Analysis And Solving The Problem Of Synthesis Of An Automatic Control System For A Tube Furnace

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Abstract

It is known that the oil refining industry is considered one of the leading sectors of the national economy. The primary oil refining units is the main technological complexes of this industry. The purpose of these facilities is to ensure the production of a wide range of high quality petroleum products from crude oil. The requirements for quality indicators of various petroleum products produced at these technological facilities require the creation of more modern and advanced control systems.

Tube furnaces are one of the main technological devices in technological complexes of primary oil refining. The fulfillment of the given criterion of solving the issues of controlimg technological objects directly depends on the performance of control systems at the local level. From this point of view temperature control in tube furnaces is a topical issue.

In order for automatic control systems (ACS) to work properly, they must first of all be stable. It must have such properties that the dynamic processes emerging in the system as a result of any non-zero initial conditions can gradually pass into a stationary state. After providing the sustainability requirements, the systems must meet the quality requirements; which is determined by a number of indicators characterizing the dynamic regime. In other words, the dynamic characteristics of the ACS should be investigated. To solve the problem, the issue of optimal tuning of controllers that are part of automatic control systems is considered, the stability of control systems is established and the parameters of the quality of trancient response of ACS is determined.

İn this paper the dynamic characteristics of the control object has been studied without disturbing the normal operating modes of the technological unit in order to find the quality parameters of the ACS

Keywords: tube furnae, transfer function, controller, control system, dynamic characteristics, response

1. Introduction

Tube furnaces are known to be used in refinery processes to heat crude oil to the desired temperature. This is major technological device of the technological complex of primary oil refining. The main purpose of the controller used here is to maintain a constant temperature of the raw material at the outlet of the tube furnace at the given set points [1, 2]. The control of this temperature is carried out due to the consumption of liquid fuel supplied to the furnace.

Control of this device involves a number of issues [3, 4], These problems include:

1. Complexity of tube furnace in term of control object;
2. Wide variation in both quantity and quality of raw materials used;
3. The presence of a large number of controllable and uncontrollable disturbance factors influencing the technological process;
4. Observation of non-stationarity in static and dynamic characteristics of processes;
5. The presence of a high measurement error of some parameters in the process, and sometimes the lack of operational measurement methods.

It should be noted that the development of new control systems that adequately respond to changing external and internal disturbing factors in the control of this complex technological equipment remains one of the problematic issues of control theory.

As a rule, in all tube furnaces used in the primary oil refinery unit single- and cascade connected control systems are applied in order to control output temperatures. In our opinion, in each of the tube furnaces, regulation schemes could be applied, which would be more effective in terms of providing better quality stabilization of regulated parameters and saving fuel consumption.

The efficiency of the tube furnace is to ensure optimal heat using released during combustion of fuel. In previous studies, the absence of the use of a gas-air ratio control system in tube furnaces leads to a decrease in the accuracy of fuel temperature control and incomplete combustion of the fuel gas. This eventually reduces the efficiency of the furnaces. Taking into account all these results and problems, in this paper solves the issue of synthesis providing optimal control of the tube furnace control system and its operation in safe conditions [5, 6].

2. Material and methods

During operation of the automatic control system it is necessary to reduce the accuracy in order to obtain a high level of stability, or it is necessary to reduce the level of stability of the system in order to ensure high accuracy. Which indicator to prefer will depend on the characteristics of the system and the technological requirements for the regulation process.

The quality indicators of the automatic control system in dynamic modes depend on the characteristics of the control object. For this reason, in order to develop control systems with sufficient stability, reliability and high quality indicators, it is necessary first of all to study the dynamic characteristics of the automatic control object. Static and dynamic characteristics are studied both experimentally and analytically, depending on the characteristics of the object under study. However, to assess the dynamic characteristics of control objects, active experiments are carried out with open states of control circuits, which is generally not allowed in many technological installations, especially in explosive and fire hazardous installations. If the physical and chemical processes occurring in the objects of regulation are studied in advance with sufficient completeness and high accuracy, then the analytical method is more widely used to compile static and dynamic characteristics. Otherwise, it is necessary to use experimental methods for studying the characteristics of regulated objects. Taking into account all this, in the paper a methodology is given for solving the above issues without interfering the normal operating modes of control systems.

2. 1. The determination of the system transfer function

To solve the synthesis problem, first of all, the transfer function is determined based on the step response. The transfer function defines the relation between the output and the input of a dynamic system. The step response is shown in **Fig. 1.** Here, in order to adjust the temperature it is necessary to change the fuel consumption, that is, to change the movement of the actuator. On the commissioning curve, the distance of the actuator is Δx=5%, and the temperature change corresponding to this distance is 530-540°C (7.5%). There are various methods for calculating the transfer function. To calculate the transfer function in this paper the Simoyu method was used. The input and output variables of the object were observed by performing an active experiment. A stepped control action was applied and a recording was made of the resulting output data, which was in the form of a transient response.

In this method, the calculation is performed in the following sequence [6, 7].

1. The time characteristic is divided into intervals with $\Delta t = 1$min;
2. Let us write down the ratio of the values $\Delta y(t)$ and Δy_{max} corresponding to the intervals Δt;
3. The fields are determined by performing appropriate calculations.

Field F1 is defined as follows:

$$F_1 = \Delta t \left\{ \sum_{i=1}^{n} [1 - y(i\Delta t)] - 0.5[1 - y(0)] \right\}. \qquad (1)$$

Then [1-y(t)] is established in a different timeline. Therefore, the variable θ implies.

$$\sum_{i=1}^{n} [1 - y(i\Delta\theta)][1 - i\Delta\theta], \qquad (2)$$

$$\sum_{i=1}^{n} [1 - y(i\Delta\theta)][1 - 2i\Delta\theta + \frac{(i\Delta\theta)^2}{2}]. \qquad (3)$$

Then the F2 and F3 fields are calculated:

$$F_2 = F_1^2 \cdot \Delta\theta \left\{ \sum_{i=1}^{n} [1 - y(i\Delta\theta)][1 - i\Delta\theta] - 0.5[1 - y(0)] \right\}, \qquad (4)$$

$$F_3 = F_1^3 \cdot \Delta\theta \left\{ \sum_{i=1}^{n} [1 - y(i\Delta\theta)][1 - 2i\Delta\theta + \frac{(i\Delta\theta)^2}{2}] - 0.5[1 - y(0)] \right\}, \qquad (5)$$

The results are shown in **Table 1**.

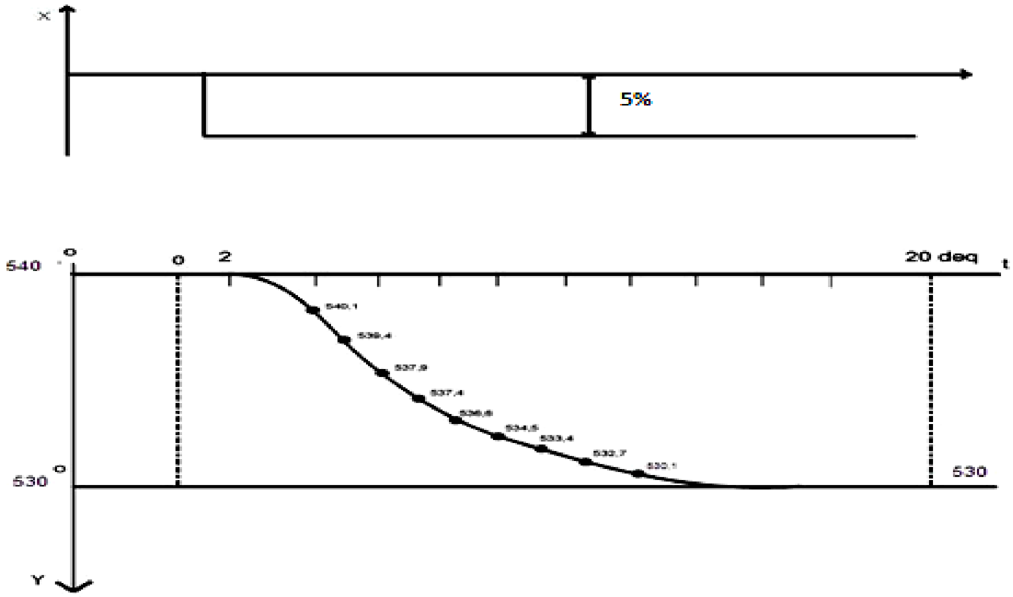

Fig. 1. Step response

Table 1 The calculation results of transfer function

y(t)	1-y(t)	Tet	1-tet	(1-tet)*(1-y)	1-2tet+tet^2/2
0	1	0	1	1	1
0,07244	0,92756	0,13012	0,86988	0,806866211	0,748225607
0,209825	0,790175	0,26024	0,73976	0,58453975	0,513382429
0,302248	0,697752	0,39036	0,60964	0,425377452	0,295470465
0,398002	0,601998	0,52048	0,47952	0,288670241	0,094489715
0,438801	0,561199	0,6506	0,3494	0,196082931	-0,08955982
0,485429	0,514571	0,78072	0,21928	0,112835171	-0,256678141
0,555371	0,444629	0,91084	0,08916	0,039643164	-0,406865247
0,601166	0,398834	1,04096	-0,04096	-0,01633625	-0,540121139
0,669442	0,330558	1,17108	-0,17108	-0,05655184	-0,656445817
0,706078	0,293922	1,3012	-0,3012	-0,08852923	-0,75583928
0,773522	0,226478	1,56144	-0,56144	-0,12715377	-0,903832563
0,815154	0,184846	1,69156	-0,69156	-0,12783207	-0,952432383
0,86761	0,13239	1,82168	-0,82168	-0,10878195	-0,984100989
0,905079	0,094921	2,08192	-1,08192	-0,10269682	-0,996644557
0,947544	0,052456	2,47228	-1,47228	-0,07723034	-0,888475801
0,960033	0,039967	2,6024	-1,6024	-0,06404263	-0,81855712
0,975853	0,024147	2,73252	-1,73252	-0,04183437	-0,731707225
0,994172	0,005828	3,12288	-2,12288	-0,01237316	-0,369570253
1	0	3,253	-2,253	0	-0,2149955

If any of the fields is negative then the transfer function will be in the form:

$$W(p) = \frac{b_1 p + 1}{a_3 p^3 + a_2 p^2 + a_1 p + 1} \tag{6}$$

or

$$W(p) = \frac{b_1 p + 1}{a_2 p^2 + a_1 p + 1}. \tag{7}$$

If all fields are positive, then the transfer function will be as follows:

$$W(p) = \frac{1}{a_3 p^3 + a_2 p^2 + a_1 p + 1}. \tag{8}$$

Here we can write a transfer function, given the calculated values a1=F1, a2=F2, a3=F3:

$$W(p)=\frac{k}{1.47p^3+0.47p^2+4.72p+1}. \qquad (9)$$

The next step is to convert the transfer function from a dimensionless form to a dimension form:

$$W_0(p)=K_{ob}W(p). \qquad (10)$$

In this formula

$$K_{ob}=\frac{\Delta y_{\max}}{\Delta x}=\frac{7.5}{5}=1.5,$$

then $W_{ob}(p)$ takes the following form:

$$W(p)=\frac{1.5}{1.47p^3+0.47p^2+4.72p+1}. \qquad (11)$$

2. 2. Investıgatıon of the stabılıty of the automatıc control system

A steady-state analysis in control systems is an exploration of behavior of transfer function after entire system has stabilized in defined manner. The stability of a system is its response to inputs or disturbance factors. A system which remains in a previous state after the discontinuing of the influences of the of an external action [8, 9].

We used the Nyquist criterion to study the stability of ACS. This criterion makes it possible to express the stability of a closed loop based on the amplitude-phase frecuency of an open loop . For the stability of a closed loop, the following condition must be met:

- If the system is stable in the open state, then the closed system will be stable if W(jw) does not cover the critical point (-1,j0) of the hodograph of the amplitude-phase-frequency responce.

Using the transfer function it is possible to creat the frequency response of the object by the Matlab program .

The algorithms of the operations performed by Matlab are shown below.

Extended amplitude-frequency characteristic of the object:

```
Trial>> w=0:0.01:3;
m=0.241;
W=1./(1.47.*(j-m).*w.^3+0.47.*(j-
m).*w.^2+4.72.*(j-m).*w+1);
Agen=abs(W);
plot(w,Agen);grid
```

The extended amplitude-frequency response is shown in **Fig. 2.**

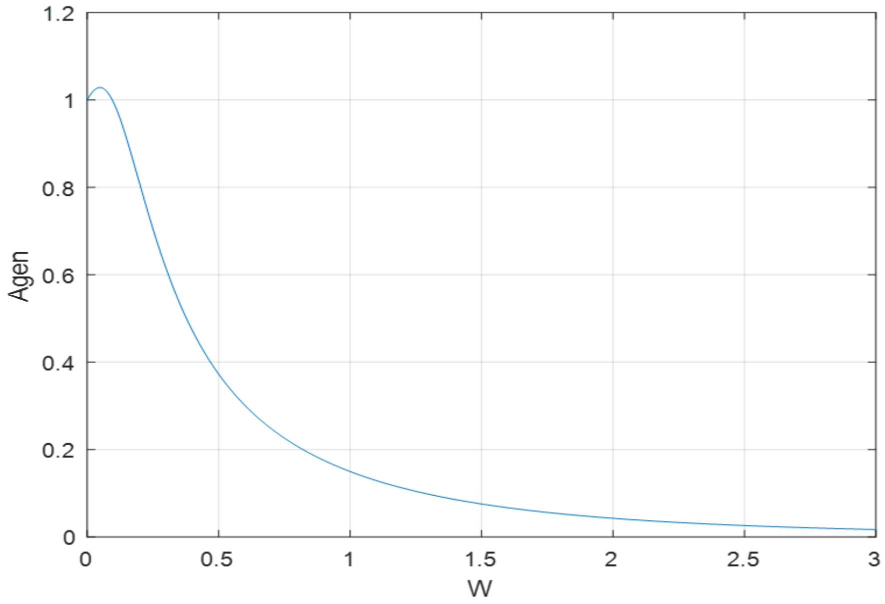

Fig. 2. The extended amplitude-frequency response

Extended phase-frequency characteristic of the object:

```
Trial>> w=0:0.01:3;
m=0.241;
W=1./(1.47.*(j-m).*w.^3+0.47.*(j-
m).*w.^2+4.72.*(j-m).*w+1);
F=angle(W);
plot(w,F);grid
```

The extended phase-frequency response is shown in **Fig. 3**.

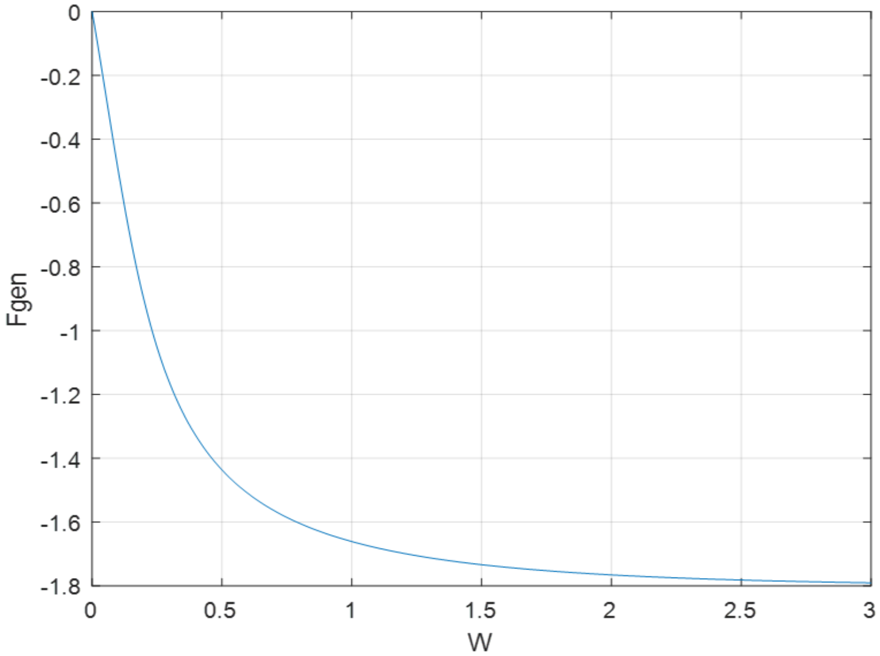

Fig. 3. The extended phase-frequency response

Amplitude-phase-frequency characteristic of the object:

```
Trial>> w=0:0.01:3;
m=0.241;
W=1./(1.47.*(j-m).*w.^3+0.47.*(j-
m).*w.^2+4.72.*(j-m).*w+1);
F=angle(W);
plot(w,F);grid
w=0:0.01:3;
m=0.241;
W=1./(1.47.*j.*w.^3+0.47.*j.*w.^2+4.72.*j.*w+1);
U=real(W);
V=imag(W);
plot(U,V);grid
```

The amplitude-phase-frequency responce is shown in **Fig. 4**.

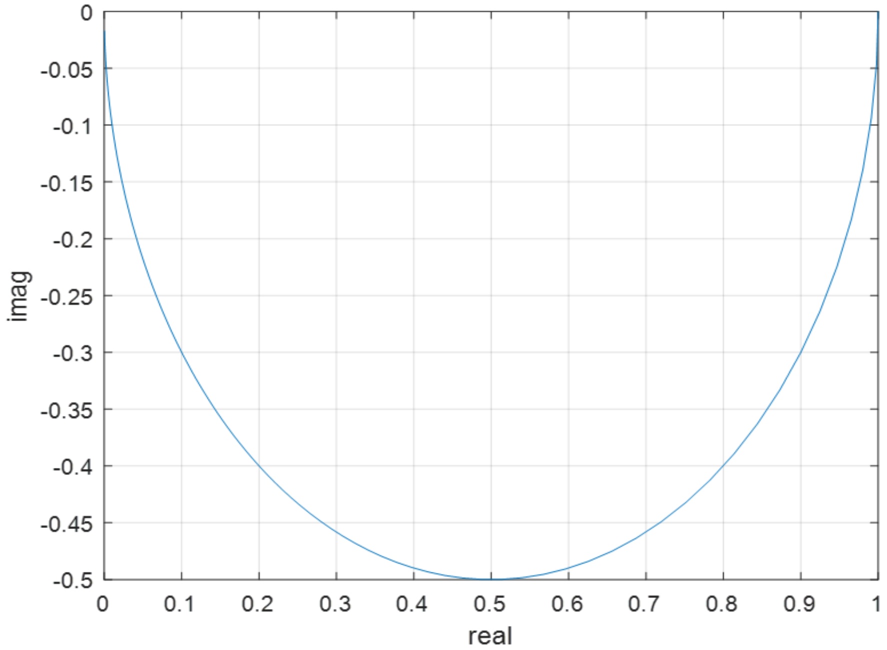

Fig. 4. Amplitude-phase-frequency response

2. 3. Determine optimum controller settings

The adjustment of the controller parameters to achieve satisfactory control is called tuning. The selection of the controller parameters is essentially an optimization problem in which the designer of the control system attempts to satisfy some criterion of optimality, the result of which is often referred to as "good" control. The process of tuning can vary to find suitable control parameters for "good" control to an elaborate optimization calculation based on a model of the process and a specific criterion of optimal control [10, 11].

Algorithm of the optimal tuning parameters of the PI controller is as follows:

```
Trial>> w=0:0.01:0.8;
m=0.241;
W=1.5./(0.47*((j-m).*w).^3+1.47*((j-
m).*w).^2+4.72*((j-m).*w)+1);
Win=1./W;
R=real(Win);
J=imag(Win);
C0=w*(m^2+1).*J;
C1=m.*J-R;
plot(C1,C0);grid
```

The optimal tuning parameters of the PI controller are shown in **Fig. 5**.

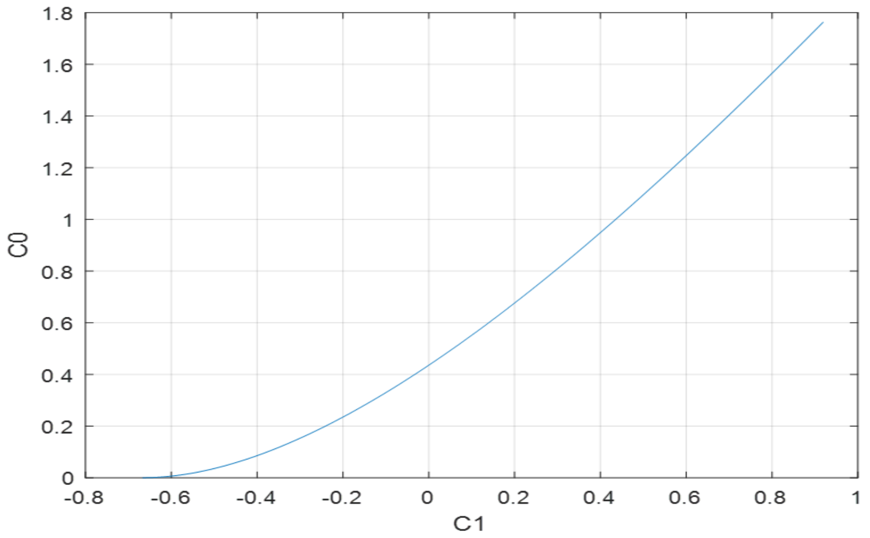

Fig. 5. The optimal tuning parameters of the PI controller

2. 4. Building of transient response

After applying input to the control system, output takes certain time to reach steady state. So, the output will be in transient state till it goes to a steady state. Therefore, the response of the control system during the transient state is known as transient response.
Algorithm of obtaining a transition response is as follows:

```
Trial>> Wten=tf([1.5],[0.47 1.47 4.72 1]);
Wten=tf([0.1 0.5],[1 0]);
Wob=tf([1.5],[0.47 1.47 4.72 1]);
W1=series(Wten,Wob);
Fi=feedback(W1,1);
step(Fi);grid
```

3. Reaseach results

Recently, two ways are usually chosen to eliminate the harmful effect of the non-stationarity of the dynamic characteristics of objects on the performance of the ACS.

The first way is the adding of self-regulating periods into the existing control system. This way leads to the complication of the structure of the control system, which reduces its reliability and in many cases does not justify itself from an economic point of view.

The second method involves periodic adjustment of the system without making any complex changes to the structure of the system. However, this method requires prompt and safe assessment of the dynamic characteristics of objects without disturbing the normal operation of technological objects.

Therefore, using second method of ACS should be considered as more suitable.

First of all, it is considered to obtain the transfer function on the control and disturbance influence channels of the control object. Then the issue of ACS synthesis is solved. For the synthesis of ACS, it is necessary to carry out the following operations consecutively [12]:

- the tuning parameters of the connected regulator are changed;
- the transfer function of the closed loop is calculated based on the transition process;
- based on the transfer function of the control system, the transfer function of the controlled object is calculated;
- using of one of the appropriate methods, the optimal values of the control parameters of the regulator that meet the required quality indicators are calculated;
- other quality indicators of the control system are determined.

The transfer function of the controller:

$$W(p)=\frac{k}{1.47p^{3}+0.47p^{2}+4.72p+1}.$$

The transfer function of the control object:

$$W(p)=\frac{1.5}{1.47p^{3}+0.47p^{2}+4.72p+1}.$$

Determination of the Nyquist stability criterion:

```
Trial>> W=tf([1],[4.72 0.47 1.47 1])
W =
1
--------------------------------
4.72 s^3 + 0.47 s^2 + 1.47 s + 1
Continuous-time transfer function.
Trial>>nyquist(W)
```

Nyquist diagram is shown in **Fig. 6**.

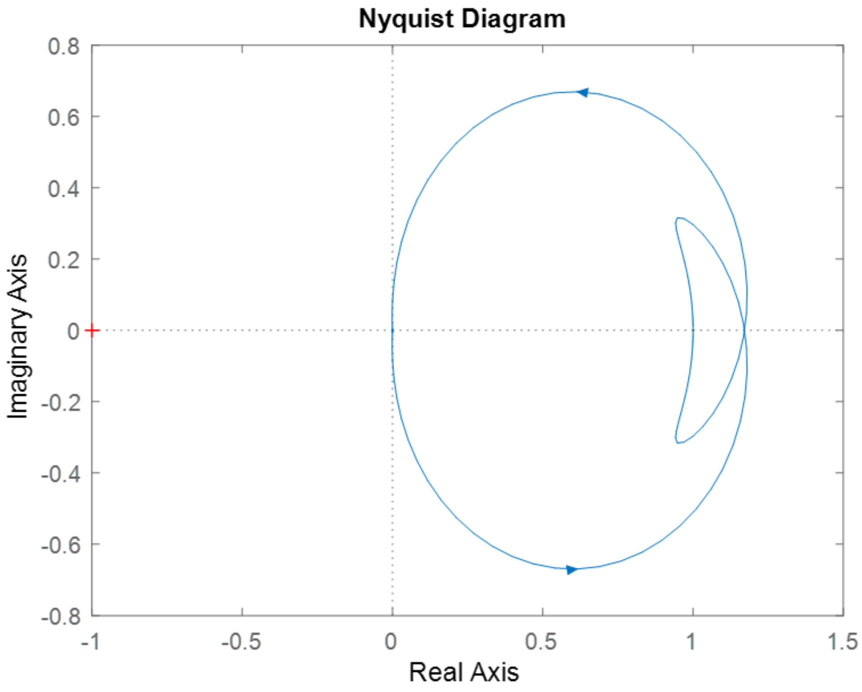

Fig. 6. Nyquist diagram

By changing, $\omega = 0 \div \infty$ we calculate the values of Rea(w) Ima(w) based on the program and build the amplitude-phase-frequency responce of the open loop (**Fig. 4**). As can be seen from the figure, the godograph does not cover the point (-1,j0). It can be concluded from here that the closed system itself is stable since the godograph of the amplitude-phase frequency response of the open loop does not cover the critical point (-1,j0).

The values of the tuning parameters of the PI controller are calculated as follows:
C1=0.1 isodrome time of the controller;
C0=0,5 gain coefficient of the controller.

The optimal tuning parameters of the PI controller are shown in **Fig. 5**.

The transient state response of control system gives a clear description of how the system functions during transient state. Based on the transition response, we determine the following quality indicators:
Overshoot - 35%
Rise time - 7.91

The degree of damping - 0.24
Static error – 0

The transition response is shown in **Fig. 7**.

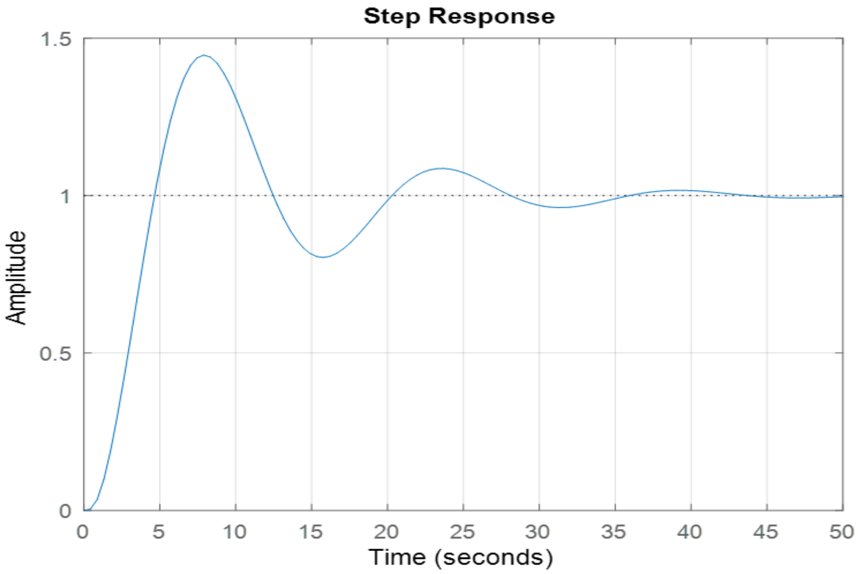

Fig. 7. The transition response

4. Conclusions

In the presented article, the tube furnace, which is the main technological device of the primary oil refining unit, has been studied as a control object. Due to the non-stationarity of the dynamic characteristics of this control object, the necessity of periodic and operational assessment and adjustment of control systems is substantiated. The evaluation of dynamic model of the tube furnace of a technological facility and the operational synthesis of automatic control system are solved. İt involves calculation of transfer function of the controller and control object, determination of stability of the control system, calculation optimal values of tuning parameters of control system, building of transient response and determination quality indicators of the transient response.

The conducted studies have made it possible to improve the reliability, stability and performance of automatic control system used at a fire hazardous facility, such as a tube furnace operating under external disturbing influences.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

- manuscript has no associated data

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