phase of the critical state. Line ABC is saturation line; line BD is isotherm, which is boundary bee twin liquid and critical phase; line BE is boundary bee twin critical and vapor phase, this line describes by special equation. Point C is a critical point. For regions 1, 2 uses the fundamental equation for the Gibbs energy. For region 3 fundamental equation Helmholtz free energy.
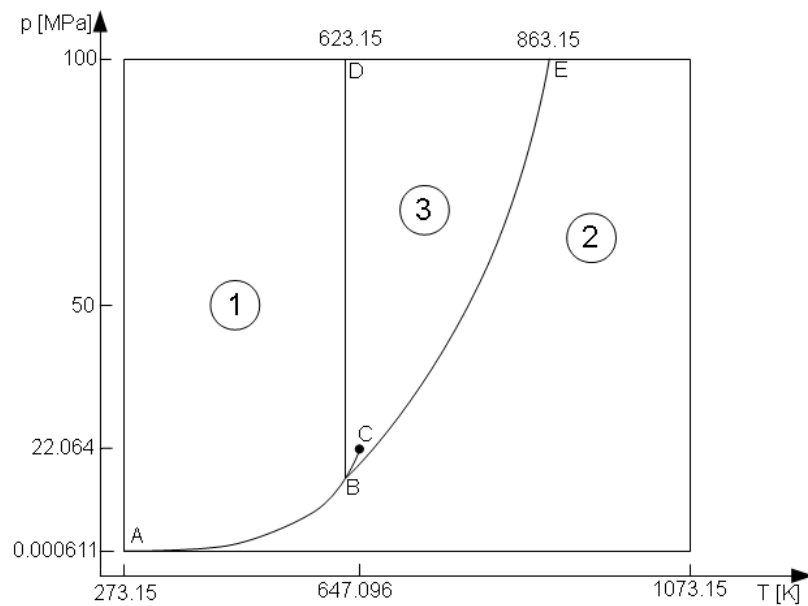

Figure1 - Diagram water and steam.

1.1 Region 1- liquid phase

For region 1 uses equation for the Gibbs energy [1]:

$$\frac{g(p,\mathrm{T})}{R \cdot \mathrm{T}} = \gamma(\pi,\tau) = \sum_{t=1}^{34} n_t \times (7,1 - \pi)^{I_t} \times (\tau - 1,222)^{J_t} \tag{1}$$

R- specific gas constant, 0,461526 [kJ/(kg*K)];

$\pi = p / p^*$ [1], $p^* = 16{,}53$ [Mpa];

$\tau = T / T^*$ [1], $T^* = 1386$ [K];

n_i - specific coefficients for region 1 [1];

I_i, J_i - specific exponents for region 1 [1].

Equation for determine enthalpy [1]:

$$h / (R \cdot T) = \tau \cdot \left(\frac{\delta \gamma}{\delta \tau} \right)_\tau \tag{2}$$

h- enthalpy, [kJ/kg];

Equation for determine entropy [1]:

$$s / (R \cdot T) = \tau \cdot \left(\frac{\delta \gamma}{\delta \tau} \right)_\tau - \gamma \tag{3}$$

s- entropy [kJ/(kg*K)];

1.2 Region 2- vapor phase

For region 2 uses equation for the Gibbs energy , consisted of two part: $\gamma^0(\pi, \tau)$ - ideal gas part, $\gamma^r(\pi, \tau)$ - real part [1]:

$$\frac{g(p, \mathrm{T})}{R \cdot \mathrm{T}} = \gamma(\pi, \tau) = \gamma^0(\pi, \tau) + \gamma^r(\pi, \tau) \tag{4}$$

$$\gamma^0(\pi, \tau) = \ln \pi + \sum_{i=1}^{9} n_i^0 \cdot \tau^{J_i^0} \tag{5}$$

$\tau = T / T^*$ [1], $T^* = 540$ [K];

n_i^0 - specific coefficients for region 2 [1];

J_i^0 - specific exponents for region 2 [1].

$$\gamma^r(\pi, \tau) = \sum_{i=1}^{43} n_i \cdot \pi^{I_i} \cdot (\tau - 0{,}5)^{J_i} \tag{6}$$

$\pi = p / p^*$ [1], $p^* = 1$ [MPa];

n_i - specific coefficients for region 2 [1];

I_i, J_i - specific exponents for region 2 [1].

Enthalpy and entropy determining by equations (2) and (3).

1.3 Region 3- phase of critical state

For region 3 uses fundamental energy equation Helmholtz. [1]:

$$\frac{f(\rho,\text{T})}{R\cdot\text{T}} = \phi(\delta,\tau) = n_1 \cdot \ln\delta + \sum_{i=2}^{40} n_i \cdot \delta^{I_i} \cdot \tau^{J_i} \tag{7}$$

$\delta = \rho/\rho_c$ [1], ρ - density [kg/m³], ρ_c - density in critical point, 322 [kg/m³];

$\tau = T/T_c$ [1], T_c -temperature in critical point, 647.096 [K];

n_i - specific coefficients for region 3 [1];

I_i, J_i - specific exponents for region 3 [1].

Equation for determine enthalpy [1]:

$$h/(R\cdot T) = \tau\cdot\left(\frac{\delta\phi}{\delta\tau}\right)_\delta + \delta\cdot\left(\frac{\delta\phi}{\delta\delta}\right)_\tau \tag{8}$$

Equation for determine entropy [1]:

$$s/(R\cdot T) = \tau\cdot\left(\frac{\delta\phi}{\delta\tau}\right)_\delta - \phi \tag{9}$$

For determine, **consistency** to pressure and temperature uses equations system from (2).

1.4 Saturation line

Main equation for saturation line [1]:

$$\beta^2\cdot\vartheta^2 + n_1\cdot\beta^2\cdot\vartheta + n_2\cdot\beta^2 + n_3\cdot\beta\cdot\vartheta + n_4\cdot\beta\cdot\vartheta + n_5\cdot\beta + n_6\cdot\vartheta^2 + n_7\cdot\vartheta + n_8 = 0 \tag{10}$$

$$\beta = (p_s/p^*)^{1/4} \tag{11}$$

$$\vartheta = T_s/T^* + n_9/((T_s/T^*) - n_{10}) \tag{12}$$

P_s- saturation pressure, [MPa];

T_s - saturation temperature, [K];

Decide this equation relative to P_s, determine depend saturation pressure to saturation temperature; decide this equation relative to T_s, determine depend saturation temperature to saturation pressure. To determine enthalpy and entropy for saturated liquid uses equation for region 1. For saturated dry steam equation for region 2.

2   MATLAB functions

Based on the previous equations were developed functions to determine enthalpy and entropy from temperature and pressure.

2.1 Basis
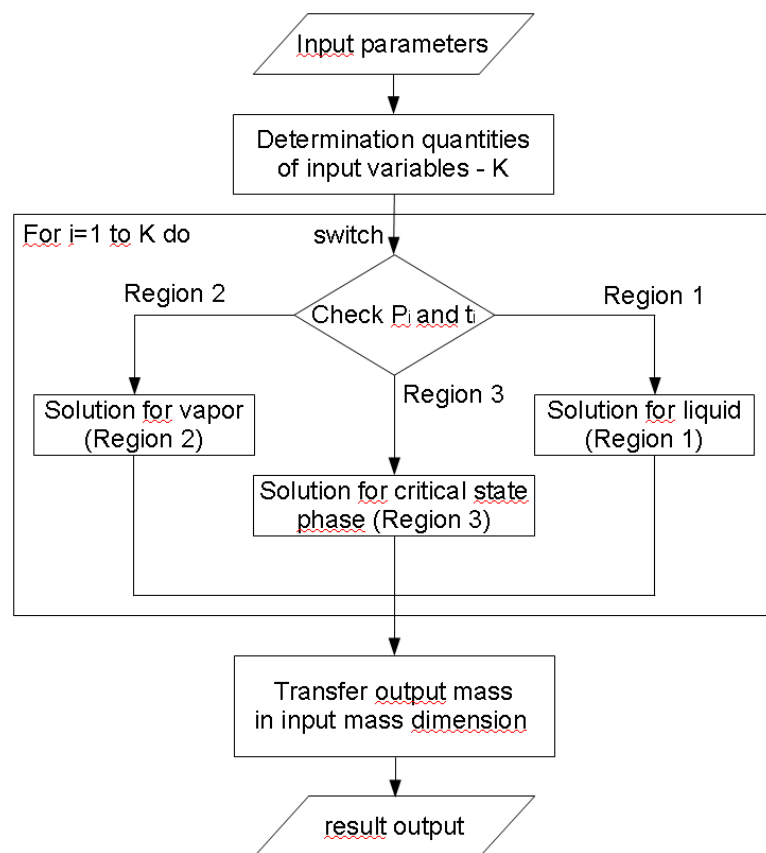
Structure of this program prefer on Figure 2.

Figure 2 - Structure of the MATLAB function $h(p,t),s(p,t)$

The first one function required enter inlet parameters: pressure p [MPa], temperature t [^{o}C]. For inlet variables can be use vectors with the same dimension, result will be vector of values element-wise calculation enthalpy (entropy). After checking the dimensions of incoming variables it runs the cycle of calculation for corresponding elements. In the loop based on the values of inlet parameters selecting the area in which located the point and solve the corresponding equation for enthalpy (entropy). Boundaries of the region:

Region 1: $0\ ^oC<t<350\ ^oC;\ \ P_s(t)<p<100\ MPa$.

Region 2: $0\ ^oC < t < 350\ ^oC;\ \ P_s(t) \geq p;$

. $350\ ^oC < t < 800\ ^oC;\ \ P_{97}(t) > p.$

Region 3: $350\ ^oC < t < 800\ ^oC;\ \ P_{97}(t) \leq p.$

As for the critical region enthalpy equation has form , for calculation is also used equation of the form to finding value of density at the point. Equations (2),(3),(8),(9) were differentiated before and written in symbolic form without differentials. This is increasing calculating speed.

2.2 Interface

For applied use functions were developed interface program, which calculate enthalpy (entropy) to temperature and pressure and mark this point on diagram. Interface prefer at Figure 3.
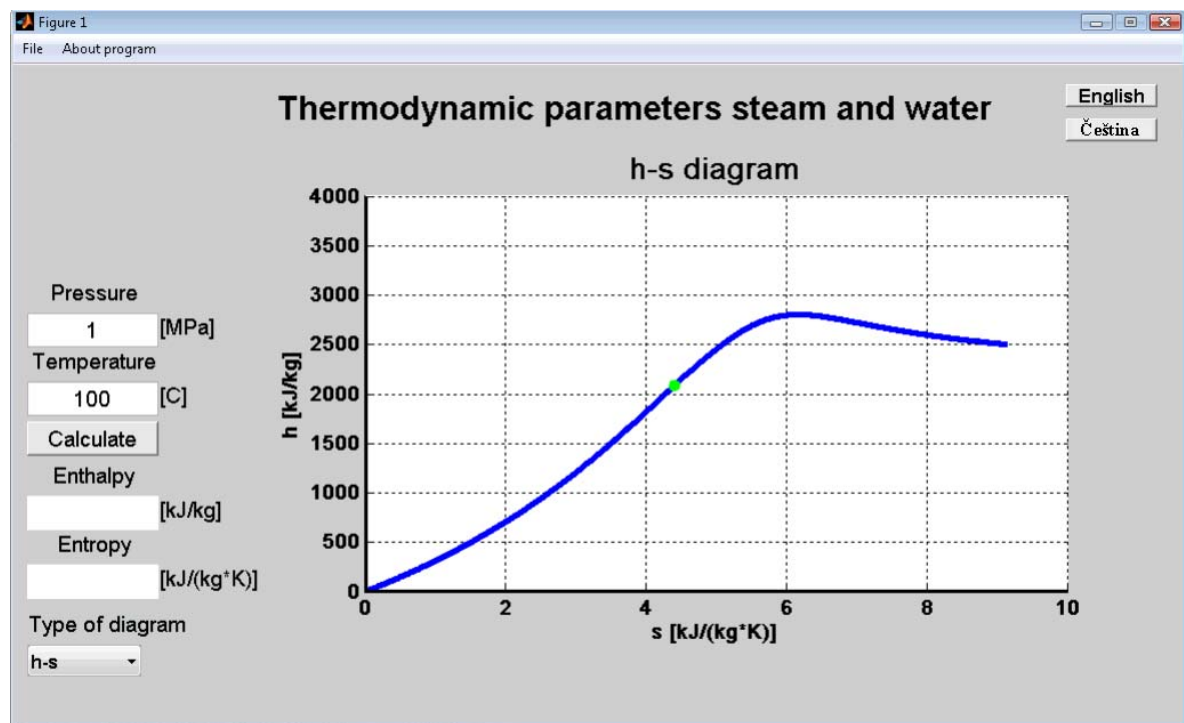

Figure 3 - Interface for developed functions

Input data fields for input data: pressure p [MPa] and temperature t [^{o}C] for calculation. Output data fields for output data: enthalpy h [kJ/kg] and entropy s [kJ/(kg*K)]. Graphic window is diagram with thermodynamic properties in coordinate axes. On this diagram displayed saturation line and marking given point. Properties on axes can be change by menu "Type of diagram". Button "Calculate" should be click after input pressure and temperature. Menu "Type of diagram" for change parameters of coordinate axes. Menu "About program" for call help file. Buttons "English" and "Čeština" is for change program language on appropriate.

3   Results

These functions were developed within the framework of dissertation. During building a model of heat exchanger became necessary determining enthalpy of heat carriers at a certain temperature and pressure to solve the equations of thermal balance. Using developed functions are not restricted a single model. As the water – the main operating fluid in power equipment: heat carrier in boilers and heat exchanger, operating body in turbines, etc – these functions also can be used to build model of these equipment. In construction these models the need arises to identify other water parameters (entropy, density, specific volume, thermal conductivity, etc.) with other initial values (enthalpy, entropy, specific volume) and therefore were have been developed other functions in a similar method. Functions can be used to build various figures because of their support as input a set of values (vector).

For the applied use functions outside Matlab has been designed program with user interface. It can rapidly calculate enthalpy and entropy of water (steam) and notes position of the point with the specified parameters to the different diagrams. For better perception on the diagrams indicate saturation line and critical point, at the *p-t* diagram also indicate boundaries of the various phases of water: liquid, vapor and phase of critical state. This visualization allows use the program as applied to calculations instead of tables and diagrams, to rapidly determine enthalpy and entropy and for learning purposes for better understanding of thermodynamic process and phase transition. Language of program interface can change between English and Czech.

References
[1] Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam: Lucerne, Switzerland 2007.
[2] Supplementary Release on Backward Equations for Specific Volume as a Function of Pressure and Temperature *v(p,T)* for Region 3 of the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam: Santorini, Greece July 2005.

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