Development of Internet algorithms and some calculations of power plant COP

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Abstract. The authors have analyzed Internet resources containing information on some thermodynamic properties of technically important substances (the water, the air etc.). There are considered databases those possess such resources and are hosted in organizations (Joint Institute for High Temperatures (Russian Academy of Sciences), Standartinform (Russia), National Institute of Standards and Technology (USA), Institute for Thermal Physics (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 \( \rho \) – the density, \( s \) – the entropy, \( h \) – the enthalpy of a substance. It is known a small number of Internet resources those have the following characteristic. The resource allows a customer to realize a number of options, for example: i) to enter the input data, \( Y = (p, T) \), here \( p \) - the pressure, \( T \) – 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 (OI) Internet resource ("a client function", “template”). A computing part of OI 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 OI resource is based on Informatics and Internet technologies. We have proposed some methods and tools those are related to this part and let us: a) to post OI 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 OI – resources those 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 those are aimed to determine \( R \) 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 OI resources, among them OI 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 an information that relates to thermodynamic properties, \( R = (p,T,s, ... ) \), 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 included
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 \( Z = (Z_1, Z_2, Z_3 \text{ etc.}) \), here \( Z_1 \) - an electric coefficient of performance of PP (COP\(_e\)), \( Z_2 \) - an internal COP of PP cycle, \( Z_3 \) - a thermal COP\(_t\) of the cycle, \( Z_4 \) - a gas turbine job, \( Z_5 \) - an input heat of the cycle and other characteristics of the cycle. The client uses its own program or a soft were (SW), which is referred to as Code\(_1\)(Z,R,Y), here \( Y = (Y_i, i = 1 \ldots N) \) are set values including \((p_{in_1}, T_{in_1})\) those are the pressure and the temperature at the inlet of the first turbine, \( R = (ρ, T, v, h\ldots) \) are the thermodynamic properties of the working body at predetermined points of the cycle. SW 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 for Thermal Physics of the Siberian Branch of the RAS etc.). These sites contain resources those 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, \( R = (ρ, h, s\ldots) \), of a working substance (R134a, H\(_2\)O, etc.) at fixed arguments, \((ρ, T)\).

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 (OI) Internet resource (“a client function”).

2. Development of OI resources

The first phase of OI resource construction includes:

i) a Mathcad program development, for example, Code\(_2\)(ρ,Y) that allows us to calculate a value of \( ρ \) under boundary conditions, \( Y = (p, T) \), and with a help of tabulated R properties;

ii) an identification of a temperature range from - 50 to 400 °C (the first row of the array, Figure 1);

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

\[ M := \left( \begin{array}{cccc} 50 & 3.17 \times 10^{-1} & 4.13 \times 10^{-1} & 2.73 \times 10^{-1} \\ 100 & 6.34 \times 10^{-1} & 6.34 \times 10^{-1} & 6.34 \times 10^{-1} \\ 150 & 9.51 \times 10^{-1} & 9.51 \times 10^{-1} & 9.51 \times 10^{-1} \\ 200 & 1.268 & 1.268 & 1.268 \\ 300 & 1.586 & 1.586 & 1.586 \end{array} \right) \]

\[ p(\rho) := \left[ \begin{array}{c} 1 \times 10^{2} \\ 1.563 \\ 1.275 \\ 1.078 \\ 0.8226 \\ 0.6356 \\ 0.4057 \\ 0.3618 \\ 0.298 \\ 0.2537 \\ 0.1943 \\ 0.1603 \\ 0.1374 \end{array} \right] \]

Figure 1. Part 1 of Mathcad field connected with OI resource No. 1
iii) a development of a Mathcad function, csplain(X, Z), that let us perform a spline interpolation of points included in R array (Figure 1).

The array, \( R = (p, T) \), is inserted in this code (Figure 1). 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. The code let us realize a method of double spline interpolation of points included in R array. \( \text{Code}_2(p, Y) \) contains Mathcad function, \( \rho(p, T) \) (Fig. 1). The program provides: a) a choice of Y values, for example, \( Y = (p = 250 \text{ bar, } T = 175 ^\circ \text{C}) \), b) a choice of units, c) the formulas those are used for \( \rho \) calculations.

OI 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, \( \text{Code}_2(p, Y) \) and has a form of a Mathcad field. This field can be shown and seen in Figure 1.

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 a client with WEB site "Forum Mathcad", c) to implement for clients a number of interactive options. The resource can be named as \( \text{Res} – \text{Air}_2(R, U, (https://klm).key(def)), \) here \( R = p – \) the air variation that is calculated with the resource, \( U = (p, T) – \) input parameters, 2 – a number of \( \text{Code}_2(p, Y), (http://klm) – \) URL address, \( \text{def} – \) a password. For example, URL address can be written as \( http://twt.mpei.ac.ru/TTHB/ ; \) the password, \( \text{def}, \) 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.

OI 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 a textual information on the resource. These options run on the remote server (a cloud) and not on PC. An important role plays some tools those have been used in the process and related to Internet technologies (packages "Mathcad Calculation Server" and "Microsoft Expression Web 3" [7]). 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 \( \text{Code}_2(p, Y) \) and simply "insert" it in his own code; for example, he can include \( \text{Code}_2(p, Y) \) in his Code_1(Z,R,Y). As a result the client has got a modernized code named as \( \text{Code}_1.1(Z,R,Y) \). In this way the client uses an ordinary method that let him modify his program. \( \text{Code}_1.1(Z,R,Y) \) can automatically perform calculations of \( \rho \) values related to cycle points. A "copy option" is absent in known databases (JIHT RAS [2], STANDARTINFORM (Russia) etc.) those operate on closed programs (exe-files).

3. Some types of client functions

Since 2010, similar OI 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, \( \text{Res} – \text{Air}_2(R, U, (https://klm).key(def)), \) here \( (https://klm) – \) UR address, \( http://twt.mpei.ac.ru/TTHB/Ro-p-t.xmcdz. \) Firstly, this resource or OI resource No. 2 is elaborated in the following form: it is made to determine \( R = p \), to realize the program \( \text{Code}_2.1(p, Y) \) and to place 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 let a designer introduce URL address or "a link" in the form \( (http://twt.mpei.ac.ru/TTHB/Ro-p-t.xmcdz). \) Due the step, the designer gets in a contact with resource No. 2. There is a part of \( \text{Code}_1.1(Z,R,Y) \) that can be seen in Figure 2. One can see: a) \( Y = (p = 20 \text{ MPa, } T = 350 ^\circ \text{C}) \) are boundary conditions, b) \( \rho(p, T) = 103.016 \text{ kg m}^{-3} \) is the value calculated at these conditions, c) URL address is related to \( \text{Res} – \text{Air}_2.1(R, U, (https://klm).key(def)) \) and Mathcad function, \( \rho(p, T) \).
Thirdly, we remark an option, which is related to resource No. 2 and connected with Figure 2). It is seen there: 2D – graph is constructed on the base of a client function ρ(p,T) with fixed values of Y = (0.1, 5.0, 10, 20, 30) MPa. It explains a common term “a live table” that can be used for this graph and realized due to packages (“Mathcad Calculation Server”, "Microsoft Expression Web 3”).

Fourthly, the designer can use an option “to run ρ calculation” that let him determine ρ 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 ρ on a remote server with a help of "client function”, ρ(p,T), c) returning ρ value to PC.

Let us consider another variant of OI 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 ρ(p,T) is known as Res – Air_2.1(R, U,(https:\/\slash klm),key(def)) and available on the remote server. OI resource No. 3 let a client represent the properties, R = (p,T) including:
1) the pressure, p, at a density given and a temperature given,
2) the temperature, T, at a density given and a pressure given. Figure 3 shows a Mathcad – field related to resource No. 3.

It can be seen:
1) an operator ”Function” related to ρ(p,T) and Res – Air_2.1(R, U,(https:\/\slash klm),key(def)),
2) built-in Mathcad functions (root(ρ(p,T) – ρ,p), p(ρ,T)), which allows to calculate an inverse function, ρ(p,t), using the method of half division (position 1),
3) a Mathcad – function, t(ρ,p), that computes a parameter, T, using the secants method (position 2).

The authors together with specialists from the national research University "MPEI" and JIHT RAS have created a group of OI resources [8] those describe R properties of working fluids including air and H2O. There are some OI resources with approximation methods those complement spline – schemes mentioned. We have adapted a least squares method allowing to build polynomials, for example, p(T) function for the density on the saturation line for some selected substances. We have produced OI resources associated with R properties of the water using the equation of state and auxiliary formulas those contain near 100 coefficients. These client functions are approved by the International association for properties of the water and the steam (IAPWS) (http://www.iapws.org).
One more type of OI resources has been developed in the form of a complex client function that is focused on sharing:

i) a software code elaborated for PP design or PP modernization,

ii) client functions those can calculate R properties of the working body.

Some schematics are selected in the study; they 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).

We have created several complex OI resources, for example, OI resource No. 4. It is based on the program, Code - GTP_1(Z,R,Y), here GTU_1 – the name of a variant of PP that includes: a) several gas turbine units and compressor units, c) other blocs (Figure 4, b), Y = (Yₜ) – border conditions including Y₁ = 0.101 MPa – an inlet pressure of the compression bloc, Y₂ = pₚₜ₁/Y₁ – a pressure ratio in the compressor bloc, Y₃ – an inlet temperature of the the turbine bloc. It is elaborated to calculate Z criteria of a complex PP. These characteristics include Z₁ – an electric COPₑ of PP, Z₂ - an internal COP of the complex cycle, Z₃ - a thermal COPₑ of the cycle, Z₄ – a specific internal real work of the gas turbine bloc, Z₅ – a specific ideal work of an isentropic expansion in the gas turbine bloc, Z₆ - a specific ideal work of an isentropic compression in the compressor bloc. Resource No. 4 or Res - GTP_1(Z,R,U) operates with some formula, which are applied to determine R properties and Z criteria of PP. Here U – input parameters, U₁ and U₂ – p and T of the working fluid at a fixed point of PP cycle, U₃ - a relative internal COPₑ of the gas turbine bloc, U₄ - a relative internal COPₑ of the compressor bloc etc. The resource uses Z₂ criterion written in the following form [6]

\[ Z_2 = \frac{Z_4}{Z_5} \]  \hspace{1cm} (1)

Z₂ criterion is represented in the following form [6]

\[ Z_2 = Z_6 \cdot U_3 - \frac{Z_7}{U_4} \]  \hspace{1cm} (2)

We have involved Z₈ as an input heat of an ideal GTP cycle and a relation, f₁ = Z₅ / Z₈. It let us rewrite (1) in the following form

\[ Z_1 = \frac{Z_4 \cdot U_1 - Z_7}{f_1 \cdot Z_8} \]  \hspace{1cm} (3)
$Z_3$ criterion can be expressed as $Z_3 = \frac{(Z_6 - Z_7)}{Z_8}$. We have involved $f_2$ as a relation, $f_2 = Z_7/Z_8$. It let us rewrite (3) in the following form

$$Z_2 = \frac{Z_6}{f_1} \left[ Z_3 - f_2 \left( \frac{1}{Z_6} - Z_7 \right) \right]. \quad (4)$$

Res - OI – GTU_1(Z, R, U, (http://klm), key(def)) is placed on the remote server [8]. The resource let a client to determine $Z$ criteria of the cycle using (1-4).

At the calculating procedure, the client also determines R properties of the working body at predetermined points of the complex cycle (there are 12 fixed points, 3 gas turbines, 3 compressors etc., Figure 4, b). There are some client functions those are inserted in this resource and developed to describe R properties of the air [8,9]; for example, it is Res – Air_2.3(R, U,(https:\/\!/klm),key(def)) that is elaborated to determine $K = h$ or the enthalpy at arguments $U = (p,T)$ . This is one more variant of OI resource that is developed using tabulated R data of the air [10] at $T = 500... 2000$ K and at the pressures up to 10 MPa. The resource is placed on a remote server [8]. It allows a client to calculate this property in the range $T = 500... 2000$ K and at pressures up to 5 MPa.

Figure 4. A Mathcad field that of OI resource No. 4 (a) and a thermal scheme of a complex PP (b)

During these calculations, program. Code - GTP_1(Z,R,Y), let a client to use Y conditions including $Y_1$ – a number of stages in the compression bloc, $Y_3$ - the degree of an air compression in front of an intercooling unit, $Y_6$ – a number of turbine units, $Y_7$ - the degree of a gas expansion in front of the interim heat supply in a separate turbine unit etc. It can be seen a Mathcad field in Figure 4 (a) that is a part OI resource No. 4 and includes some boundary conditions ($Y_1 = 0.101$ MPa – an inlet pressure of the compression bloc, $Y_2 = 30$, $Y_3 = 1050$ °C – an inlet temperature of the the turbine bloc, etc.) and some input data ($U_3 = 88.4 \%$, $U_4 = 85.0 \%$ etc.).
Figure 5. The objective function, $Z_2(Y)$, on some isolines ($Y_3 = (1200 - 1700) \, ^oC$)

*Code - GTP_1(Z,R,Y)* has been used in Internet calculations including:
1) a determination of thermodynamic properties, $R = (p, T, s \ldots)$, of the air at predetermined points of the PP cycle; $Y$ conditions are realized in the calculation,
2) a determination of energy criteria, $Z(Y)$, for PP at $Y$ conditions,
3) an optimization procedure that is connected with an objective function, $Z(Y)$, and has a purpose of some modernizing PP equipment.

It can be seen some results, $X = (Z, Y)$, in Figure 5. They are connected with optimization calculations and describe the objective function, $Z_2(Y)$. In the case of calculations, this function has two arguments, $Z_2 (Y_2, Y_3)$ and is represented (Figure 5) on some isolines at $Y$ conditions including: $Y_2 = (1200 - 1700) \, ^oC, \, Y_3 = 10 - 100)$. 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 $Y_{3\text{opt}}$ - optimal $Y$ values. It can be seen a cycle with $Z_{2\text{max}}(Y_{2\text{opt}} = 29, \, Y_{3\text{opt}} = 1200 \, ^oC) = 38.6 \%$. This PP variant is considered as a reference cycle that is characterized by $R_{\text{opt}}$ or optimal $R$ properties in predominate points. This cycle has a primitive thermal schema and uses such conditions as $Y_2 = 29, \, Y_3 = 1200 \, ^oC, \, Y_4 = 1, \, Y_5 = 1, \, Y_6 = 1, \, Y_7 = 1$.

Our numerical information (Figure 5) let us conclude that an efficiency of the reference cycle can be improved if we involve such events of a modernization as:
1) an increase of the pressure ratio of the compressor, $Y_2 = \text{var}$,
2) an increase of the inlet temperature of the the turbine bloc, $Y_3 = \text{var}$.

We have determined some effects, $\Delta Z_2(Y_2, Y_3)$ those are associated with a 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 ($Y_2 = 10 - 100), \, Y_3 = (1200 - 1700) \, ^oC$). A shift, $\Delta Z_2(Y_2, Y_3) = Z_{2\text{M}} - Z_{2\text{R}} = 7.7 \%$, is calculated too, here $Z_{2\text{M}}$ - a criterion related to a modified scheme, $Z_{2\text{R}}$ - a criterion related to the reference scheme. The effect can be realized if a client uses the increases ($\Delta Y_2 = Y_2 - Y_{2\text{R}} = 43, \, \Delta Y_3 = Y_3 - Y_{3\text{R}} = 700 \, ^oC$) 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. It is formed Resource No. 5, which differs from Res - OI - GTU_2(Z, R, U, (http://klm.key(def)); this difference is connected with a method that is used to determine R properties of the air. For example, we have done Res - Air_2.4(R, U,(https://klm.key(def)) that is elaborated to determine $R = h$ of the air. The client function is built using an equation of state for the air [11] at $T = 500 - 2000$ K and at pressures up to 5 MPa. Resource No. 5 has been used in optimization calculations. We have got the results, $X = (Z_2,Y)$, those are familiar to data placed in Figure 5. Our comparison let us conclude that values of $Z_{2\text{max}}(Y)$ (Figure 5) are placed lower on $\delta Z_2 = (0.02 - 0.05)\%$ than $Z_{2\text{max}}(Y)$ generated by Resource No. 4. We have accepted $\delta Z_2 = 0.05\%$ as a limit of $Z_2$ data generated by Resources No.4 and No. 5.

**Code - GTP_1(Z,R,Y)** has been used in an investigation of the objective function, $Z_2(Y_2, Y_3, Y_4, Y_5, Y_6, Y_7)$. Additional arguments ($Y_4, Y_5, Y_6, Y_7$) are connected with measures those are related to a modernization of the reference cycle and include:

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

A set of numerical data on the objective function, $Z_2(Y)$, is elaborated along isolines. The data, $X = (Z_2,Y)$, let us find an optimal thermodynamic cycles of some upgraded PP, for example:

i) $PP$ cycle that are characterized with the maximum values, $Z_{2\text{max}}(Y_{\text{opt}}) = 47.6\%$, here $Y_{\text{opt}} = (Y_2 = 90,
Y_3 = 1200 \degree C, Y_4 = 2, Y_5 = 2.0, Y_6 = 3, Y_7 = 1.75)$,

ii) $PP$ cycle that are characterized with the maximum values, $Z_{2\text{max}}(Y_{\text{opt}}) = 53.1\%$, here $Y_{\text{opt}} = (Y_2 = 100,
Y_3 = 1700 \degree C, Y_4 = 2, Y_5 = 3.0, Y_6 = 3, Y_7 = 1.75)$; this value of $Z_{2\text{max}}$ can be considered as the global maximum in testing $Y$ intervals.

## 4. Conclusion

We have discussed some client functions and templates those are connected with thermodynamic properties of technologically important substances and based on innovative Internet technologies. These functions have a form of OI resources (OI resource No. 2, OI resource No. 3 etc.) and can be an effective software for PP design. The resources complements significantly traditional forms of Internet information that is reflected, for example, in the classification [12].

OI resource No. 4 has been used in Internet calculations those let us determine: a) thermodynamic properties, $R = (p, T, s \ldots)$, of the air at predetermined points of the PP cycle; b) criteria, $Z(Y)$, of PP 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.

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