"Cloud" Service on the Properties of Working Media for Thermal Engineering Calculations[1]

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Abstract—A technology of thermal engineering calculations that uses references to Internet-functions ("cloud" functions) on the properties of working media used in steam–gas cycles is described.

Those wishing to calculate cycles of steam-turbine, gas-turbine, and combined-cycle installations must know the thermodynamic properties of the working media (water and/or steam, air, flue gases, etc.) involved. When these calculations are performed "manually", it is possible to use tabulated data on the properties of specific working media on the saturation line, in the single-phase region, and in the regions of unstable states (supercooled steam, superheated water, etc.) [1]. When they are carried out on a computer, special software functions returning the values of working media properties depending on the cycle parameters are required.

WaterSteamPro [2, 3] is one of the most widely used and convenient computer programs for the properties of working media and heat carriers/coolants used in power engineering (including industry-scale installations and small installations using organic working media). After downloading WaterSteamPro from the website www.wsp.ru and installing it on a computer, more than 300 functions not only on the properties of working media, but also on some processes in thermodynamic cycles become available for thermal engineering calculations.[2]

Downloading functions from the Internet (or installing them on a computer from a disk or other carrier if the workstation does not have access to the Internet) has one essential drawback. Computer programs, in particular, those for calculating the thermophysical properties of individual substances and their mixtures are constantly upgraded and improved. This is mainly due to the fact that new formulations (sets of formulas with their description) emerge, that determine the procedures used to calculate the concrete properties of certain substances.[3,4] In addition, errors and inaccuracies in the existing computer programs are corrected, their application domains are extended, and their performance is improved (speed of operation, volume of computer memory, etc.). Such programs are also continuously updated due to changes made in the hardware and operating system software. Users of computer programs on the properties of substances frequently fail to notice these changes and work with outdated versions. Also, users face additional difficulties if they change their computer and/or operating system: old computer programs cannot be installed and started any longer.

In view of what was said above, and taking into account that at present almost all computers on which engineering calculations are carried out (in particular, thermal engineering ones) have constant high-speed connection to the Internet, we have suggested a new technology for working with functions on the thermophysical properties of working media, heat carriers/coolants, and materials used in thermal power engineering that is based not on downloading computer programs but on making reference to the functions stored on websites, or in "clouds."

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[1] This work was carried out within the project "The Moscow Power Engineering Institute National Research University: Information Support for Power Engineering, Energy Efficiency and Energy Conservation—Creating a Center for Thermophysical Properties of Substances and Solutions for Power Engineering."

[2] Almost all software environments can be used for carrying out these calculations, such as the Excel spreadsheet processor, Mathcad engineering calculator, Maple symbolic computation language, high-level programming languages C, BASIC, Pascal, and FORTRAN. In this paper, we limited ourselves to considering only the Mathcad package.

[3] As regards water and steam (including solutions, e.g. seawater), which are used as the main working fluids in power engineering, such formulations are developed and approved by the International Association for the Properties of Water and Steam, IAPWS (see the website www.iapws.org).

[4] Here is a concrete example. In September 2011, the IAPWS approved a new formulation for calculating the thermal conductivity of water and/or steam. Users who downloaded the computer programs earlier will continue to work with their old versions for a long period of time, whereas those who employ the new information technology described in this paper will immediately begin to work with the software implementation of the new formulation on the thermal conductivity of water and/or steam.
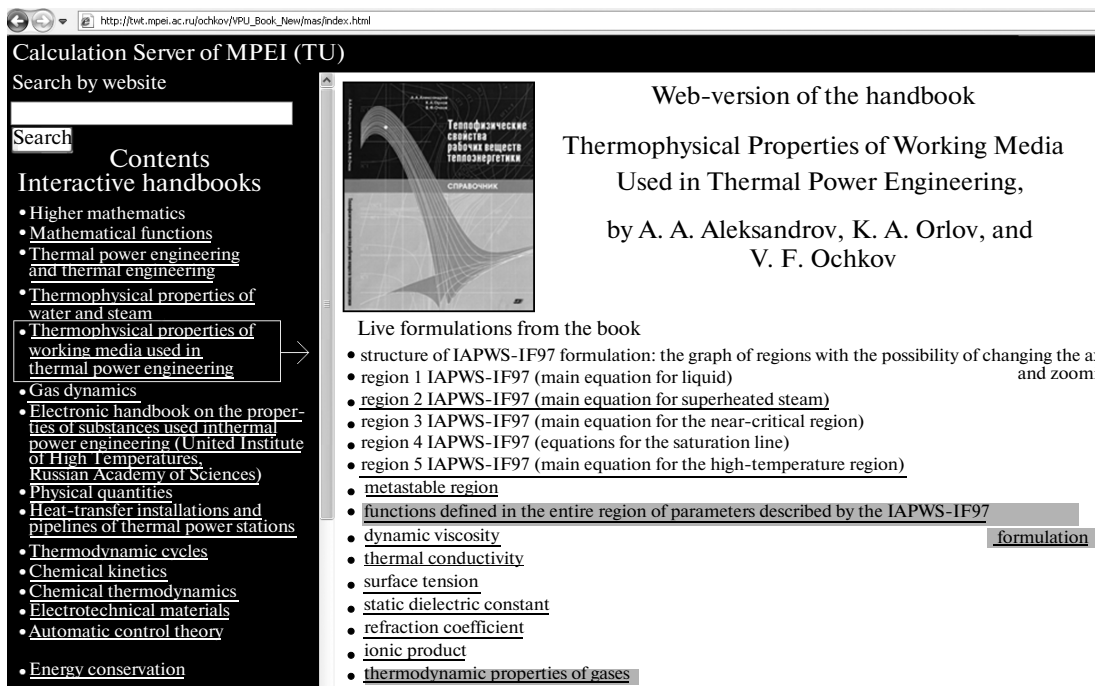
Fig. 1. MPEI (TU)—OOO Trieru's calculation server.

The handbook [1] on the thermophysical properties of working media used in power engineering was supplemented with a website arranged on the computation server of the Moscow Power Engineering University's (MPEI) National Research University (www.mpei.ru) and OOO Trieru (www.trie.ru) (Fig. 1). Apart from the above-mentioned handbook, other interactive network handbooks useful for power engineers and specialists in thermal engineering have been opened on the MEI–Triery's computation server [4].

From the website of the handbook on the thermophysical properties of working media used in thermal power engineering (see Fig. 1), a user can navigate to open interactive network calculations in individual regions of the IAPWS-IF97 formulation (see Footnote 3):
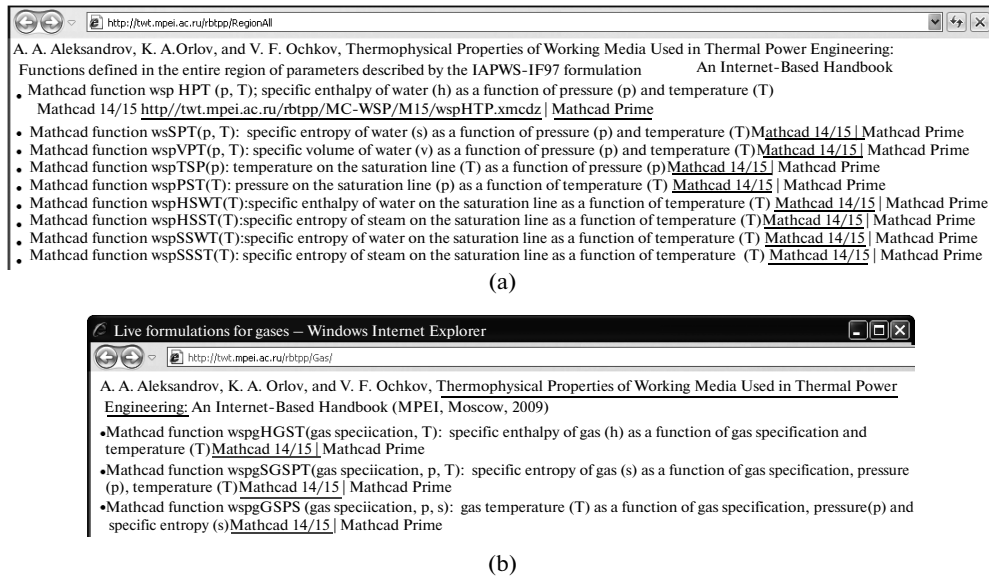
(1) The region of liquid (water)—http://twt.mpei. ac.ru/rbtpp/Region1.

(2) The region of steam—http://twt.mpei.ac.ru/rbtpp/Region2.

(3) The near-critical region—http://twt.mpei.ac.ru/rbtpp/Region3.

(4) The saturation line—http://twt.mpei.ac.ru/rbtpp/Region4.

(5) The region of high temperatures (800–2000°C)—http://twt.mpei.ac.ru/rbtpp/Region5.

(6) The metastable region—http://twt.mpei.ac.ru/rbtpp/RegionMS.

The above-mentioned websites contain interactive formulas replacing the tables of handbook [1], as well as references (highlighted in Fig. 1 by color background), following which (using a mouse) one can open websites containing functions of the thermodynamic properties of working media used in thermal power engineering. Figure 2 shows the websites containing such functions for water and/or steam and for ideal gases and their mixtures.

The engineering calculator Mathcad is a very convenient tool for solving various engineering problems, including thermal engineering ones [5]. Formulas are written in the Mathcad environment in natural notation, a feature that favorably distinguishes it from traditional programming languages and spreadsheets. There is also a possibility to use measurement units for checking the correctness of calculations and for presenting results in more convenient form. Below, this will be discussed in more detail. The results of calculations carried out in the Mathcad environment are illustrated by graphs, diagrams, and animations. These and other useful features of the Mathcad package have made it one of the most popular tools for solving engineering and technical problems on a computer.

The Mathcad environment has a convenient tool: a reference to another Mathcad document the variables and functions of which become accessible or, as programmers say, visible in the Mathcad document from which the corresponding reference is made. The Mathcad user need not open another calculation document and insert it in his or her calculation document: it is sufficient to make a reference to the appropriate file. After that, the user can use the functions programmed in the external document as if they have already been created in his or her document. Such ref-

A. A. Aleksandrov, K. A.Orlov, and V. F. Ochkov, Thermophysical Properties of Working Media Used in Thermal Power Engineering: Functions defined in the entire region of parameters described by the IAPWS-IF97 formulation   An Internet-Based Handbook

- Mathcad function wsp HPT (p, T); specific enthalpy of water (h) as a function of pressure (p) and temperature (T)
  Mathcad 14/15 http://twt.mpei.ac.ru/rbtpp/MC-WSP/M15/wspHTP.xmcdz | Mathcad Prime
- Mathcad function wsSPT(p, T): specific entropy of water (s) as a function of pressure (p) and temperature (T)Mathcad 14/15 | Mathcad Prime
- Mathcad function wspVPT(p, T): specific volume of water (v) as a function of pressure (p) and temperature (T)Mathcad 14/15 | Mathcad Prime
- Mathcad function wspTSP(p): temperature on the saturation line (T) as a function of pressure (p)Mathcad 14/15 | Mathcad Prime
- Mathcad function wspPST(T): pressure on the saturation line (p) as a function of temperature (T) Mathcad 14/15 | Mathcad Prime
- Mathcad function wspHSWT(T):specific enthalpy of water on the saturation line as a function of temperature (T) Mathcad 14/15 | Mathcad Prime
- Mathcad function wspHSST(T):specific entropy of steam on the saturation line as a function of temperature (T)Mathcad 14/15 | Mathcad Prime
- Mathcad function wspSSWT(T):specific entropy of water on the saturation line as a function of temperature (T) Mathcad 14/15 | Mathcad Prime
- Mathcad function wspSSST(T): specific entropy of steam on the saturation line as a function of temperature (T) Mathcad 14/15 | Mathcad Prime

(a)

A. A. Aleksandrov, K. A. Orlov, and V. F. Ochkov, Thermophysical Properties of Working Media Used in Thermal Power Engineering: An Internet-Based Handbook (MPEI, Moscow, 2009)

- Mathcad function wspgHGST(gas speciication, T): specific enthalpy of gas (h) as a function of gas specification and temperature (T)Mathcad 14/15 | Mathcad Prime
- Mathcad function wspgSGSPT(gas speciication, p, T): specific entropy of gas (s) as a function of gas specification, pressure (p), temperature (T)Mathcad 14/15 | Mathcad Prime
- Mathcad function wspgGSPS (gas speciication, p, s): gas temperature (T) as a function of gas specification, pressure(p) and specific entropy (s)Mathcad 14/15 | Mathcad Prime

(b)

Fig. 2. Website with references to the functions on the thermodynamic properties of water and/or steam (a) and ideal gases and their mixtures (b).
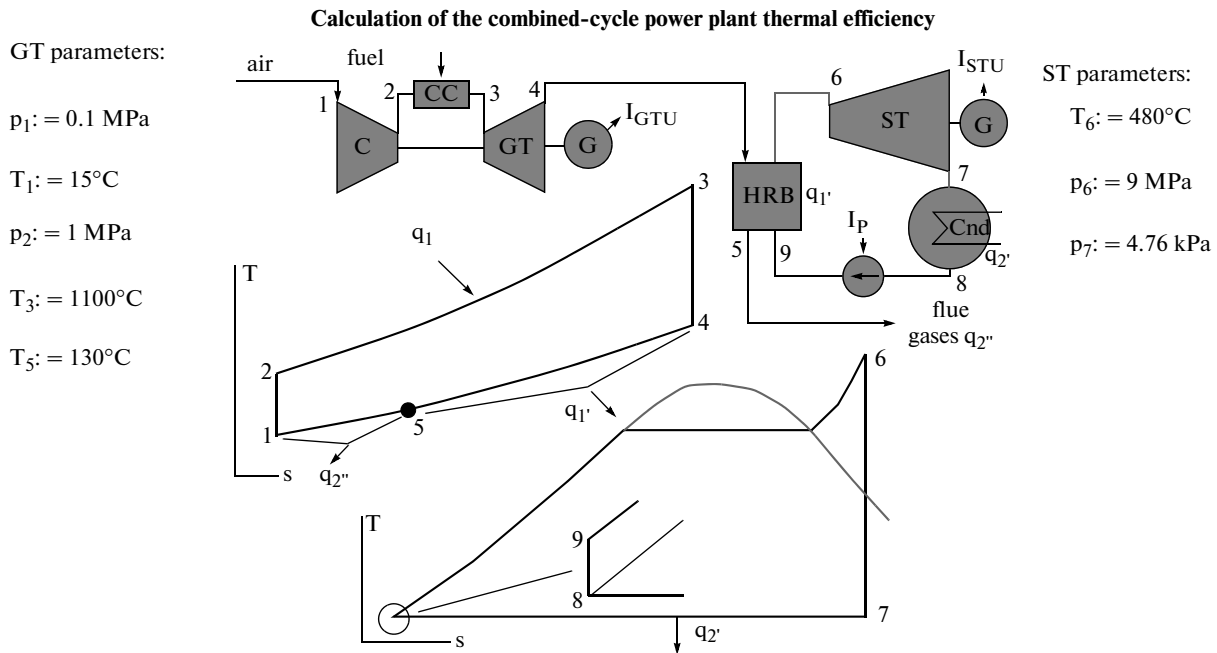
erence can be made not only to Mathcad documents (files with the extensions *.mcd, *.mcdz, *.xmcd, *.xmcdz, *.mcdx, and *.mcdxz) stored on a workstation or in a local area network (LAN), but also to documents available on websites. Owing to this circumstance, wide possibilities are opened for implementing a new technology of using functions available on websites without the need to download them on the user's computer.

Using "Cloud" functions on the properties of working media employed in thermal power installations is illustrated in Figs. 3—5 by a calculation in the Mathcad environment of the simplest ideal combined (binary) thermodynamic (Rankine) cycle on superheated steam for a boiler unit [a heat-recovery boiler (HRB)] the burner of which is replaced by a gas turbine unit (the Brayton cycle) with an air compressor (C), combustion chamber (CC), gas turbine (GT), and an electric generator (G).

The part of Fig. 3 relating to the start of calculation shows the basic circuit of the combined-cycle power plant (CCP) and T, s diagrams of the thermodynamic cycles (gas-turbine and steam—water ones) involved in this calculation. These diagrams are "dead" in the sense that a change in the initial parameters of the installation (see the assignment operators shown on the right- and left of the cycle diagram in Fig. 3) does not lead to the corresponding changes in them. But the diagrams available on the websites http://twt.mpei. ac.ru/MCS/Worksheets/PTU/Rankine.xmcd (the Rankine cycle) and http://twt.mpei.ac.ru/MCS/Worksheets/PTU/GTU.xmcd (the Brayton cycle) are "alive" and change their appearance as changes are made in the initial parameters of cycles. Moreover, the features available on the website of

Rankine cycle with superheated steam allow the user to select the axes of diagrams and construct not only 2D, but also 3D diagrams by adding a third parameter to temperature and specific entropy, e.g., pressure. However, an attempt to simultaneously show steam—water and gas cycles on a single "live" diagram involve difficulties because the working media used in these cycles (steam and mixtures of gases) have different base points for pressure and temperature in calculating enthalpy and entropy.

As was already emphasized at the beginning of the paper, thermodynamic cycles cannot be calculated if the properties of working media involved in these cycles are unknown. It was also mentioned that all functions returning the values of thermodynamic properties of water and steam that are required for calculating the Rankine cycle on superheated steam are collected on the website shown in Fig. 2. These functions can be downloaded from the site and used in a calculation by copying and pasting; they can also be placed on a working computer or in a LAN, after which references can be made to the appropriate Mathcad files for making these functions visible in calculations. But there is another possibility: to make a reference not to the user's own computer or LAN, but to the website shown in Fig. 2, which was done in the calculation shown in Fig. 3. Prior to calculate the specific enthalpy (h_6 and specific entropy (s_6) of superheated steam, references were made to files with the names wspHPT.xmdz and wspSPT.xmdz stored on the website shown in Fig. 2. After that, the functions with such names became visible in the calculation and began to return the values of specific enthalpy H and entropy S of steam vs. pressure (the first argument of these functions is P) and temperature (the second

Calculation of the combined-cycle power plant thermal efficiency

GT parameters:

$p_1 := 0.1$ MPa

$T_1 := 15°C$

$p_2 := 1$ MPa

$T_3 := 1100°C$

$T_5 := 130°C$

ST parameters:

$T_6 := 480°C$

$p_6 := 9$ MPa

$p_7 := 4.76$ kPa

Calculation of ST with accessing functions stored on a website http://twt.mpei.ac.ru/rbtpp/RegionAll

Specific enthalpy of steam at the turbine inlet:

Reference: http://twt.mpei.ac.ru/rbtpp/MC-WSP/M15/wspHPT.xmcdz $h_6 := \text{wspHPT}(p_6, T_6) = 3336.3$ kJ/kg of steam

Specific entropy of steam at the turbine inlet:

Reference: http://twt.mpei.ac.ru/rbtpp/MC-WSP/M15/wspSPT.xmcdz $s_6 := \text{wspSPT}(p_6, T_6) = 6.593$ kJ(kg of steam K)

Temperature of water at the boiler inlet:

Reference: http://twt.mpei.ac.ru/rbtpp/wspT1PS.xmcdz $T_9 := \text{wspT1PS}(p_6, s_9) = 32.21°C$

Specific enthalpy of water at the boiler inlet: $h_9 := \text{wspH1PT}(p_6, T_6) = 143.13$ kJ/kg of water

Specific heat added in the boiler: $q_1 := h_6 - h_9 = 3193.2$ kJ/kg

Specific work of the turbine: $l_T := h_6 - h_7 = 1331.95$ kJ/kg of steam

Specific work of the pump: $l_P := h_9 - h_8 = 9.011$ kJ/kg of water

Cycle thermal efficiency: $\eta_t := \dfrac{l_T - l_P}{q_1} = 41.13\%$

Fig. 3. Calculating the steam-turbine part of a combined cycle.

argument of these functions is T). References to all files of functions required in the calculation were made in the same way (not shown in Fig. 3), due to which it became possible to calculate the thermal efficiency of the steam part of the considered binary cycle (see the end part of the calculation shown in Fig. 3).

The files and names of functions on the properties of water and steam have the prefix wsp.

"Cloud" references to the files of functions returning the values of thermodynamic properties of the second working medium used in the binary cycle were made in a similar way (see Fig. 4). The calculation

Calculation of GT   Working fluid $af :=$ "Air"

Specific enthalpy of air at the compressor inlet:

Reference: http://twt.mpei.ac.ru/rbtpp/Gas/M15/wspgHGST.xmcdz $h_1 := \text{wspgHGST}(af, T_1) = 288.56$ kJ/kg of gas

Specific entropy of air at the compressor inlet:

Reference: http://twt.mpei.ac.ru/rbtpp/Gas/M15/wspgSGSPT.xmcdz $s_1 := \text{wspgSGSPT}(af, p_1, T_1) = 6.83$ kJ/(kg of gas K)

Specific entropy of air at the compressor outlet: $s_2 := s_1 = 6.83$ kJ/(kg of gas K)

Air temperature at the compressor outlet:

Reference: http://twt.mpei.ac.ru/rbtpp/Gas/M15/wspgTGSPS.xmcdz $T_2 := \text{wspgTGSPS}(af, p_2, s_2) = 279.02°C$

Specific enthalpy of air at the compressor outlet: $h_2 := \text{wspgHGST}(af, T_2) = 557.39$ kJ/kg of gas

Gas pressure at the GT inlet: $p_3 := p_2 = 1$ MPa

Specific entropy of gas at the GT inlet: $s_3 := \text{wspgSGSPT}(af, p_3, T_3) = 7.847$ kJ/(kg of gas K)

Specific enthalpy of gas at the GT inlet: $h_3 := \text{wspgHGST}(af, T_3) = 1483.61$ kJ/kg of gas

Gas pressure at the GT outlet: $p_4 := p_1 = 0.1$ MPa

Specific entropy of gas at the GT outlet: $s_4 := s_3 = 7.85$ kJ/(kg of gas K)

Gas temperature at the GT outlet: $T_4 := \text{wspgTGSPS}(af, p_4, s_4) = 498.08°C$

Specific enthalpy of gas at the GT outlet: $h_4 := \text{if}(T_4 > T_6), \text{wspgHGST}(af, T_4), \text{"Error"}) = 790.87$ kJ/kg of gas

Specific heat added in the combustion chamber: $q_1 := h_3 - h_2 = 926.22$ kJ/kg of gas

Specific work of the gas turbine: $l_{GT} := h_3 - h_4 = 692.74$ kJ/kg of gas

Specific work of the compressor: $l_C := h_2 - h_1 = 268.83$ kJ/kg of gas

GT cycle efficiency: $\eta_{GTU} := \dfrac{l_{GT} - l_C}{q_1} = 45.77\%$

Fig. 4. Calculating the gas-turbine part of a combined cycle.

here should be more complex. The point is that the first working fluid (water and steam) changes only its parameters and phase state as is circulates over the cycle. As regards the working fluid used in the binary installation's second cycle, it additionally changes its composition: air–air-and-fuel mixture–flue gases. In our website, we placed calculations of gas-turbine cycles with different degrees of complexity, which take into account a change in the composition of working fluid, humidity of initial air, and other features. Readers can see one of such calculations on http://twtmas.mpei.ac.ru/mas/Work-sheets/orlov/gases/simple_gtu.mcd. The calculation shown in Fig. 4 uses air with the standard composition as working fluid (see the first assignment operator in the figure: af: = "Air"). Designations of other gases (H2, N2, O2, etc.), as well as those of gas mixtures, can also be written in this line constant. The files and

names of functions on the properties of individual gases and gas mixtures have the prefix wspg.

Figures 3 and 4 show calculations of thermal efficiencies for the Rankine cycle on superheated steam and for the gas turbine cycle (the Brayton cycle) for the case as if they would operate independently with the initial parameters given at the beginning of Fig. 3.

Figure 5 shows calculation of the efficiency of a binary cycle (see its schematic diagram shown in Fig. 3), in which part of the heat of gas turbine exhaust (q_1) is spent in the heat-recovery boiler for generating superheated steam (point 6) from feed water (point 9). The operator *if* incorporated in the gas turbine calculation checks whether this process is theoretically possible [see the fifth line from the bottom in Fig. 4: the temperature of flue gases from the gas turbine (T_4) must be higher than the temperature of steam supplied

Calculation of CCP (binary cycle)

Specific enthalpy of gas at the HRB outlet: $h_5 :=$ wspgHGST$(af, T_5) = 404.51$ kJ/kg of gas

Part of heat contained in the gas turbine exhaust is
spent for producing steam in the HRB $m \cdot (h_4 - h_5) = h_6 - h_9$

$$m := \frac{h_6 - h_9}{h_4 - h_5} = 8.265 \ \frac{\text{kg of gas}}{\text{kg of steam}}$$

Specific heat supplied to the CCP: $q_1 := m \cdot (h_3 - h_2) = 7655.13$ kJ/kg of water

Specific useful work done by the CCP gas part: $l_{GT} := (h_3 - h_4) - (h_2 - h_1) = 423.91$ kJ/kg of gas

Specific useful work done by the CCP steam-water part: $l_{ST} := (h_6 - h_7) - (h_9 - h_8) = 1322.94$ kJ/kg of water

Thermal efficiency of the combined-cycle power plant:

$$\eta_{CCP} := \frac{m \cdot l_{GT} + l_{ST}}{q_1} = 63.05\%$$

where: $m = 8.265 \ \dfrac{\text{kg of gas}}{\text{kg of steam}}$ (the ratio of gas flowrate to the flowrate of water and steam),

$l_{GT} = 423.913$ (specific work of gas turbine)

$m \cdot l_{GT} = 3503.62$ kJ/kg of water (specific work of gas turbine per kg of water and steam),

$l_{ST} = 1322.94$ kJ/kg of water (specific work of steam turbine),

$m \cdot l_{GT} + l_{ST} = 4826.55$ kJ/kg of water (specific work of gas and steam turbines), and

$q_1 = 7655.13$ kJ/kg of water (specific heat supplied to the CCP).

Fig. 5. Calculating the thermal efficiency of a combined cycle.

to the steam turbine (T_6)]. Otherwise, a line value ("Error") is assigned to the variable h_4 (the specific enthalpy of gas leaving the gas turbine) instead of a numerical value; in this case, an error message interrupts further calculation.

Below, the main three aspects that should be taken into account in considering the calculations shown in Figs. 3—5 are given.

(1) All functions on the thermodynamic properties of working fluids used in the above-mentioned calculations are dimensional ones. This means that the arguments of a function have dimensions of pressure, temperature, etc. and return values of dimensional quantities: specific enthalpy, specific entropy, etc. The mechanism of dimensions is supported in the environment of the engineering calculator Mathcad, which makes calculations essentially more efficient and prevents the occurrence of possible errors when a quantity with incorrect measurement unit is substituted in calculation [e.g., technical atmospheres (at) instead of physical atmospheres (atm)] or even with another dimension (e.g., temperature instead of pressure).

(2) The presented calculations operate not only with dimensions (mass, length, etc.) and measurement units (kilogram, meter, etc.), but also with physical quantities having the same dimension and, hence, the same measurement units. In calculations of binary cycles, specific thermodynamic quantities, in particular, enthalpy and entropy are related to unit mass of

working fluid measured in kilograms. But the measurement units of mass of water and/or steam and mass of air or flue gas (kilogram) are related to different physical quantities. To prevent the occurrence of possible errors in a calculation and make it more clear, different measurement units are introduced for specific enthalpy and specific entropy of water and/or steam: [kJ/kg of steam, kJ/(kg of steam K)] and air [kJ/kg of gas, kJ/(kg of gas K)]. Owing to this feature, an attempt of summing, e.g., the specific work done by a steam turbine (l_{STU}) and the specific work done by a gas turbine (l_{GTU}) will produce the error message "attempt to sum different physical quantities" and not an erroneous physical result. In view of this, in particular, an important quantity m (the ratio of working fluid mass flowrate in the primary cycle to the working fluid mass flowrate in the secondary cycle used in calculations of binary cycles) is no longer a dimensionless one (see Fig. 5).

(3) The following two variables are usually reserved in thermal engineering calculations for temperature: T and t, of which T denotes temperature on the Kelvin scale and t, on the Celsius scale. In the calculations shown in Figs. 3 and 4, only one variable T is reserved for temperature, with a subscript denoting the binary cycle point at which this temperature is specified or calculated. It should be noted that temperature values are indicated only on the Celsius scale. This feature (refusal from denoting one quantity by two different

variables depending on the measurement unit) is because the engineering calculator Mathcad has been designed so that in performing calculations by formulas involving dimensional quantities, it automatically (by default) converts them into the basic units of the international system SI: megapascals into pascals, Celsius scale into Kelvin scale, kilojoules or calories into joules, etc., letting the user to enter and output quantities on the display screen and on printouts in the units convenient to him or her.

For the functions described in this paper to become accessible in a calculation document, the following actions should be performed:

—enter the portal of the MEI's computation server (www.vpu.ru/mas) and choose "Thermophysical Properties of Working Media Used in Thermal Power Engineering" from the interactive handbooks listed in the table of contents[5] In the opened handbook choose "Show the handbook structure according the table of its contents;"

—in the opened window, choose the function required for the calculations (see Fig. 2);

—click on the chosen function by the right-hand mouse button;

—in the pop-up menu, choose "Properties," highlight and copy the corresponding URL address;

—choose the menu items "Insert" and then "Reference" in the Mathcad document in which this function has to be used, and insert the previously copied address in the appeared window;

—now, in order to use the required function, it is sufficient to enter its name and the available input data as the arguments of this function, e.g., wspHPT (13 MPa, 800 K); on having been called, this function returns the specific enthalpy of steam at the specified parameters.

In this manner, all functions required for carrying out a concrete thermal engineering calculation can be made accessible. Such calculation will work on any computer with the Mathcad software package installed on it and having access to the Internet. The Mathcad file of the problem described in this paper can be downloaded

from the Internet on http://twt.mpei.ac.ru/TTHB/2/Web-Function-PGU.xmcdz.

If necessary, the user can click with the left-hand mouse button on any reference shown in Fig. 2, download, and open the chosen Mathcad document storing the desired function for independently working with it. This document can be saved on a workstation (on the own computer) or in the LAN of the user's company and make a reference to it already in the new place of its storage: not in the Internet (in "clouds"), but in a local ("grounded") place. This is advisable if the connection with the Internet is insufficiently reliable or has limitations. But in that case it is best to install all functions on the properties of working substances used in thermal power engineering on the user's computer from a disk recieved from the developers or simply by visiting the website WaterSteamPro, which was mentioned in the beginning of the paper.

The technologies of references and downloading described in this paper have their advantages and drawbacks. A compromise (intermediate) technology consists in installing the WatersteamPro software on the user's computer and regularly updating it. If thermal engineering calculations are carried out on computers having reliable connection with the Internet, the technology of references described in this paper can be used. This technology allows users to access a rich set of other functions useful for specialists in thermal power engineering, which are placed on the MEI−OOO Trieru's computation server.

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[5] By the time of publishing this paper, the printed handbook and Internet portal *Properties of Working Fluids and Materials Used in Nuclear Power Engineering and Processes Associated with Them* will appear, in which the appropriate functions will be placed in accordance with the technology described in this paper.

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