A new reference book for power engineers

The article concerns a new reference book for power engineers and supporting Internet site

The publishing house of MPEI (**http://mpei-publishers.ru**) has issued a new reference book «Thermophysical properties of working substances of heat power engineering» [1]. The word «new» means here both that the book has been issued recently, it contains new data on properties of working substances of heat power engineering (water and steam, gases, etc.) and also that it is a new type of reference book, a set «book-Internet site». By now some of the reference books, particularly on heat power engineering, primarily published on paper [3] have been supplemented later with the Internet sites [4-11] animating formulae, tables, and plots of the books. The reference book described has been created in reverse order: at first, the Internet site has been created and then a guidebook based on the site has been written.

The reference book contains tables on specific volume, enthalpy, entropy, isobaric heat capacity, sound velocity, surface tension, dynamic viscosity, thermal conductivity, Prandtl number, static permittivity, refraction index, ionic product of water and steam calculated by formulations approved by the International Association for the Properties of Water and Steam (**www.iapws.org**) for industrial calculations. The tables of thermodynamic properties comprise properties at temperatures from 0°C to 800°C and at pressures up to 100 MPa (at temperatures up to 2000°C at pressures up to 50MPa) including saturation state and metastable supercooled steam.

Nowadays gas-turbine power plants and combined cycle gas turbines are introduced into power industry in Russia and CIS countries to increase flexibility and efficiency of power stations. In this respect the reference book includes tables on internal energy, enthalpy, entropy, and isobaric heat capacity for the components of working mediums of combined cycle gas turbines and combustion gases of boilers: oxygen, nitrogen, atmospheric nitrogen, air (as well as moist air),carbon dioxide, carbonic oxide, sulphur dioxide, sulphur oxide, nitrogen dioxide, nitrogen oxide, steam and hydrogenium. The tables of properties of these gases at ideal gas state are given at temperatures from –50 °C up to 2200 °C.

In the reference book **are** represented all the equations that were used to calculate the tables. The heading of each table shows the addresses of the Internet sites enabling interactive work with these equations.

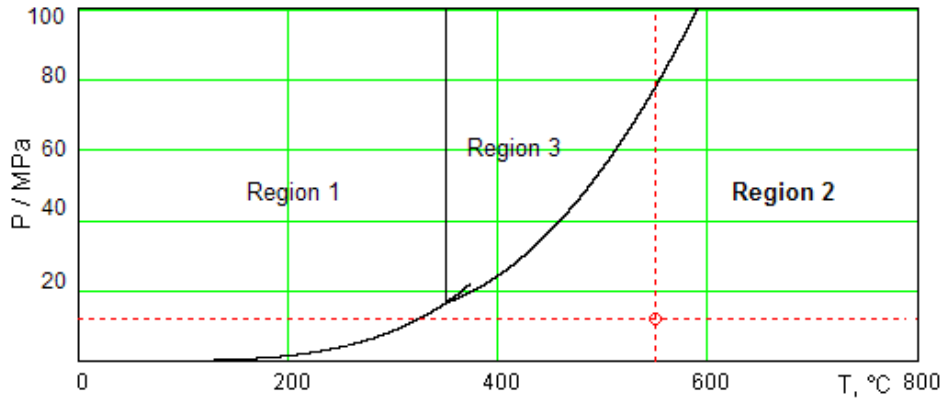
Thus, Figure 1 shows transparent interactive network calculation of the properties of superheated steam (region 2 of formulation IAPWS-IF97 [2]).

http://twt.mpei.ac.ru/ochkov/WSPHB/Region2.html

Structure of IAPWS-IF97: Region 2

Go to the base page eng rus

p := 12 MPa T := 550 °C Recalculate



$p = 12\,MPa$ $p^* := 1MPa$ $\pi := p / p^* = 12$

$T = 823.15\,K$ $T^* := 540\,K$ $\tau := T^* / T = 0.6560165$

Gibbs free energy:

Ideal part $\gamma_0(\pi,\tau) := \ln(\pi) + \sum_{i=1}^{9} \left(n0_i \cdot \tau^{J0_i}\right) = -5.1830761$ J_0 and n_0 see >>>

Real part $\gamma_r(\pi,\tau) := \sum_{i=1}^{43} \left[n_i \cdot \pi^{I_i} (\tau - 0.5)^{J_i}\right] = -0.0725457$ I, J and n see >>>

$\gamma 0_\pi := \frac{\partial}{\partial \pi}\gamma_0(\pi,\tau) = 0.0833333333$ $\gamma_{r\pi} := \frac{\partial}{\partial \pi}\gamma_r(\pi,\tau) = -6.1970028 \times 10^{-3}$

Specific volume $\frac{R \cdot T}{p} \cdot \pi \cdot \left(\gamma 0_\pi + \gamma_{r\pi}\right) = 0.0293044874\,m^3/kg$

$\gamma 0_\tau := \frac{\partial}{\partial \tau}\gamma_0(\pi,\tau) = 14.4335605495$ $\gamma_{r\tau} := \frac{\partial}{\partial \tau}\gamma_r(\pi,\tau) = -0.4634717265$

Specific internal energy $R \cdot T \cdot \left[\tau \cdot \left(\gamma 0_\tau + \gamma_{r\tau}\right) - \pi \cdot \left(\gamma 0_\pi + \gamma_{r\pi}\right)\right] = 3130.0281265\,kJ/kg$

Specific entropy $R \cdot \left[\tau \cdot \left(\gamma 0_\tau + \gamma_{r\tau}\right) - \left(\gamma_0 + \gamma_r\right)\right] = 6.6553114889\,kJ/(kg\,K)$

Spesific enthalpy $R \cdot T\tau \cdot \left(\gamma 0_\tau + \gamma_{r\tau}\right) = 3481.6819756\,kJ/kg$

$\gamma 0_{\tau\tau} := \frac{d^2}{d\tau^2}\gamma_0(\pi,\tau) = -10.9031963261$ $\gamma_{r\tau\tau} := \frac{d^2}{d\tau^2}\gamma_r(\pi,\tau) = -2.092796937$

Specific isobaric heat capacity $c_p := -\tau^2 \cdot \left(\gamma 0_{\tau\tau} + \gamma_{r\tau\tau}\right) \cdot R = 2.5812805\,kJ/(kg\,K)$

$\gamma 0_{\pi\tau} := \frac{\partial}{\partial \pi}\frac{\partial}{\partial \tau}\gamma_0(\pi,\tau) = -6.406538 \times 10^{-14}$ $\gamma_{r\pi\tau} := \frac{\partial}{\partial \pi}\frac{\partial}{\partial \tau}\gamma_r(\pi,\tau) = -0.0410774$

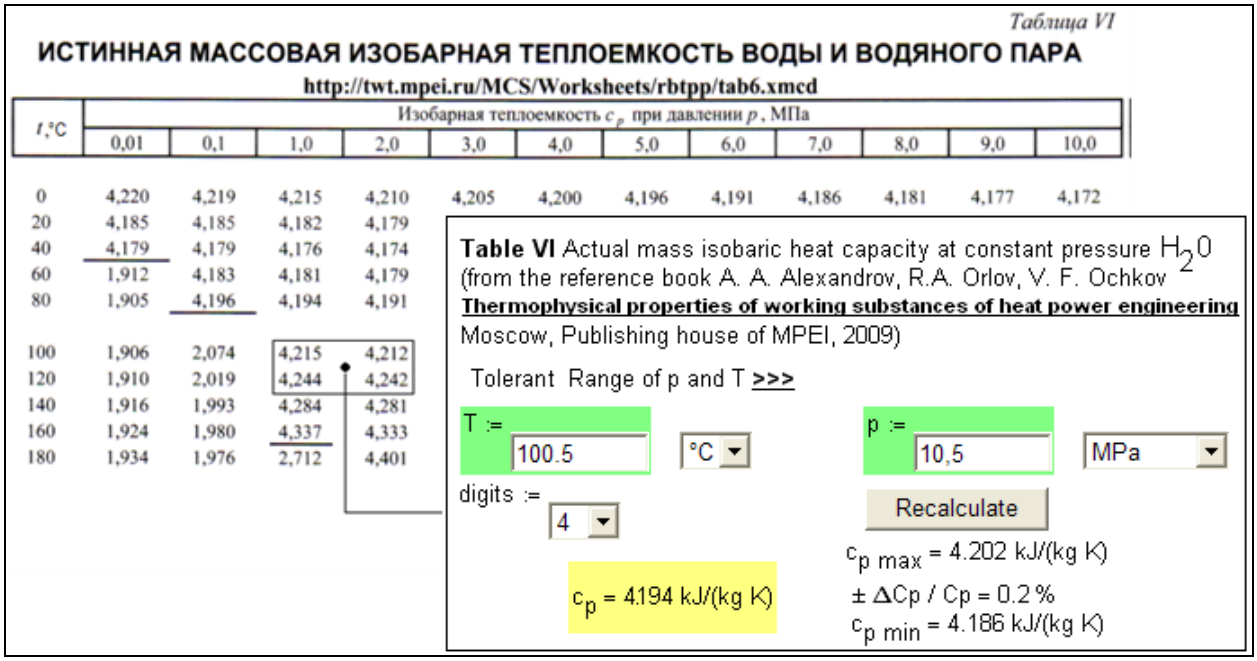
$\gamma 0_{\pi\pi} := \frac{d^2}{d\pi^2}\gamma_0(\pi,\tau) = -6.9444444 \times 10^{-3}$ $\gamma_{r\pi\pi} := \frac{d^2}{d\pi^2}\gamma_r(\pi,\tau) = -2.4767973 \times 10^{-5}$

Specific isochoric heat capacity $R \cdot \left[-\tau^2 \cdot \left(\gamma 0_{\tau\tau} + \gamma_{r\tau\tau}\right) - \frac{\left(1 + \pi \cdot \gamma_{r\pi} - \tau \cdot \pi \cdot \gamma_{r\pi\tau}\right)^2}{1 - \pi^2 \cdot \gamma_{r\pi\pi}}\right] = 1.8638518332\,kJ/(kg\,K)$

Sound velocity $\sqrt{\frac{R \cdot T \cdot \left(1 + 2 \cdot \pi \cdot \gamma_{r\pi} + \pi^2 \cdot \gamma_{r\pi}^2\right)}{1 - \pi^2 \cdot \gamma_{r\pi\pi} + \frac{\left(1 + \pi \cdot \gamma_{r\pi} - \tau \cdot \pi \cdot \gamma_{r\pi\tau}\right)^2}{\tau^2 \cdot \left(\gamma 0_{\tau\tau} + \gamma_{r\tau\tau}\right)}}} = 670.2188075\,m/s$

Figure 1. Network transparent interactive calculation of water and steam properties

A user of the similar site (the site addresses are also given in the reference book) can change initial data (in this case pressure and temperature) choosing required dimensions, click button «Recalculate», and obtain results (thermodynamic properties of steam) as well as all intermediate data and constants used in the calculation. The formulations have been published for programmers in order to write corresponding programs by them. As experience shows, a program can be written rather quickly but sometimes it is hard to find and an error in it (errors are inevitable in more or less large programs). But if a programmer puts hand on a check calculation containing all intermediate data (see Fig. 1) the program debugging and verification will be more effective due to clear error localization. Particularly, for this reason the results and the intermediate data shown on Fig. 1 are presented having superfluous numbers in mantissas. The reference book expresses the tabular values with an accuracy of 4 – 5 significant figures. Primarily, this limitation is coming from the fact that the data on the substance properties are always known to have certain uncertainties. The magnitudes of the uncertainties for the tabular values are given in the reference book and on the corresponding sites.



t,°C	Изобарная теплоемкость c_p при давлении p, МПа											
	0,01	0,1	1,0	2,0	3,0	4,0	5,0	6,0	7,0	8,0	9,0	10,0
0	4,220	4,219	4,215	4,210	4,205	4,200	4,196	4,191	4,186	4,181	4,177	4,172
20	4,185	4,185	4,182	4,179								
40	4,179	4,179	4,176	4,174								
60	1,912	4,183	4,181	4,179								
80	1,905	4,196	4,194	4,191								
100	1,906	2,074	4,215	4,212								
120	1,910	2,019	4,244	4,242								
140	1,916	1,993	4,284	4,281								
160	1,924	1,980	4,337	4,333								
180	1,934	1,976	2,712	4,401								

Figure 2. «Paper» and on-line calculation of specific isobaric heat capacity of water and steam

Figure 2 shows a part of the table and the site supplementing this table. There are some peculiarities that make the site standing out from the «paper» analogue:

- Initial data (pressure and temperature) in the «paper» table are given with significant increment (20 degrees for the temperature) that demands interpolations in the intermediate points. The site is free of this limitation that is fixed by calculation in the intermediate point of the table (t = 110°C p = 1.5 MPa).
- Initial data can be entered using various temperature scales and pressure units customary in engineering practice in Russia and all over the word.
- The misprints and errors on the site can be corrected immediately. «Word is but wind, the written letter remains»: corrections in the «paper» reference book can be only done during re-edition.

A user can change number of significant figures in results (the variable digit is described below).
But the main distinctive feature of the site is that it represents not only required value (specific isobaric heat capacity of water and steam depending on temperature and pressure) but also the uncertainty of

the given value which is depends on temperature and pressure, too. The value of the uncertainty in the region of water differs from the value in the region of superheated steam and from that in the near-critical region which is shown on the separate diagram of p and T acceptable values. The site shown on Fig. 2 has a link to this diagram. Beside the uncertainty value this site represents the range of possible values for the separate water property determined by the given uncertainty.

Using a value from the tables or from the Internet sites in heat engineering calculation it is always necessary to keep in mind that these data have certain errors and the errors influence anyhow to the result, for example, to obtained efficiency of a power plant. Moreover, ideally the result in an engineering calculation (the value of power plant efficiency) should be represented with the error defined by the errors of initial data and the calculation technique.

The site shown on Fig. 2 enables a user to choose a number of decimal places of the required value. Although, it is the uncertainty that defines the number of decimal places if it is specified and in principle, the values from table 2 must contain only three decimal places – 4,23 kJ/kg·K. The guide site allows a user to increase the decimal places for example, for checking variation in a calculated value with minor change of initial data, i. e. to determine a behavior of derivate of current function with respect to the given parameter (estimation of partial derivate). This «consumer» property of the reference book is discussed in description of Figure 3.
Each scientific and technical reference book is a collection of formulae, tables, plots, and texts commenting them. The plots (diagrams) are presented in the reference book and on the sites supporting it.

If an engineer needs any value he (she) can find it in a table. If it is required to obtain how this value is changed with varying of initial data, the engineer addresses to a plot (diagram). Change-over from the «paper» book to the Internet site allows us to combine useful properties of a table and a plot. As an example, Figure 3 shows such a site supporting the reference book.

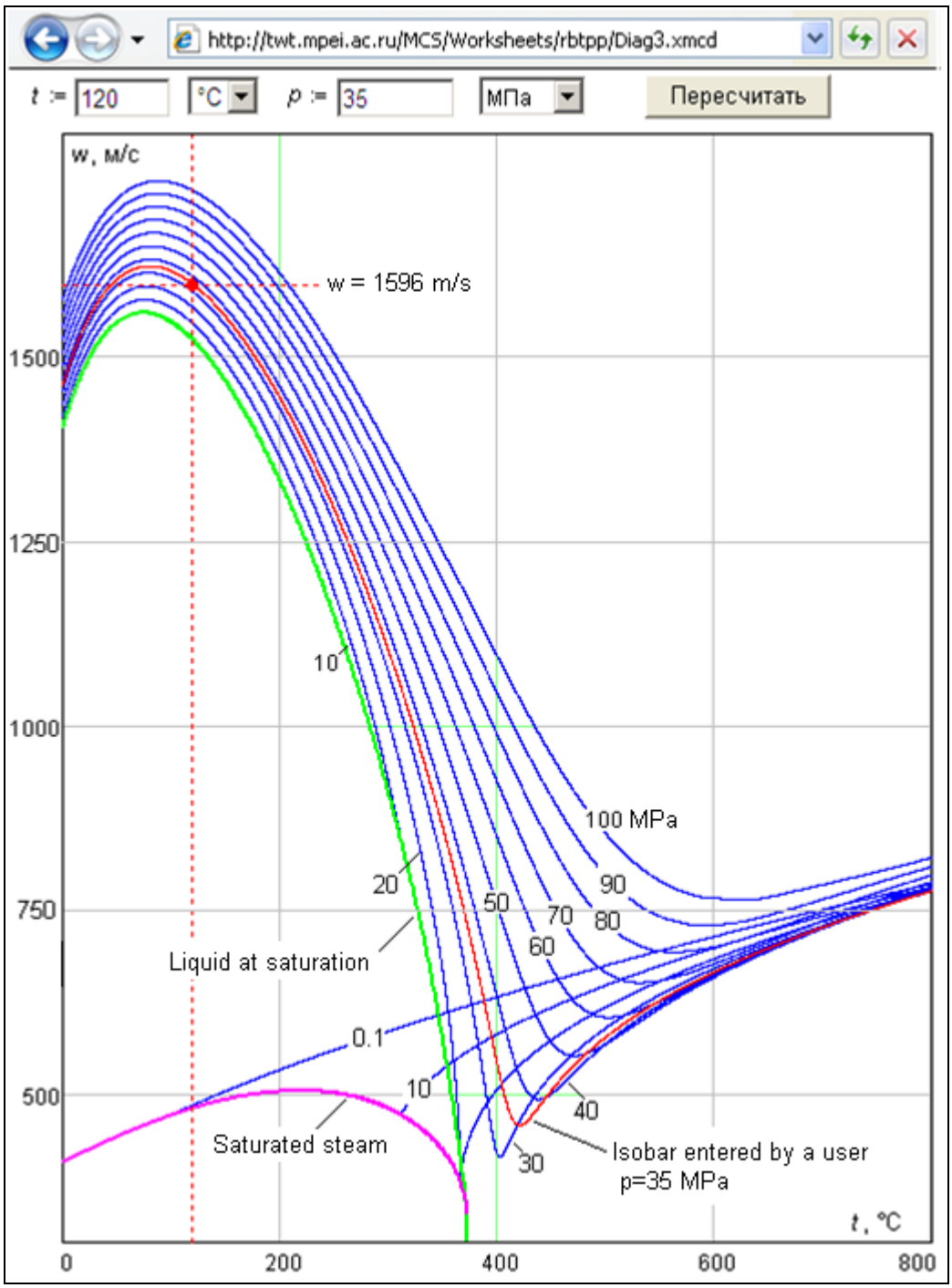


Figure 3. Interactive network diagram of water and steam properties

Entering temperature and pressure a user of this site obtains not only required value of sound velocity in water and steam but also corresponding point on the set of isobars on the plot of sound velocity against temperature. At that, the plot (diagram) automatically shows wanting isobar (in this case, p=35 MPa). Some pages of the site represent the points not on the set of isobars (isotherms, or isochors) but on the surface, thermodynamic surface, connecting three parameters of water and steam, two of which are initial data and the third is a determined value. Figure 4 shows such a surface.

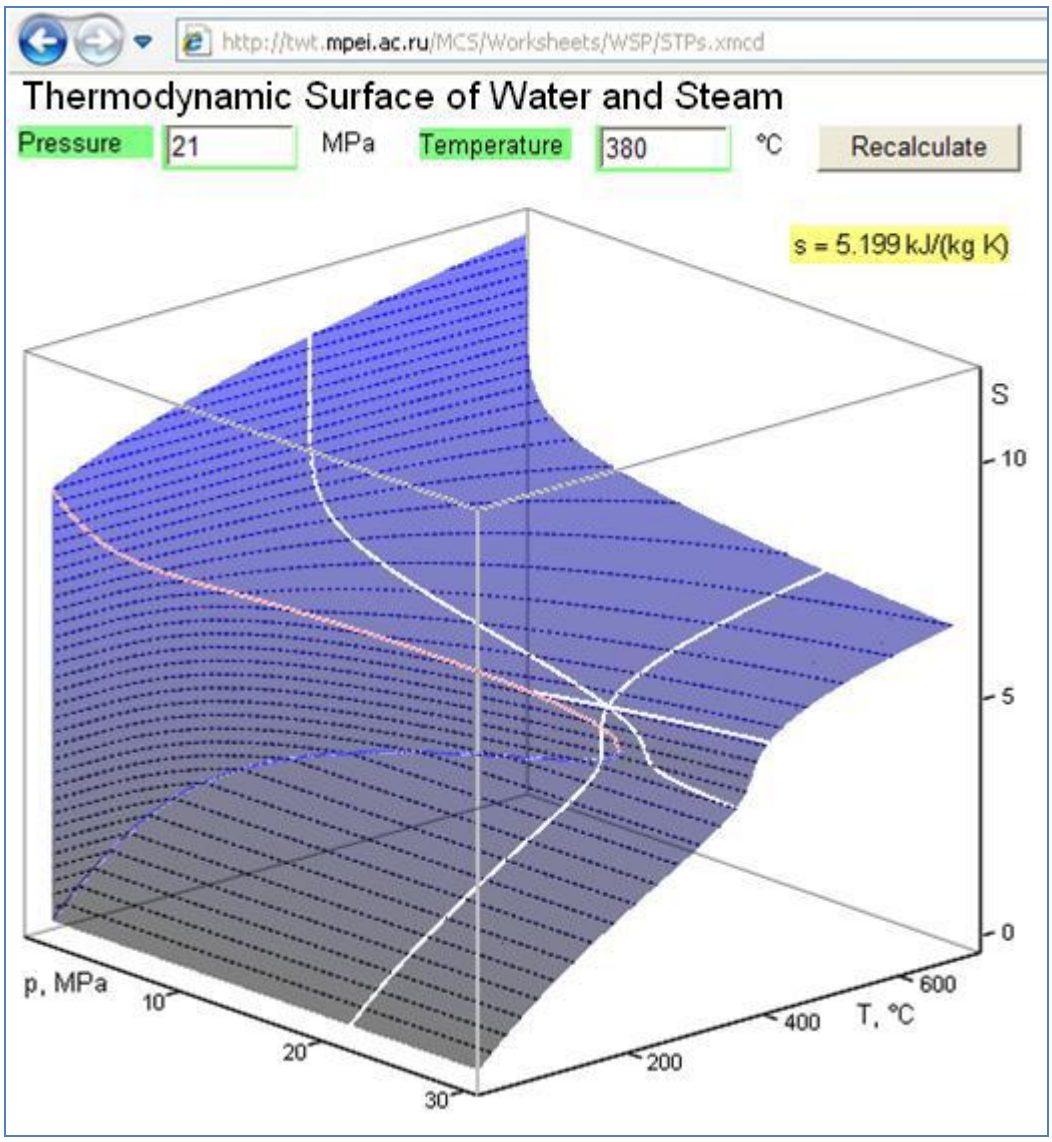


Figure 4. Interactive network thermodynamic surface of water and steam

Choosing pages of the site a user can simply calculate required property of water and steam (Fig. 2), additionally find out its behavior on the set of curves (Fig. 3) or on the surfaces (Fig.4).
«Paper» reference book contains properties of water and steam depending only on temperature and pressure, while the site enables us to use the other pairs of parameters as initial data: pressure and enthalpy, pressure and entropy, enthalpy and entropy, etc. that makes calculations more convenient. Figure 5 shows a table of the reference book and two calculation cases on the supporting site connecting with state of water and steam.

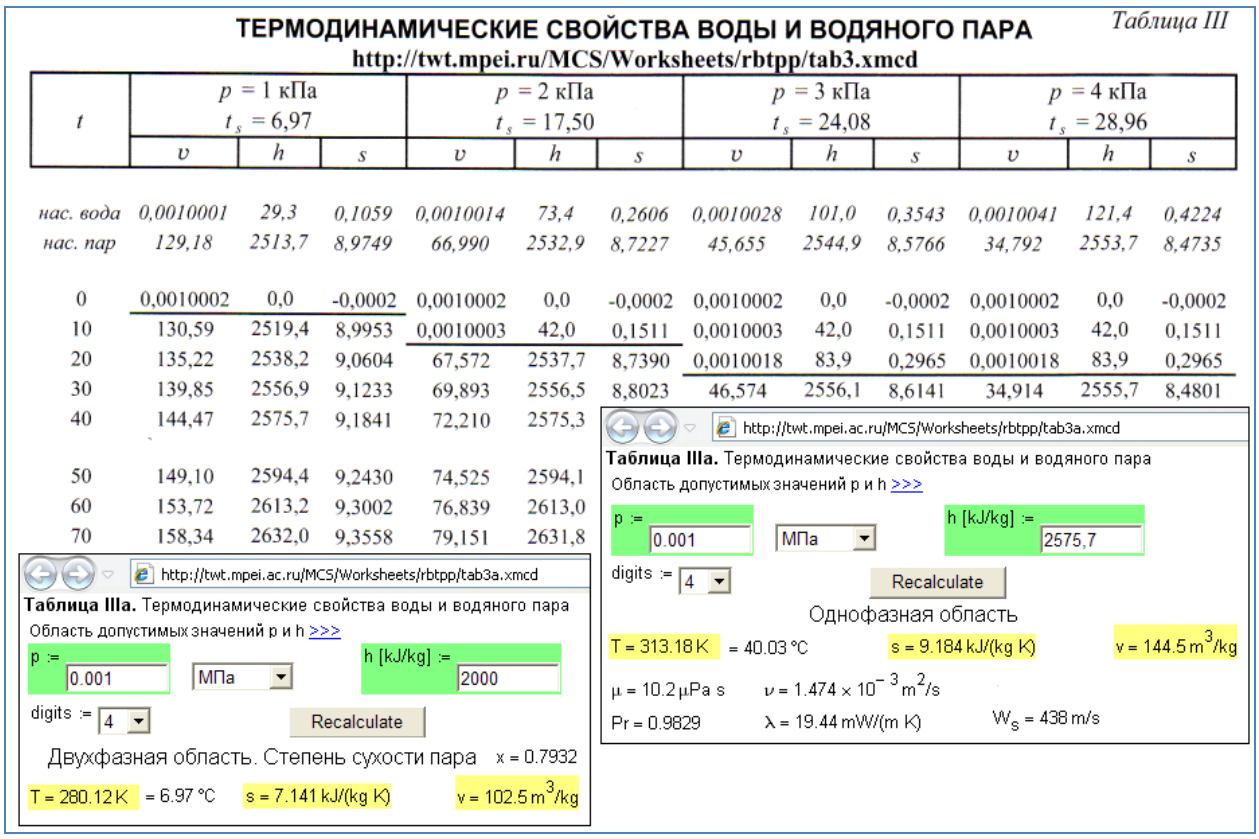


Figure 5. «Paper» table and network calculation of water and steam properties

Direct initial data of the table are pressure (heading of the table) and temperature (the first column), initial data of the site shown on Fig. 5 are pressure and enthalpy. Certainly, working with the table one can solve a reverse problem – estimate parameters of water and steam by pressure and specific enthalpy (or entropy), but it is rather difficult to do. Besides, it is impossible to work in two-phase region (region of moist steam), which is compressed to the horizontal lines on the table separating water (upper part of the table) from the steam (bottom part). The Internet site shown on Fig. 5 shows that state of water and steam is noted by corresponding messages: «Two-phase region» or «Single-phase region» depending on initial data. In the single-phase region at given p and h a user gets thermodynamic properties of water and steam (temperature T, specific enthalpy s, and specific volume v) and also some other thermophysical properties: dynamic viscosity μ, kinematic viscosity v, the Prandtl number Pr, thermal conductivity λ, and sound velocity w. In the two-phase region only quality of wet vapor x is additionally represented.

All the tables of the «paper» reference book concerning properties of the gases are integrated with pages of the Internet site, too. Figure 6 shows such a tandem. The paper table contains thermodynamic properties of wet air at specific humidity 10 g of water per 1 kg of dry air whereas the Internet site enables us to make calculations at other values of specific humidity. Obviously, we have in mind that all the source data of the page supporting the reference book have limitation on the tolerance range. If a user sets the initial data outside the limits of region of validity intentionally or by chance the error message is appeared together with instructions how it is corrected.

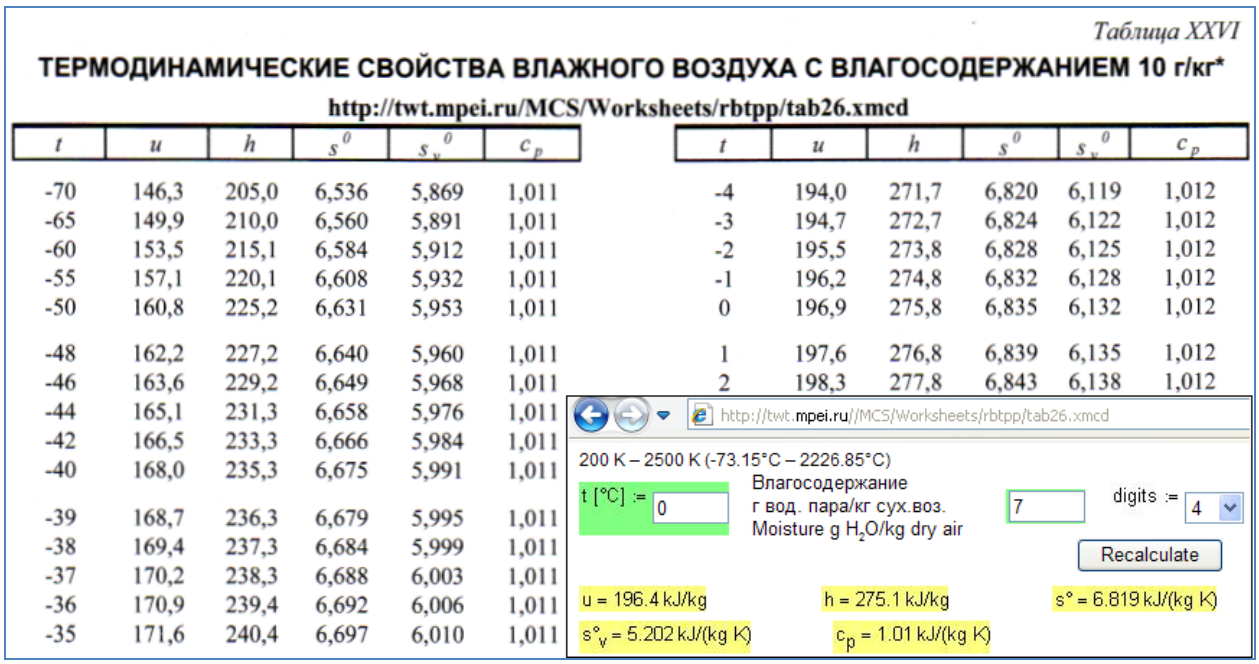


Таблица XXVI

ТЕРМОДИНАМИЧЕСКИЕ СВОЙСТВА ВЛАЖНОГО ВОЗДУХА С ВЛАГОСОДЕРЖАНИЕМ 10 г/кг*

http://twt.mpei.ru/MCS/Worksheets/rbtpp/tab26.xmcd

t	u	h	s^0	s_v^0	c_p
-70	146,3	205,0	6,536	5,869	1,011
-65	149,9	210,0	6,560	5,891	1,011
-60	153,5	215,1	6,584	5,912	1,011
-55	157,1	220,1	6,608	5,932	1,011
-50	160,8	225,2	6,631	5,953	1,011
-48	162,2	227,2	6,640	5,960	1,011
-46	163,6	229,2	6,649	5,968	1,011
-44	165,1	231,3	6,658	5,976	1,011
-42	166,5	233,3	6,666	5,984	1,011
-40	168,0	235,3	6,675	5,991	1,011
-39	168,7	236,3	6,679	5,995	1,011
-38	169,4	237,3	6,684	5,999	1,011
-37	170,2	238,3	6,688	6,003	1,011
-36	170,9	239,4	6,692	6,006	1,011
-35	171,6	240,4	6,697	6,010	1,011

t	u	h	s^0	s_v^0	c_p
-4	194,0	271,7	6,820	6,119	1,012
-3	194,7	272,7	6,824	6,122	1,012
-2	195,5	273,8	6,828	6,125	1,012
-1	196,2	274,8	6,832	6,128	1,012
0	196,9	275,8	6,835	6,132	1,012
1	197,6	276,8	6,839	6,135	1,012
2	198,3	277,8	6,843	6,138	1,012

Figure 6. Interactive network calculation of thermodynamic properties of the gases

The reference book site is supplied with the pages for calculation of processes connecting with use of water and steam. Usually similar «paper» reference books are supplied with paper sheets of T-s and h-s diagrams of water and steam properties representing isotherms, isobars, curves of the same humidity, etc. The site of the reference book is integrated with such diagrams in a digital form.

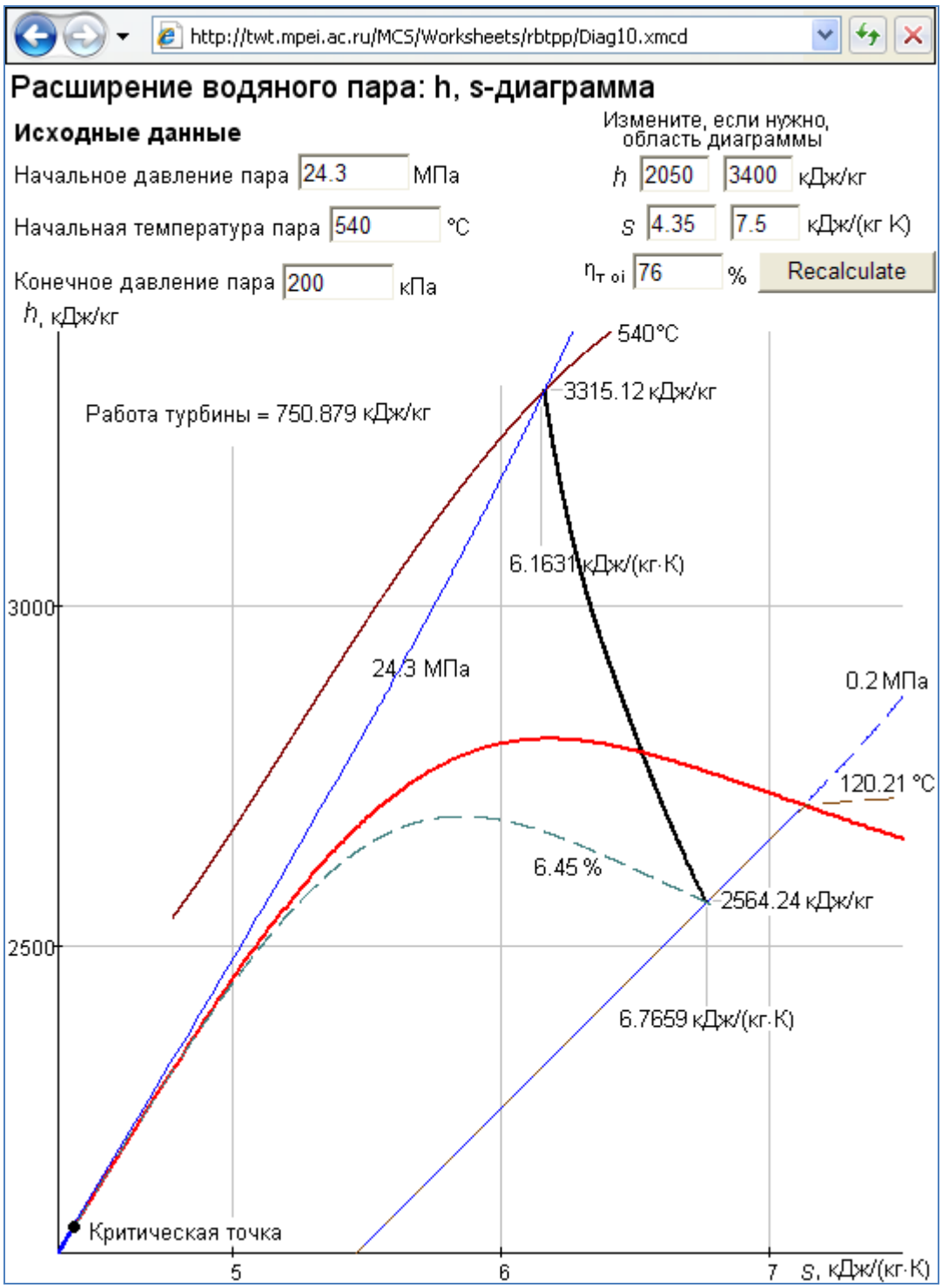


Figure 7. Interactive network h-s diagram

Thus, Figure 7 shows «live» h, s –expansion diagram of steam. A user defines initial parameters of the steam (t and p: the reference point of expansion is meant to be superheated steam), finaL pressure and internal relative efficiency of the expansion process. The guide site receives these data, treats them, and represents the line of expansion process. By the way, if the value of efficiency is defined equal to zero (or close to zero) the expansion line will become horizontal (almost horizontal) and will represent throttling process, the process at h=const (h ≈ const).
The site of the reference book is supplied with many other calculations and diagrams involving water and steam. Some of them are listed below:

- Phase transitions «ice-water-steam»

- Dependence of specific enthalpy of water and steam on temperature and pressure
- Dependence of specific isobaric thermal capacity of water and steam on temperature and pressure
- Dependence of sound velocity of water and steam on temperature and pressure
- Dependence of dynamic viscosity of water and steam on temperature and pressure
- Dependence of thermal conductivity of water and steam on temperature and pressure
- Dependence of Prandtl number of water and steam on temperature and pressure
- Dependence of isentropic exponent of water and steam on temperature and pressure
- Document listing of Mathcad mathematical package for calculation composition of methane combustion products
- Parameters of damp steam: plot
- T-s diagram of steam throttling
- Melting, sublimating, and evaporation pressures of the system «ice-water-steam»
- Dependence of density of hl modification ice on temperature and pressure
- Dependence of sea water parameters on temperature, pressure, salinity, etc

The reference book and the site may be compared with two nonequal parts of an iceberg. An iceberg can't exist without an above-water part. And each more or less significant on-line information resource can't exist without its «above-water part», without a small paper book, which first, contains lists of contents of the site, second, gives instructions how to use the site, and third, represents some formulae, tables, plots for example, for additional data check generated on the site.
Reference:

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2. Revised Release on the IAPWS Industrial Formulation 1997 for Thermodynamic Properties of Water and Steam. International association for the properties of Water and Steam. Executive Secretary Dr. R.B. Dooley. Structural Integrity Associates Inc. 2904 . South Sheridan Way, Suite 303.Oakville, Ontario, L6J 7L7 Canada. 2007. 48 p.
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