About Fuzzy Management of the Safety of the Process of Oxidative Pyrolysis

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Abstract. The process of oxidative pyrolysis of natural gas in the production of acetylene is characterized by a complex flow, a large number of internal and external factors. These factors influence the process of oxidative pyrolysis of natural gas often in an unpredictable manner, which makes it difficult to assess its states and generates many control problems whose solution is aimed at compensating for the influence of random causes of abnormal situations. The main task of the system of effective diagnostics and ensuring the technological safety of this process is the timely detection of violations that lead to extraordinary situations with a view to preventing them. The paper proposes an approach to controlling the process of oxidative pyrolysis based on the application of the fuzzy-logic approach. The fuzzy-logical approach is defined as one of the directions of artificial intelligence. This circumstance contributes to improving the quality of the decisions made, and, accordingly, the quality of the management system of the process under consideration. The control object taking into account the features of this process is the sequence of the initial components connected in the preheater and the oxidative pyrolysis reactor. The control system is designed to provide the required composition of the pyrolysis gas at the outlet from the reactor provided, that the technological safety of the process is ensured. The paper proposes a variant that includes two levels of control: at the lower level, local regulation of process parameters is carried out; at the upper level, regulation is carried out with the calculation of tasks for local circuits using a fuzzy regulator. Such regulation is designed to ensure technological safety of the process. Depending on the values of the parameters that determine the safety of the process, control actions are calculated: the costs or ratios of the costs of natural gas, oxygen and water to "hardening" the pyrolysis gas.

1. Introduction

The production of acetylene by the oxidative pyrolysis of natural gas belongs to the group of organic synthesis productions, which are characterized by increased explosion hazard and fire hazard [1], and therefore it is especially important to ensure its safe conduct. The process under consideration is unpredictably affected by a large number of both external and internal factors, which makes it difficult to directly control the acetylene concentration as the resultant product of the oxidative pyrolysis reaction.

The process of production of acetylene by oxidative pyrolysis of natural gas takes place in conditions of incompleteness and uncertainty of information. These conditions arise due to: changes in the characteristics of the equipment during its operation (the "coking" of a number of elements), the inconstancy in the time of the composition of the feedstock for the reaction (natural gas and oxygen), the short residence time of the reaction mixture in the reaction zone, etc. At the same time, the effectiveness of this process depends to a large extent on compliance with the requirements for ensuring the safety and uninterrupty of chemical-technological processes (CTP). Therefore, there is a need to develop new approaches to the diagnosis of conditions and the effective management of the safety of the oxidative pyrolysis process.

In connection with the above, it is required to ensure the maximum possible amount of acetylene produced (the resulting product) by stabilizing the main technological parameters in the field of technological safety. This will lead to a rational use of the starting materials for the process of oxidative pyrolysis. In the course of implementation of these objectives, a process control system should be developed that provides the best quality control indicators for the process of oxidative pyrolysis in conditions of ensuring its technological safety.

2. Technological process of oxidative pyrolysis

In the production of acetylene by oxidative pyrolysis of natural gas, natural gas and oxygen are used, which, after preheating in the preheater, enter the oxidative pyrolysis reactor. The reactor consists of a mixer, a burner block, a reaction zone and a "hardening" zone (figure 1).

In the mixing zone (in mixer) there is a physical mixing of the jets of the initial components for oxidative pyrolysis in order to obtain a methane-oxygen mixture. In the reaction zone, the methane-oxygen mixture is ignited, resulting in the decomposition of methane during its combustion (oxidative pyrolysis) to produce a large amount of by-products. The high temperature in the reactor (1400−1500 ^{o}C), necessary for the decomposition of methane with the formation of acetylene, is achieved as a result of combustion of a part of natural gas [1, 2]. Acetylene at the reaction temperature is an unstable compound, therefore rapid cooling (hardening) of the reaction products with water is required in order to prevent decomposition of the formed acetylene on hydrogen and carbon (carbon black) and cooling the resulting pyrolysis gas to 60−80 ^{o}C.

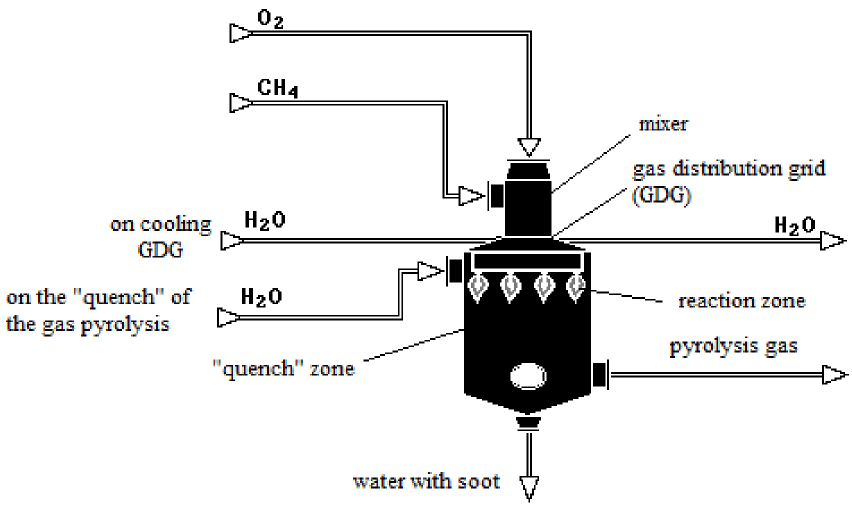


Figure 1. The oxidizing pyrolysis reactor.

For each stage of oxidative pyrolysis, a mathematical description is compiled, including the equations of material and thermal balances [2]. As a result of simulation modeling using the Simulink system of the MatLab package, it has been established that the amount of acetylene in the pyrolysis gas is affected by the preheating temperature of the initial components for the reaction, and the ratio of their costs.

From the analysis of the obtained data it follows that for the control system (CS) the process most important are the consumption of natural gas on the heater burner, the costs and temperatures of methane and oxygen at the reactor inlet, the water consumption for "quenching" the pyrolysis gas. It has been established that the parameters of the output process flow can be controlled. The parameters are controlled only by changing the values of the input process parameters. The main task of the CS in this case is to ensure the required composition of the pyrolysis gas at the outlet from the reactor, provided that the technological safety of the process is ensured. The perturbing effects in this case are:

- change in the ratio of methane and oxygen consumption on the reaction due to the variability of the composition of natural gas supplied to the reaction of oxidative pyrolysis;
- "coking" (plugging of the soot) of internal elements of the reactor;
- change in weather conditions, (especially seasonal temperature changes), etc.

The technological safety of the process of oxidative pyrolysis is ensured by the obligatory observance of the following restrictions:

- the maximum permissible temperature of the methane-oxygen mixture at the entrance to the reaction zone of the reactor in order to prevent premature ignition of the mixture or backfiring of the flame from the reaction chamber to a mixer (710 °C);
- the maximum permissible concentrations of oxygen and methane in the pyrolysis gas at the outlet from the reactor in order to prevent the formation of explosive concentrations of products of oxidative pyrolysis (0.8 and 9% (vol.));
- minimum water consumption for "quenching" reaction products (10 m^3/s);
- minimum and maximum permissible pyrolysis gas temperature at the reactor outlet (50 and 100 ^{o}C).

If any of the above parameters go beyond the appropriate allowable range, the process is put into the "candle" mode: the resulting pyrolysis gas is burned in a torch, and the entire system is purged with nitrogen to prevent an emergency. In this case, even a high content of acetylene in the pyrolysis gas does not matter.

3. Development of a process control system

The main task of the process control system of oxidative pyrolysis is to maintain the composition of the resulting pyrolysis gas. This should provide technological safety must be ensured on the basis of the definition of the safety area and the safety center by stabilizing the parameters of the input and output flows within the areas determined by the appropriate technological limitations [3].

The highest level of process safety is achieved, if it is maintained at a point the most remote from the borders defined by the limitations of the process. Such a point is a safety center that geometrically is the point of intersection of normals to lines corresponding to technological limitations. However, finding the process at the safety center point may not provide the specified composition of the pyrolysis gas. For example, the content in the gas of pyrolysis of acetylene as the required commercial product will be insufficient. Therefore, the notion of a security area is introduced where, at some permissible distance from the safety center (reducing the safety index), the required pyrolysis gas composition is provided both from the point of view of ensuring technological safety and obtaining the required acetylene of content. An obligatory condition here is that the boundaries of the safety area are determined by the distances from the values of the parameters of technological limitations to the current values of the process parameters at which a specified level of technological safety in dynamics is ensured.

Thus, the task of controlling the process of oxidative pyrolysis is to determine the control vector $\bar{u}$, that does not allow the technological process to enter the region of unacceptable approximation to the boundaries of the safety region. This leads to the inclusion of a system of constraints:

$$y_i^* - y_i(\bar{a},\bar{u}) \le \delta_i, \quad i = 1,...n$$

where $y_i(\bar{a},\bar{u})$ – variables, real measured values, characterizing the technological process at the reactor outlet; $\bar{a}$ – elements of matrix *A*, which determines the constraints of a piecewise linear model; $\bar{u}$ – control vector; y_i^* – limit values of technological variables that determine the safety of the process; δ_i – deviation of real measured values from the boundary of the safety region on the given variable *i*. The deviations δ_i are determined by the following relations:

$$\delta_{T_{GDG}} = T^*_{GDG} - T_{GDG}, \text{ where } T^*_{GDG} = 710\ ^{o}C$$

$$\delta_{C_{O_2}} = C^*_{O_2} - C_{O_2}, \text{ where } C^*_{O_2} = 0.8\%(vol.)$$

$$\delta_{C_{NG}} = C^*_{NG} - C_{NG}, \text{ where } C^*_{NG} = 9\%\ (vol.)$$

$$\delta_{G_{WH}} = G^*_{WH} - G_{WH}, \text{ where } G^*_{WH} = 10\ m^3/s$$

$$\delta T^1_{PG} = T^*_{PG} - T_{PG}, \text{ where } T^*_{PG} = 100\ ^{o}C$$

$$\delta T^2_{PG} = T_{PG} - T^*_{PG}, \text{ where } T^{*2}_{PG} = 50\ ^{o}C$$

The values of the oxygen and methane content, as well as the temperature of the pyrolysis gas, characterize the state of the physic-chemical situation in the reactor as follows:

- an increase in the oxygen content means that oxygen enters the pyrolysis reactor in excess. This may be caused by an insufficiently high methane content in the natural gas fed to the reactor, which requires adjusting the ratio of natural gas and oxygen consumption on the reaction;
- increasing the methane content means that not all methane reacts. This can be caused by the high content of methane in the natural gas fed to the reactor, which also requires an adjustment of the ratio of natural gas and oxygen consumption on the reaction;
- increasing the methane content and decreasing the oxygen content means lowering the temperature in the reaction zone (until the flame goes out). This is due to the reduction of oxygen consumption to ensure the decomposition of methane and lowering the temperature to a temperature below the required for the formation of acetylene;
- an increase in the temperature of the pyrolysis gas is caused by insufficient water consumption to "quench" the pyrolysis gas and requires an adjustment of this flow rate.

When developing the control system, a sequence of connected initial components, a heater and an oxidative pyrolysis reactor was used as a control object. Figure 2 shows the process of oxidative pyrolysis as a control object where G_{NG} and G_{O2} are discharge rates of natural gas and oxygen per reaction, m^3/s; G_b is a discharge rate of natural gas per heater burner, m^3/s; G_{WH} is a water flow rate for pyrolysis gas 'hardening', m^3/s; T_{NG} and T_{O2} are temperatures of natural gas and oxygen after a heater, K; C_{C2H2}, C_{O2}, C_{CH4} are contents of acetylene, oxygen, and methane in pyrolysis gas at the reactor outlet, % (vol.); T_{PG} is pyrolysis gas temperature at the reactor outlet, K. It should be noted that the distributor grid temperature T_{dg}, as one of technological restrictions, is determined by natural gas and oxygen temperatures at the heater outlet.

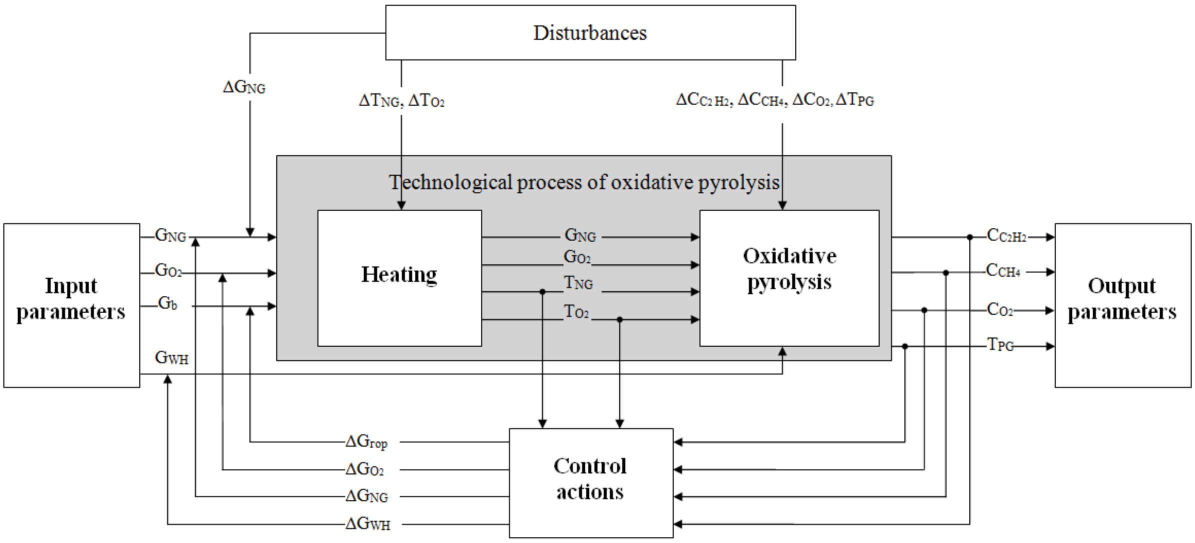


Figure 2. The process of oxidative pyrolysis as a control object.

To control the process safety of the oxidative pyrolysis process, a periodic analysis of the pyrolysis gas composition is performed to determine the content of potentially explosive concentrations of methane, oxygen, acetylene in it. In addition, a constant control of the temperature of oxygen and natural gas at the outlet of the heater and the temperature of the pyrolysis gas at the outlet of the reactor are carried out. The values of the measured parameters are fed to the controller input, where the safety index is determined, as a point in the multidimensional space formed by technological limitations. It is important that for the content of methane and oxygen, the maximum value of the safety index will correspond to their minimum values. For the temperature of natural gas and oxygen in front of the reactor and the pyrolysis gas after the reactor, the maximum value of the safety index will correspond to values that are in certain average acceptable ranges.

After comparing the actual values of the process parameters with the parameters calculated by the mathematical model [3], the control actions are calculated for: changes in the flow of natural gas and oxygen on the reaction of oxidative pyrolysis (or their ratio), the flow of natural gas to the heater burner, the flow of water to the "quenching" of the pyrolysis gas in the direction of increasing the safety index while ensuring the required content of acetylene in the pyrolysis gas [4].

The functioning of the process of oxidative pyrolysis is constantly affected by random disturbances, in connection with which it is required to constantly monitor the displacement of the operating point of the process. In this case, the values of the control actions are determined taking into account her current position. As an estimate of the bias, the process safety index is used, which characterizes the degree of fuzzy equality of the current situation and the situation corresponding to the security center. As a safety center, a point may be considered that corresponds to the best regulatory conditions, or, for example, the point, whose value is established on the basis of an expert survey of engineers and skilled workers serving the process of oxidative pyrolysis.

To determine the optimal method for controlling the process of oxidative pyrolysis, a control system is synthesized (figure 3). In this system, the required output flow characteristics are achieved by stabilizing the parameters of the internal control loops depending on the values of the output parameters (acetylene, methane and oxygen in the pyrolysis gas, pyrolysis gas temperature at the reactor outlet) based on the prediction of fuzzy inference and the generation of the control vector. This vector includes:

- change in natural gas consumption on the reaction;
- changing the oxygen consumption rate on the reaction or changing the ratio of oxygen and natural gas consumption on the reaction;
- change of natural gas consumption to the heater burner;
- change in water consumption for "quenching" of pyrolysis gas.

At the lower level of the proposed control system controllers C_1 and C_2 regulate the inlet flow of natural gas and oxygen to reactor R; controllers C_3 and C_4 regulate the supply of natural gas to the burner of a heater to control the temperature of natural gas and oxygen at the outlet of heater H; controller C_5 regulates the water supply for "quenching" the pyrolysis gas to control the pyrolysis gas temperature at the reactor outlet.

The upper level is a basic one as regards the ensuring of process safety: it provides the calculation of tasks for the first level controllers with due regard to safety center.

Synthesis of the regulator for the upper level due to technological features of the oxidative pyrolysis process is expedient to be carried out using the fuzzy logic [5, 6], since such regulators in some cases are able to provide higher quality parameters of transient processes in comparison with classical regulators [7, 8]. In this context, the following linguistic variables are defined:

- 'natural gas discharge per burner';
- 'natural gas discharge per reaction';
- 'oxygen discharge per reaction';
- 'temperature deviation of the distribution grid';
- 'deviation of methane content in pyrolysis gas';
- 'acetylene content in the pyrolysis gas';
- 'deviation of the oxygen content in the pyrolysis gas';
- 'deviation of the pyrolysis gas temperature';
- 'discharge of water per "hardening" of pyrolysis gas'.

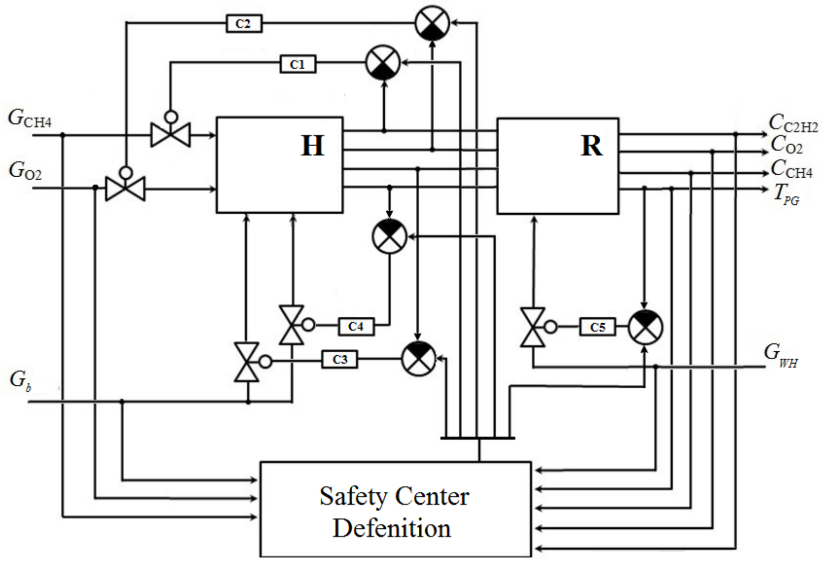


Figure 3. Two-level control system based on safety center definition.

Terms "LOW" (small), "MIDDLE" (medium), "HIGH" (many) are chosen for the description of linguistic variables, with the method of defuzzification being centroid [7].

Linguistic rules for fuzzy controller formulated by IF ... AND ... THEN ... are as follows:

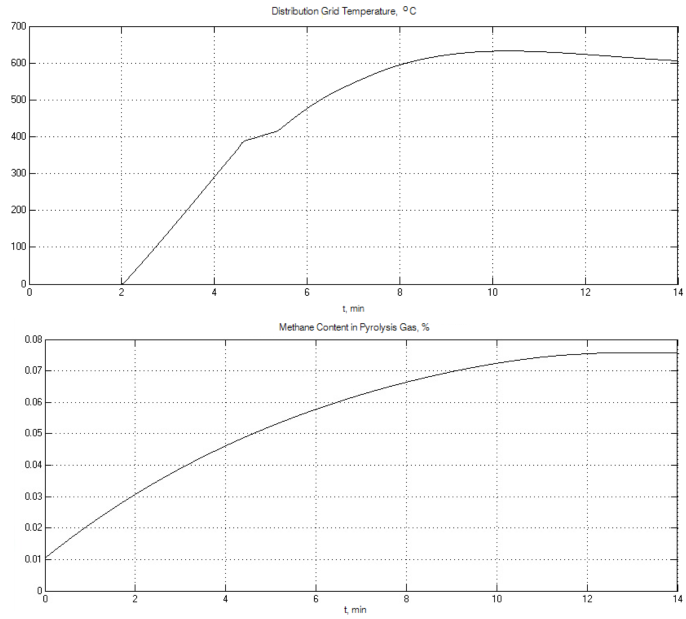
- IF (δT_{GDG} is «HIGH») THEN (G_b is «LOW»);
- IF (δT_{GDG} is «MIDDLE») THEN (G_b is «MIDDLE»);
- IF (δT_{GDG} is «LOW») THEN (G_b is «HIGH»);
- IF (δC_{O2} is «HIGH») AND (C_{C2H2} is «LOW») AND (δC_{CH4} is «LOW») THEN (G_{O2} is «HIGH»);
- IF (δC_{O2} is «HIGH») AND (C_{C2H2} is «HIGH») AND (δC_{CH4} is «LOW») THEN (G_{CH4} is «HIGH»);
- IF (δC_{O2} is «LOW») AND (δC_{CH4} is «MIDDLE») AND (C_{C2H2} is «LOW») THEN (G_{NG} is «MIDDLE») AND (G_{O2} is «MIDDLE»);

- IF (δC_{O2} is «MIDDLE») AND (δC_{CH4} is «LOW») AND (C_{C2H2} is «LOW») THEN (G_{NG} is «MIDDLE») AND (G_{O2} is «MIDDLE»);
- IF (δC_{O2} is «LOW») AND (δC_{CH4} is «MIDDLE») AND (C_{C2H2} is «HIGH») THEN (G_{O2} is «HIGH»);
- IF (δC_{CH4} is «HIGH») AND (δC_{C2H2} is «HIGH») THEN (G_{NG} is «MIDDLE») AND (G_{O2} is «MIDDLE»);
- IF (δC_{CH4} is «HIGH») THEN (G_{O2} is «MIDDLE»);
- IF (δC_{CH4} is «HIGH») AND (C_{C2H2} is «LOW») THEN (G_{O2} is «MIDDLE»);
- IF (C_{C2H2} is «LOW») AND (δC_{CH4} is «HIGH») THEN (G_{NG} is «MIDDLE») AND (G_{O2} is «MIDDLE»);
- IF (C_{C2H2} is «LOW») AND (δC_{O2} is «HIGH») THEN (G_{NG} is «MIDDLE») AND (G_{O2} is «MIDDLE»);
- IF (δT_{PG} is «LOW») AND (C_{C2H2} is «LOW») THEN (G_{WH} is «HIGH»);
- IF (δT_{PG} is «HIGH») THEN (G_{WH} is «HIGH»);
- IF (δT_{PG} is «HIGH») THEN (G_{WH} is «LOW»);
- IF (δT_{PG} is «MIDDLE») THEN (G_{WH} is «MIDDLE»).

When finding the operating point of the process in the region defined by the values of "MIDDLE" or "HIGH" for variables δC_{O2}, δC_{CH4}, "MIDDLE" variable δT_{PG} and δT_{GDG}, "HIGH" for the variable C_{C2H2} it is sufficient to stabilize the available values of the controlled variables of the local control loops. When moving the process working point to the area defined by the "LOW" values for any of the above variables, it is necessary to redirect the process to a safer area of flow ("MIDDLE" or "HIGH" for the corresponding variables) with the help of control actions in accordance with the proposed rules of fuzzy output.

4. Research results

As a result of simulation of the proposed version of the control system in the Simulink package of the MatLab system, transient graphs were obtained for the parameters that determine the technological safety of the oxidative pyrolysis process (figure 4).



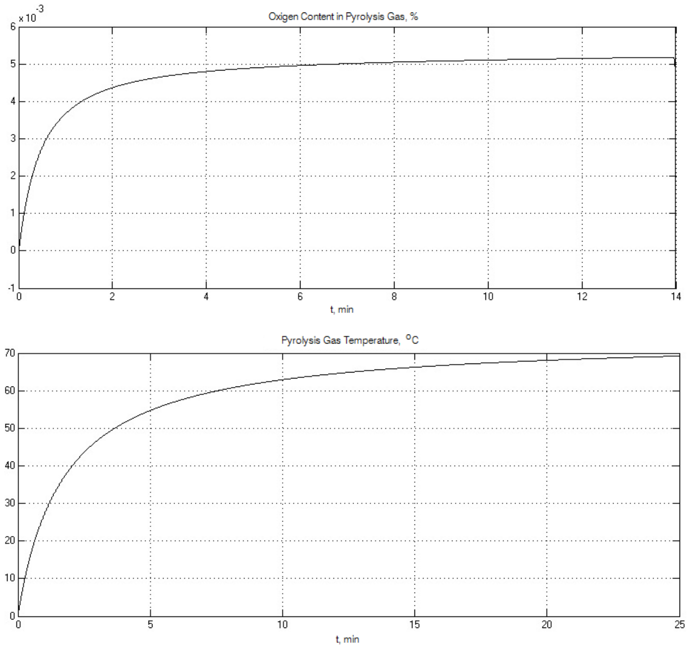


Figure 4. Transient curves.

In none of the cases under consideration exceeded the permissible values of the variables determining the technological safety of the oxidative pyrolysis process. Also, there is no overshoot on any of the variables that determine the safety of the oxidative pyrolysis process.

5. Conclusions

The paper considers an approach to managing a complex technological process based on the application of an fuzzy-logical approach. This approach is one of the directions of artificial intelligence methods. Its implementation will improve the quality of decisions, and, accordingly, the quality of the management system for the industrial production of acetylene. The functioning of the technological process occurs in the context of the occurrence of various accidental disturbances. In this case, there are difficulties in evaluating the state of the process, which generate a lot of management tasks. The solution of management tasks in this case is aimed at compensating for the influence of random causes of abnormal situations. In this connection, the solution of the problems of managing the security of dynamic processes in weakly structured and poorly formalized environments is extremely urgent.

6. References

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