Development of Internet algorithms and some calculations of power plant COP

E E Ustjuzhanin¹, V F, Ochkov¹, V E Znamensky¹, A T Y Tun¹, and V V Shishakov¹

¹National Research University "Moscow Power Engineering Institute", Krasnokazarmennaya 14, Moscow, 111250, Russia

Abstract. The authors have analyzed Internet resources containing information on some thermodynamic properties of technically important substances (water, air, etc.). Here, we consider the databases that possess such resources and are located in the following organizations: Joint Institute for High Temperatures (Russian Academy of Sciences), Standartinform (Russia), National Institute of Standards and Technology (USA), Institute of Thermophysics (Siberian Branch of the Russian Academy of Sciences), etc. Currently, a typical form is an Internet resource that includes a text file, for example, it is a file containing tabulated properties, \( R = (\rho, s, h...) \), here \( \rho \) is the density, \( s \) is the entropy, \( h \) is the enthalpy of a substance. A small number of Internet resources, which have the following characteristic, are known. Every resource allows a customer to realize a number of options, for example: i) to enter the input data, \( Y = (p, T) \), here \( p \) is the pressure, \( T \) is the temperature, ii) to calculate \( R \) property using "an exe-file" program, iii) to copy the result \( X = (p, T, \rho, h, s, ...) \). Recently, some researchers (including the authors of this report) have requested a software (SW) that is designed for \( R \) property calculations and has a form of an open interactive (OS) Internet resource ("a client function", "template"). A computing part of OS-resource is linked: 1) with a formula, which is applied to calculate \( R \) property, 2) with a Mathcad program, Code_1(R,Y). An interactive part of OS-resource is based on Informatics and Internet technologies. We have proposed some methods and tools that are related to this part and let us: a) to post OS-resource on a remote server, b) to link a client PC with the remote server, c) to implement a number of options to clients. Among these options, there are: i) to calculate \( R \) property at given \( Y \) arguments, ii) to copy mathematical formulas, iii) to copy Code_1(R,Y) as a whole. We have developed some OS-resources that are focused on sharing: a) SW that is used to design power plants, for an example, Code - GTP_1(Z,R,Y) and b) client functions, aimed at determination of the \( R \) properties of the working fluid at fixed points of the thermodynamic cycle. The program let us calculate energy criteria, \( Z \), including the internal coefficient of performance (COP) for a power plant. We have discussed OS-resources, among them OS-resource that includes Code - GTP_1(Z,R,Y) and connected with a complex power plant included: i) several gas turbines, i) several compressors etc.

1. Introduction

We have analyzed information, which relates to thermodynamic properties, \( R = (p,T,s, \ldots) \), of technologically important substances and posted on several WEB sites. These \( R \) properties have to be used in a design of power plants (PP). Let us consider example No. 1 associated with PP including several gas turbines and compressors, several steam turbines, a heat recovery boiler, etc. In the
example, a client-designer should calculate the values of the energy criteria \( Z = (Z_1, Z_2, Z_3, \ldots) \), here \( Z_1 \) is an electric coefficient of performance (COP) for PP, \( Z_2 \) is an internal COP of PP cycle, \( Z_3 \) is a thermal COP of the cycle, \( Z_4 \) is a gas turbine job, \( Z_5 \) is an input heat of the cycle and other characteristics of the cycle. The client uses its own program or a software (SW), which is referred to as Code_1(\( Z,R,Y \)), here \( Y = (Y_i, i = 1 \ldots N) \) are the set values including \( (p_{\text{ref}}, T_{\text{ref}}) \), which are the pressure and the temperature at the inlet of the first turbine, \( R = (p, T, v, h, \ldots) \) are the thermodynamic properties of the working body at predetermined points of the cycle. Software is developed as a Mathcad code. The above-mentioned \( R \) values are taken by the designer usually from an external source. Currently, a typical source of the information is a WEB site related to organizations (the Joint Institute for High Temperatures of RAS [1,2], Standartinform (Russia), the National Institute of Standards and Technology [3], the Institute of Thermophysics of the Siberian Branch of the RAS etc.). These sites contain resources that have the form of a text file. This name means that the resource does not use a computer program or an exe-file to calculate \( R \) properties by mathematical formulas. Such resource contains tabulated properties, \( R = (\rho, h, s, \ldots) \), of a working substance (R134a, H₂O, etc.) at fixed arguments, \( (p, T) \).

Our analyses has shown [4-7] that there is a need of SW, which allows us to adapt some \( R \) values to PP design, for example, to some modernization of the program Code_1(\( Z,R,Y \)). We have developed a special technology and tools for creating SW in the form of an open interactive (OS) Internet resource (“a client function”).

2. Development of OS-resources

The first phase of OS-resource construction includes:

i) the development of a Mathcad program, for example, Code_2(\( \rho,Y \)), which allows us to calculate a value of \( \rho \) under boundary conditions, \( Y = (p, T) \), and with a help of tabulated \( R \) properties;

ii) the identification of a temperature range from -50 to 400°C;

iii) an identification of a pressure range from 1 to 300 bar,

iii) the development of a Mathcad function, csplain(\( X,Z \)), which lets us perform the spline interpolation of points included in a \( R \) array.

The array, \( R = (p,\rho,T) \), is inserted in this code. The \( Y \) conditions include: a) \( (p, T) \) parameters entered by an operator, b) \( (p,T)_{\text{max}} \) data and \( (p,T)_{\text{min}} \) data, c) other parameters. Due to the code, we realize a method of double spline interpolation related to the \( R \) array. Code_2(\( \rho,Y \)) contains Mathcad function, \( p(\rho,T) \). The program provides: a) a choice of \( Y \) values, for example, \( Y = (\rho = 250 \text{ bar}, T = 175^\circ\text{C}) \), b) a choice of units, c) the formulas, which are used for \( \rho \) calculations.

The OS-resource No 1 is produced in the second phase of the process. We have used WEB site “Forum Mathcad” and its remote server where we have placed this resource. It includes a computing part [7], which is associated with mathematical formulas (M) and used to calculate the density \( \rho \) of the air. This part is based on the program, Code_2(\( \rho,Y \)) and has a form of a Mathcad field in the example.

The second part of the resource is interactive and connected with the computer science and Internet technologies. This part gives an ability: a) to post the resource on the remote server, b) to connect a personal computer (PC) of the client with WEB site "Forum Mathcad", c) to implement for clients a number of interactive options. The resource can be named as Res – Air_1(R, U, (https://klm), key(def)), here \( R = \rho \) is the air property that is calculated with the resource, \( U = (U_1 = \rho, U_2 = T) \) are input parameters, \( 1 \) is a number of Code_2(\( \rho,Y \)), (http://klm) is URL address, key(def) is a password. For example, URL address can be written as http://twt.mpei.ac.ru/TTHB/; the password, key(def), can be written as 123ABCabcDEF.

The third part of resource No 1 has a text form that includes: 1) a background information on the working fluid, 2) \( R \) array, 3) commentaries on M formulas, etc.

The OS-resource implements to the client such options as: a) to calculate value of \( \rho \) at \( U \) data, b) to copy M formulas or the code in general, c) to read textual information on the resource. These options are run on the remote server (a cloud) and not on PC. Some tools that have been used in the process and related to Internet technologies (packages "Mathcad Calculation Server" and "Microsoft
Expression Web 3” [7]) play an important role. We have realized these options due to the positive features of Mathcad [4, 5].

Using “copy option” the client can make a copy of the program Code_2(\( \rho, Y \)) and simply “insert” it in his own code; for example, he/she can include Code_2(\( \rho, Y \)) in his/her Code_1(\( Z, R, Y \)). As a result, the client has got a modernized code named as Code_1.1(\( Z, R, Y \)). In this way the client uses an ordinary method, which lets him modify his/her program. Code_1.1(\( Z, R, Y \)) can automatically perform calculations of \( \rho \) values related to cycle points. A "copy option" is absent in the known data bases (JIHT RAS [2], STANDARTINFORM (Russia) etc.) that operate on closed programs (exe-files).

3. Some types of client functions
Since 2010, similar OS-resources are placed not only on "Mathcad Forum" but also on other WEB sites including a site [8], [13]. Let us consider one more variant, \( \text{Res} - \text{Air}_2(\text{R, U},(\text{https:\klm}),\text{key}(\text{def})) \), here \( \text{https:\klm} - \text{http://twt.mpei.ac.ru/TTHB/Ro-p-t.xmcdz} \). This resource or OS-resource No 2 has some characteristics. Firstly, it is elaborated to determine \( R = \rho, \) to realize the program Code_2(\( \rho, Y \)) and to be placed on a remote server owned by the National research university "MPEI" [8]. Secondly, resource No 2 provides a client with several options. There is an option, which lets a designer introduce URL address or "a link" in the form (http://twt.mpei.ac.ru/TTHB/Ro-p-t.xmcdz). Due to the step, the designer gets in a contact with resource No 2. There is a part of program Code_1.1(\( Z, R, Y \)), which consists of: a) \( Y = (p = 20 \text{ MPa}, T = 350°C) \) are boundary conditions, b) a result, for example, \( \rho(p, T) = 103.016 \text{ kg m}^{-3} \) is calculated under these conditions, c) URL address is related to \( \text{Res} - \text{Air}_2(\text{R, U},(\text{https:\klm}),\text{key}(\text{def})) \). Thirdly, we remark an option, which is related to resource No 2 and connected with a graph, which has the 2D – form. The graph is constructed on the basis of \( \text{Res} - \text{Air}_2(\text{R, U},(\text{https:\klm}),\text{key}(\text{def})) \) with fixed values of \( U = (0.1,5.0, 10, 20, 30) \text{ MPa} \). Fourthly, the designer can use an option “to run \( \rho \) calculation”, which lets him determine \( \rho \) value; in the case, the resource performs the following actions: a) sending the parameters \( Y \) to the remote server from PC, b) computing the value of \( \rho \) on a remote server with a help of “client function”, \( \rho(p, T) \), c) returning \( \rho \) value to PC.

We have elaborated another variant of OS-resource named as No 3, which has been developed in a relation to the so - called inverse functions. We have accepted that the client function \( \rho(p, T) \) is known as \( \text{Res} - \text{Air}_2(\text{R, U},(\text{https:\klm}),\text{key}(\text{def})) \), which deals with \( R = \rho \) and is available on the remote server. The OS-resource No 3 allows a client to represent the properties, \( R = (p, T) \) including: 1) the pressure, \( p \), with arguments \( (\rho, T) \), 2) the temperature, \( T \), with arguments \( (\rho, P) \).

Together with specialists from the national research University "MPEI" and JIHT RAS, the authors have created a group of OS-resources [8], which describe \( R \) properties of working fluids including air and \( \text{H}_2\text{O} \). There are some OS-resources associated with \( R \) properties of water using the equation of state and auxiliary formulas, which contain almost 100 coefficients. These client functions are approved by the International association for properties of water and steam (IAPWS) (http://www.iapws.org).

One more type of OS-resources has been investigated in the form of a complex client function, which is focused on sharing: i) a software code elaborated for a PP design and ii) client functions, which can calculate \( R \) properties of working bodies. Some of these resources are related to integrated power plants and can be used: 1) in some modernization of the existing PP (there are gas turbine plants upgraded), 2) in a design of new PP (there are gas turbine plants with complex thermodynamic cycle).

4. Algorithms and calculations of power plants efficiency
We have created several complex OS-resources, which are oriented on the efficiency of gas turbine plant (GTP). For example, OS-resource No 4 is based on the Mathcad program, \( \text{Code} - \text{GTP}_1(\text{Z, R, Y}) \), here \( Y \) is border conditions including \( Y_1 = 0.101 \text{ MPa} \) is an inlet pressure of the compression block, \( Y_2 = p_{\text{up}}/ Y_1 \) is a pressure ratio in the compressor block , \( Y_3 \) is an inlet temperature of the the turbine block. This GTP includes: a) several gas turbine units and compressor units, b) other blocks. The OS-resource No 4 allows us to calculate criteria, \( Z = (Z_1, Z_2, Z_3, Z_4) \) (a specific internal real work of
the gas turbine block), $Z_5$ (a specific real input heat), $Z_6$ (a specific ideal work of an isentropic expansion in the gas turbine block), $Z_7$ (a specific ideal work of the isentropic compression in the compressor block)).

The resource uses $Z_2$ criterion written in the following form [6]

$$Z_2 = \frac{Z_4}{Z_5}. \quad (1)$$

$Z_4$ criterion is represented in the following form [6]

$$Z_4 = Z_6 \cdot U_4 - \frac{Z_2}{U_4}. \quad (2)$$

where $U_4$ is relative internal COP of the gas turbine block, $U_4$ is relative internal COP of the compressor block.

We have involved $Z_8$ as the input heat of an ideal GTP cycle, the relation, $f_1 = Z_2/Z_6$ and rewrite (1) as

$$Z_2 = \frac{Z_6 \cdot U_4 - Z_2}{f_1 \cdot U_4}. \quad (3)$$

$Z_3$ criterion can be expressed as $Z_3 = (Z_6 - Z_7)/Z_5$. We have involved $Z_2 = Z_7/\ Z_4$ and rewrite (3) as

$$Z_2 = \frac{Z_6 \cdot f_1}{Z_7} \left[ Z_1 - f_1 \left( \frac{1}{Z_6 \cdot Z_7} - 1 \right) \right]. \quad (4)$$

At the calculating procedure, the client also determines $R$ properties of the working body at predetermined points of the complex cycle, which includes more than 10 fixed points. There are some client functions, which are inserted in this resource and described in [8],[9].

The OS-resource No 4 lets a client to use $Y$ conditions including: $Y_4$ is a number of stages in the compression block, $Y_5$ is the degree of an air compression in front of an intercooling unit, $Y_6$ is a number of turbine units, $Y_7$ is the degree of a gas expansion in front of the interim heat supply in a separate turbine unit etc. The OS-resource includes some input data ($U_3 = 88.4 \%$, $U_4 = 85.0 \%$ etc.) and has been used in Internet calculations, among them:

1) determination of thermodynamic properties, $R = (p, T, s, ...)$, of the air on the basis of Res – Air_2(R, U, (https:\klm), key(def)) at predetermined points of the PP cycle;
2) determination of energy criteria, $Z(Y)$, for PP at $Y$ conditions;
3) optimization, which is connected with objective functions, $Z(Y)$, and has a purpose of some modernization of GTP.

For example, we have got It can be seen some results, $X = (Z_2, Y_2, Y_3)$, on some isolines including:

$Y_2 = (1200 - 1700)°C$, $Y_3 = 10 - 100$. The data let us find optimal thermodynamic cycles, which are characterized with the maximum values, $Z_{2\text{max}}(Y_{2\text{opt}}, Y_{3\text{opt}})$, here $Y_{2\text{opt}}$ and $Y_{3\text{opt}}$ are optimal $Y$ values. A cycle with $Z_{2\text{max}}(Y_{2\text{opt}} = 29, Y_{3\text{opt}} = 1200 °C) = 38.6 \%$ is chosen. This PP variant is considered as a reference cycle, which is characterized by $R_{\text{opt}}$ or optimal $R$ properties at predetermine points. This cycle has a primitive thermal scheme and uses such conditions as $Y_2 = 29, Y_3 = 1200 °C, Y_4 = 1, Y_5 = 1, Y_6 = 1, Y_7 = 1$. The numerical information let us conclude that an efficiency of the reference cycle can be improved if we involve such events of modernization as:

1) an increase in the pressure ratio of the compressor, $Y_2 = \text{var}$,
2) an increase in the inlet temperature of the the turbine block, $Y_3 = \text{var}$.

We have determined some effects, $\Delta Z_2(Y_2, Y_3)$ that are associated with modernization due to the variation of arguments ($Y_2, Y_3$) in interval, $\Delta U$. For example, it is determined the global maximum, $Z_{2\text{max}} = 46.5 \%$, in testing $Y$ intervals ($Y_2 = 10 - 100, Y_3 = (1200 - 1700) °C$). A shift, $\Delta Z_2(Y_2, Y_3) = Z_{2\text{opt}} - Z_{2\text{opt}} = 7.7 \%$, is calculated too, here $Z_{2\text{opt}}$ is a criterion related to a modified scheme, $Z_{2\text{opt}}$ is a criterion related to the reference scheme. The effect can be realized if a client uses the increases ($\Delta Y_2 = Y_2 - Y_{2\text{opt}} = 43, \Delta Y_3 = Y_3 - Y_{3\text{opt}} = 700 °C$) of $Y$ arguments.

It is an interesting question: what is an error of $Z_2(Y)$ determined in the procedure? We have decided the problem in the following way. The OS-resource No 5, which differs from OS-resource No
5, is formed; this difference is connected with a method, which is used to determine R properties of the air. The OS-resource No 5 includes special client functions. Among them, $\text{Res} = \text{Air}_3(R, U, (https:\/\!/klm), key(def))$ is elaborated to determine $R = h$ of the air. This client function is built using an equation of state for the air [11] at T = 500 - 2000 K and at pressures of up to 10 MPa. This resource has been used in optimization calculations. We have got the results, $X = (Z_2, Y)$, and compared them with data, which are generated by Resource No 4. We have concluded that values of $Z_{2\text{max}}(Y)$ are placed lower on $\delta Z_2 = (0.02 - 0.05) \%$ than $Z_{2\text{max}}(Y)$ generated by Resource No 4. It is accepted that $\delta Z_2 = 0.05\%$ as a limit of $Z_2$ data generated by Resources No 4 and No 5.

The OS-resource No 5 has been used in an investigation of the objective function, $Z_2(Y_2, Y_1, Y_4, Y_5, Y_6, Y_7)$, related to GTP. Additional arguments ($Y_4, Y_5, Y_6, Y_7$) are connected with some modernization measures. The latter are associated with an increase in the efficiency of the basic thermal scheme and include:

1) an increase in a number of stages in the compression block, $Y_4$,
2) a usage of the air compression in front of an intercooling unit, $Y_5$,
3) a usage of a turbine unit number, $Y_6$, 4) an usage of a gas expansion degree, which is realized in front of the inter heat supply in the turbine block, $Y_7$.

A set of numerical data on the objective function, $Z_2(Y)$, is determined. For example, these data, $X = (Z_2, Y)$, are got at $Y_1 = 1200$ °C in the pressure interval $Y_2 = Y_{2\text{low}} - Y_{2\text{high}}$, these values let us find an optimal thermodynamic cycles of some upgraded PP with optimal characteristics:

1) $Z_{2\text{max}}(Y_{\text{opt}}) = 47.6 \%$, here $Y_{\text{opt}} = (Y_2 = 90, Y_3 = 1200$ °C, $Y_4 = 2, Y_5 = 2.0, Y_6 = 3, Y_7 = 1.75)$,
2) $Z_{2\text{max}}(Y_{\text{opt}}) = 53.1 \%$, here $Y_{\text{opt}} = (Y_2 = 100, Y_3 = 1700$ °C, $Y_4 = 2, Y_5 = 3.0, Y_6 = 3, Y_7 = 1.75)$.

In the last case, $Z_{2\text{max}}(Y_{\text{opt}}) = 53.1 \%$ can be considered as the global maximum, which is related to the objective function, $Z_2(Y)$, in the testing $Y$ conditions and belongs to the upgraded GTP.

To investigate the efficiency of a steam gas plant (SGP), we have created OS-resource No 6. It is based on the Mathcad program, $\text{Code-SGP}_1(Z, R, Y)$, here $Z$ represents the criteria of the combined cycle, $Y$ represents the border conditions related to the combined cycle. The OS-resource No 6 is adapted to SGP, which includes several components, among them: a) a gas turbine block, c) a compressor block, d) a recovery boiler, e) a steam turbine block. The combined cycle of SGP includes the Briton cycle. The resource deals with some criteria ($Z_b, Z_{10}, Z_{11}$), which are united in the following equation (criteria designations are given below)

$$Z_b = Z_{10} + Z_{11}. \quad (5)$$

Secondly, we have chosen criteria, which are related to the following equation

$$Z_{10} = \frac{Z_{13}}{Z_{15}} \left[ Z_{14} - Z_{16} \left( \frac{1}{Z_{14}Z_{15}} - 1 \right) \right], \quad Z_{11} = Z_{17}Z_{18}Z_{19} - \frac{Z_{11}Z_{20}}{Z_{17}Z_{19}Z_{20}}. \quad (6)$$

We have accepted the criteria designations in the form:

$Z_b$ - the internal COP of SGP,
$Z_{10}$ - the internal COP of GTP based on the Briton cycle,
$Z_{11} = l_k/l_q$ - a relation, which includes: a) the internal work, $l_k$, of the steam turbine plant based on the Rankine cycle to the real input heat, $q_1$, of SGP,
$Z_{12}$ - the internal COP of the compression process, which is related to the compressor block,
$Z_{13}$ - the internal COP of the expansion process, which is related to the gas turbine block,
$Z_{14}$ - a thermal COP of the gas turbine plant,
$Z_{15} = q_1/q_{l,q}$ - a relation, which includes: a) the real input heat, $q_1$, b) the ideal input heat, $q_{l,q}$, of SGP,
$Z_{16}$ - the relative compression work of the gas turbine plan.

Our analyses of (5), (6) shows that the criterion $Z_b$ can be improved by several methods. For example, the first path is associated: a) with an increase in criterion $Z_{10}$ and b) with an increase in criterion $Z_{11}$.

The OS-resource No 6 lets us do some Internet calculations including:

1) determination of thermodynamic properties, $R = (p, T, s \ldots)$, of the air at predetermined points of the combined cycle;
2) optimization, which is connected with an objective function, $Z_9(R,Y)$, and is associated with some modernization of SGP.

During optimization, $Y = (Y_2, Y_3, ...)$ parameters are varied in bright intervals including: a) $(1200 - 1700) \, ^\circ\text{C}$ for $Y_2$, b) $10 - 50$ for $Y_3$. We have chosen $Y$ conditions, which correspond to the basic scheme of SGP and follow to $Y_{PA} = (Y_2 = 1200 \, ^\circ\text{C}, Y_3 = 10)$. In the point, $Z_{2\,A}$ criterion follows to $Z_{2\,A} = 55.1 \%$. It is estimated: $Z_{2\,max} = 64.3 \%$ is related to border conditions $Y_{opt} = (Y_2 = 1200 \, ^\circ\text{C}, Y_3 = 29.2)$.

5. Conclusion
We have discussed some client functions, which are connected with thermodynamic properties of technologically important substances and based on innovative Internet technologies. These functions have a form of OS-resources (OS-resource No 2, OS-resource No 3, etc.) and can be effective software of GTP design. The resources complement significantly traditional Internet instruments, which is reflected, for example, in the classification [12].

The OS-resource No 5 has been used in Internet calculations, which let us determine: a) thermodynamic properties, $R = (p, T, s \ldots)$, of the air at predetermined points of the GTP cycle; b) criteria, $Z(Y)$, of GTP cycles. The objective function, $Z_2(Y)$, is investigated. A set of numerical data on $Z_2(Y)$ is got. These data let us find an optimal thermodynamic cycles of some upgraded PP.

The OS-resource No 6 let us investigate criteria, $Z(Y)$, related to SGP. Some optimization of SGP cycles is fulfilled. Numerical data on the objective function, $Z_9(Y)$ are dot and can be used in the modernization of SGP.

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