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ADVANCED SYSTEM CONTROL FOR HYDROGEN PLASMA CONVERSION OF INDUSTRIAL HAZARDOUS RECYCLABLE LIQUID WASTE

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Abstract

This paper presents the design of some equipment within an installation for plasma processing of liquid hazardous waste with hydrogen. The authors present the design and simulation in Solidworks and Ansys of hydrogen plasma torches components used for heat treatment of hazardous industrial liquids, the development in Matlab & Simulink of algorithms for controlling the power sources of torches and the non-interactive multivariable control system through thermoregulatory with PID and PID one step ahead control laws from the power supply of the reactor, and the dimensional design and functional simulation of the pump blade that ensures the circulation of the cooling liquid (water) in the torch.

Key words: hydrogen, liquid waste, management, plasma, PID and one-step predictive, recycling, systems design, zero emissions

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1. Introduction

Waste gasification technologies for industrial liquid waste are proposed as an alternative to conventional Waste-to-Energy plants. This article is defining a conceptual framework to assess waste gasification technologies, the potential benefits that may justify their adoption relate to material recovery and operation / emission control.

Cost-benefit analysis of technologies allows the choice of the most efficient waste processing plant (Consonni and Viganò, 2012; Couto et al., 2015; Miron et al., 2019). The management of plasma hydrogen reactor (Gomez et al., 2009) involves the temperature control of plasma reactor, based on the information on the type, chemical composition, viscosity, quantity and density of hazardous industrial liquids, so that it can evolve as a profile imposed by technology.

The main objective of this paper is to design a plasma technology to optimize syngas production by controlling the plasma conversion of liquid waste according to the results obtained from modeling and simulation of thermochemical plasma processing (Begum et al., 2014; Brunner and Rechberger, 2015; Lombardi et al., 2014; Materazzi et al., 2013; Mukherjee et al., 2020; Peters et al., 2017).

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2. Materials and methods

2.1. Design of automatic control system of the plasma reactor

The laboratory installation equipped with plasma on hydrogen for the conversion of recyclable liquid waste is presented in Fig 1.

Fig. 1. Hydrogen plasma plant for the processing of industrial liquid waste

System design for automatic control of a reactor temperatures assume the following steps:

1. mathematical characterization of the controlled plasma hydrogen reactor, setting goals adjustment determined by the type of reactor process management and acting on operating mode, external signals and nature awareness of the mathematical model of the reactor (Martínez et al., 2013; Mazzoni et al., 2017; Ramos et al., 2018);

2. mathematical modeling of the operation of the plasma reactor control and actuation on its external components depending on the mode of operation;

3. setting goals adjustment determined by the type of hydrogen reactor process management, choice of method design involves optimizing parameter values agree, establish criteria for the selection and award regulators and determining optimal control algorithms and external signals and nature awareness of the mathematical model of the reactor;

4. the experimental model for process, identification is performed online without raw material inside the reactor in safe working condition, as input data becomes available through measurement processing (Farzad et al., 2016; Hofbauer and Materazzi, 2019);

5. simulating the control structure using the Matlab & Simulink package of the plasma hydrogen reactor, the optimal choice of equipment that ensures a precise implementation of the algorithm of management, test design and analysis of algorithms, possibility of achieving implementation;

6. finite element analysis of the evolution in time of the heat flow an temperature of the raw material subjected to heat conducted in the plasma reactor with thermoregulator controlled by PID algorithm.

7. implementing the heat control structures in the plant and tracking simulated time evolution of track parameters;

8. validation solution by analyzing the performance of the entire control system implemented if if necessary the reactor is redesign or adjustment parameters for the operating agreement.

2.2. Design of noninteractive multivariable control system from plasma hydrogen reactor

Real-time control of the temperature in the plasma reactor according to the established technology for waste processing is the main problem of the plasma gasification plant.

The control of the plasma chemical gasification unit assume the regulated temperature profile of plasma hydrogen reactor are machines with very long delay times, errors due to adjustment must be 0 and the quality of the thermal process is given by the accuracy of the control system.

Simulation and optimization of parameters for the management of the plasma reactor control process was performed using the Matlab, the functions and parameters in the equations below are calculated using specific subroutines developed in Simulink software package using PID and PID predictive one-step control algorithms.

Thermal processes can be modeled with some transfer functions for first-order elements with dead time. PID and PI algorithms are successfully implemented in the control of such reactors but downtime has unfavorable effects in regulation, the best regulation can be achieved using a one-step predictive algorithm. The design of an automatic adjustment system involves the following steps:

1. the mathematical characterization of the behavior of the process conducted from the thermal installation and of the external quantities that act on it, depending on the operating mode, the transducers - thermocouples and execution elements - plasmatrons and related equipment are chosen and dimensioned.

The effect of the disturbances is cumulated at the output, the models will be linear in small size and will include disturbance filters.

2.the establishment of the regulation objectives are determined according to the type of process management in the plasma installation, the nature of the external signals and the degree of knowledge of the mathematical model of the hydrogen plasma installation. Predictive adjustment of the adjustment algorithm is a discrete method of guidance that is based on knowledge of the mathematical model of the fixed part and the reference trajectory. Usually ARX (Auto-Rregressive eXogenous) type mathematical models (Cucos et al., 2015) of the form (Eq. 1) are used.

Tracking accurately the required temperature profile is a goal difficult to achieve with conventional control algorithms, therefore in this paper for reactor use a command control system with predictive PID algorithm, heat processes are modeled to adjust a PID one step ahead models ARX type has the form given by Eq. (1):

$$A(z^{-1})\cdot y(k)=B(z^{-1})\cdot u(k-d-1)+e(k) \quad (1)$$

where:
- *y(k)* and *u(k)* is the input respectively the output signal, *k* is discrete times $t_k = kT$, (*T* is period for sampling);
- *e(k)* is a sequence of zero mean white noise;
- *d* is discrete dead time $\tau = dT$;

while the polynomials $A(z^{-1})$ and $B(z^{-1})$ is expressed by Eq. (2):

$$\begin{aligned} A(z^{-1}) &= 1 + a_1 \cdot z^{-1} + \cdots + a_{na} \cdot z^{-na} \\ B(z^{-1}) &= b_0 + b_1 \cdot z^{-1} + \cdots + b_{nb} \cdot z^{-nb} \end{aligned} \quad (2)$$

To obtain ARX model is applied to the input element assembly execution - reactor - temperature transducer signal overlapped step signal type of band-limited white noise, analyzing the response obtained polynomials are required *na* and *nb* grades, dead time τ, and by a parametric estimation method is obtained coefficients a_1 ... a_{na} and b_0, b_1 … b_{nb} experimentally determined for polynomials $A(z^{-1})$ and $B(z^{-1})$.

A predictive control law allowing compensation for time τ is an algorithm one-step-ahead that determines the order *u(k)* adjusted so that the output *y(k)* follow the reference trajectory, control law is determined by minimizing a cost function, $J(u(k))$ in the form given by Eq. (3):

$$J(u(k)) = \frac{1}{2}(y(k+d) - r(k+d))^2 + \frac{\lambda}{2}\cdot u(k)^2 \quad (3)$$

where: - *r (k + d)* is the reference set size required; - λ is a weighting factor which adjusts the transient performance.

Minimizing the cost function (Eq. 3) with respect to *u(k)* results in the expression of predictive control law a PID one-step-ahead (Eq. 4), which highlights a controller with two degrees of freedom.

$$\begin{aligned} u(k) &= \frac{\beta_0}{\beta_0 \cdot \beta(z^{-1}) + \lambda}\cdot z^d \cdot r(k) - \frac{\beta_0 \cdot \alpha(z^{-1})}{\beta_0 \cdot \beta(z^{-1}) + \lambda}\cdot y(k) \\ u(k) &= \frac{1}{G_e(z^{-1})}[G_r(z^{-1})\cdot z^d \cdot r(k) - G_y(z^{-1})\cdot y(k)] \end{aligned} \quad (4)$$

In the expression of Eq. (4) have been used the following notations (Eq. 5):

$$\begin{aligned} &G_r(z^{-1}) = \beta_0 \\ &G_y(z^{-1}) = \beta_0 \cdot \alpha(z^{-1});\ G_e(z^{-1}) = \beta_0 \cdot \beta(z^{-1}) + \lambda \end{aligned} \quad (5)$$

where the polynomials *Gr*, *Ge* and *Gy* are calculated off-line using Eqs. (6-8).

$$G_R(s) = K_R \cdot (1 + \frac{1}{s\cdot T_i}) \quad (6)$$

where K_R is the proportionality factor and integration time T_i.

Granting PI controller Haalman method is considering the transfer function of open circuit control system (Eq. 7).

$$G_d(s) = \frac{2}{3\cdot\tau\cdot s}\cdot e^{-\tau\cdot s} \quad (7)$$

which leads to the parameters given by Eq. (8):

$$K_R = \frac{2\cdot T_f}{3\cdot\tau\cdot K_f},\ T_i = T_f \quad (8)$$

2.3. Design of plasma torches on hydrogen of the plasma reactor

Design, modeling and simulating the functioning of plasma torches of hydrogen (Fig. 2) were conducted with the SolidWorks software and then different forms of the anode surface and the cathode analyzed so as to obtain a swirl uniform mixture of air, very fine water spray and industrial dangerous liquids. In this way it was obtained a flame evenly divergent distributed, which does not touch the walls of the torch.

3. Results and discussion

3.1. Implementation of the control structure with PID algorithm and PID predictive of the hydrogen plasma reactor

Simulation of the industrial hydrogen plasma reactor controlled by temperature regulators with PID algorithm one step ahead was realized with the help of the Matlab & Simulink.

The experimental research methodology required the following steps:

- mathematical modeling for the prediction of the technological control parameters of the hydrogen plasma chemical gasification unit.
- finite element analysis with special software of the time evolution of heat flux of temperature in the plasma - chemical gasification unit controlled with PID and PID one - step ahead type thermo-regulators.
- experimental identification performed online in the normal working conditions of the installation of the driven process model, as the input data become available by measurement.
- simulation using the Simulink package of the control structure of the plasma - chemical gasification unit based on the synthetic model presented in the previous paragraph (Eqs. 1–8) whose parameters will be refined following the experimental determinations on the research installation.
- implementation on the hydrogen plasma gasification unit of the simulated optimized control structures following the evolution in time of the monitored parameters.

(a) (b)

Fig. 2. Solidworks design of hydrogen plasma torches with nozzle diameter 1.5 and 2.5 mm
(a) Industrial plasma torch; (b) 3D drawing of redesigned hydrogen plasma

The hydrogen plasma reactor control system uses PID and PID one step ahead control algorithms (managed by the Simulink software package) is simulated time evolution of the main adjustment parameters (temperature control in the plasma gasification reactor and gas purification system), the obtained solution is validated by analyzing the performance of the entire control system implemented on the reactor and if necessary, the operating parameters are adjusted in real time.

The sampling of the data from the reactor (temperature measured by optical pyrometers located in the coating) is performed with a data acquisition plate mounted in the computer that controls the plasma chemical gasification unit, this information is processed by the mathematical model to determine the agreement parameters of thermo–regulators which adjusts the plasma supply voltage separately for each area of the reactor.

The sampling period used by the control system algorithms is 5 sec equal to the thermal inertia of the optical pyrometers used to measure the temperature in the installation. the actual results from the installation obtained from the plasma control has been calculated with a sampling period of 10 sec.

Real time implementation of the temperature regulation structure with one–step predictive algorithm, to improve the performance of the dead time control system used to control the heat treatment reactor, we used in the following experiment thermo–regulators controlled with one–step predictive type control algorithm.

To improve the performance of the dead time control system used to control the plasma hydrogen reactor, we used in the following experiment thermoregulators ordered with one–step predictive type regulation algorithm in accordance with the scheme shown in Fig 3.

The experimental tests were performed on the plasma chemical gasification unit shown in Fig. 4, non–interactive open circuit decoupling structure is modified in the sense that the two heating zones are supplied separately with electricity through a system based on thermo–regulators controlled with classical, PID and PID one–step predictive algorithms.

The decoupling controllers together with the main one–step predictive type controllers with the real–time Simulink scheme, the experimental results are obtained with the real–time control structure from Fig. 5.

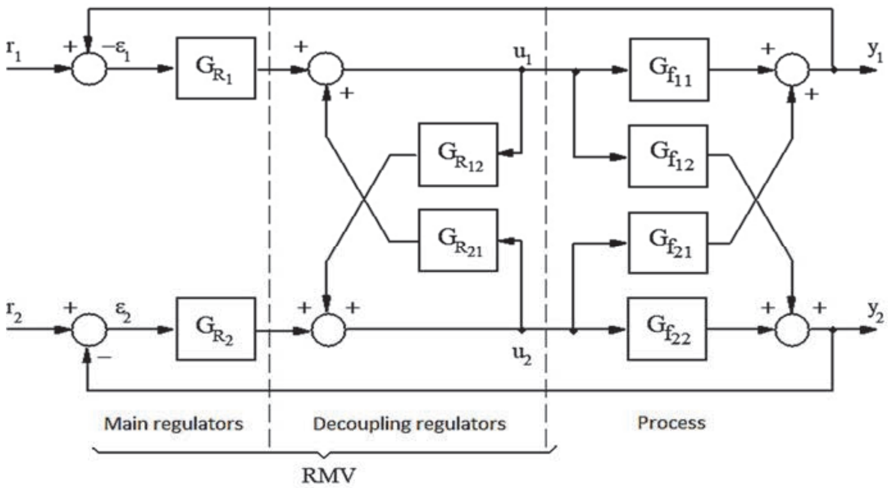

Fig. 3. Non–interactive multivariable adjustment of a reactor with two temperature zones

The decoupling controllers were implemented using the Simulink Filter 4 and Filter 6 blocks, and the main controllers with the Simulink Predictive Controller Level Constraints and Predictive Controller Level Constraints1 blocks. The temperature profile, the same for both areas, was implemented with the Simulink From Workspace and From Workspace1 blocks. The controls for the two static contactors that supply electricity to the heating resistors of the two temperature zones are delivered through two D / A converters implemented in Simulink with the D / A port and D / A port1 blocks, the measured and processed quantities are purchased with two A / D converters implemented in Simulink with the A / D port and A / D port1 blocks.

3.2. Modeling and simulation in Ansys of plasma torches on hydrogen of the plasma reactor

Fig. 6 shows some of the results of simulating the operation of the torch, the flow of compressed air of the cooling water and the mixture of steam and industrial liquids (Li et al., 2020) is highlighted by the speed field lines, centrally the compressed air is introduced in the left side highlights the steam mixture and hazardous liquids and cooling water is introduced on the right (Moustakas et al., 2008; Sogancioglu et al., 2017; Sharma et al., 2018). In order to complete the dimensional design of the plasma with hydrogen, it is very important to study the flow of the torch cooling fluid, how to make the mixture of compressed air and steam at the anode and cathode interface and the speed of movement of the fluid mixture at the exit of the hydrogen torch.

Analysis was performed using the Ansys program, the following figures (Fig. 7 respectively Fig. 8) shows the results obtained for torch with a diameter of 1.5 mm and 2.5 mm have been experimentally validated with the existing plant in the research laboratory. The temperature generated by the plasma on hydrogen varies over 4,000 – 5,000 ºC (AL-Luhaibi and Tariq, 2013; Klomberg et al., 2014; Sunshil, 2012) for this reason the cooling is very important, for cooling the plasma the agents used are air or water, the main component of the cooling equipment is the air or water turbine.

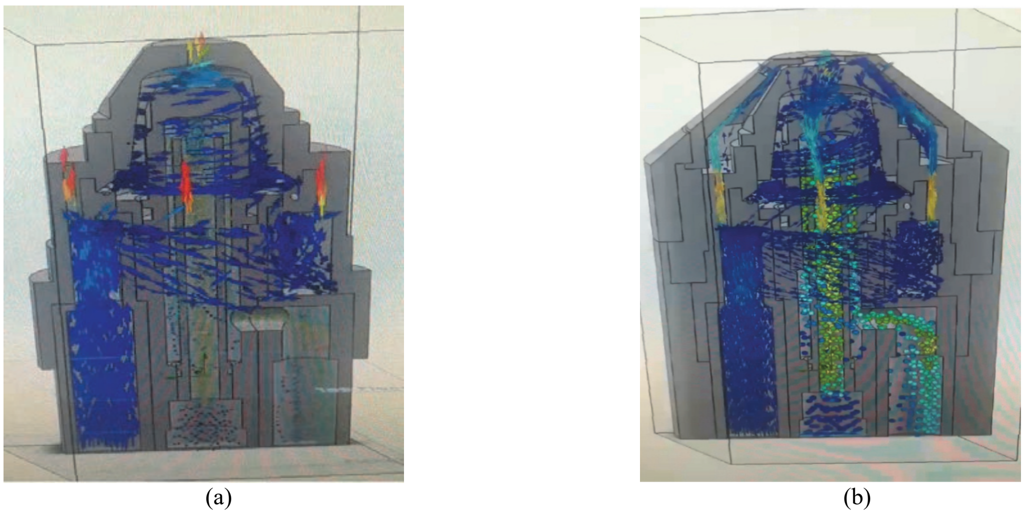

Fig. 6. Solidworks design of hydrogen plasma torches with nozzle diameter 1.5 and 2.5 mm: (a) simulation of the flow of the mixture of compressed air, steam and hazardous liquids; (b) simulating the influence of water used to cool the torch

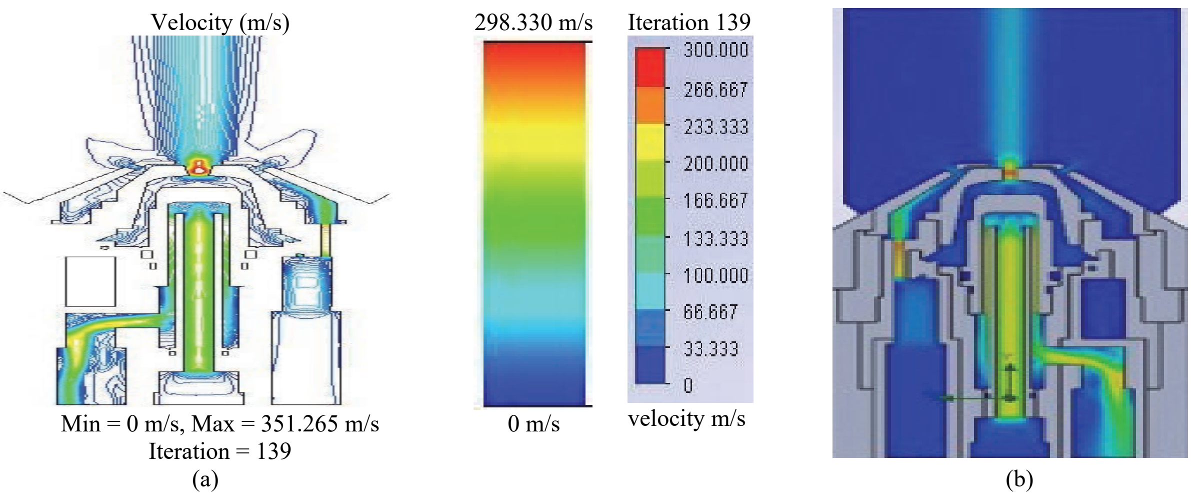

Fig. 7. Modeling in Ansys of the hydrogen torch on hydrogen nozzle diameter D=1.5 mm: (a) represent the speed the fluid mixture steam and hazardous liquids; (b) the flow of the compres--sed air, steam and hazardous liquids and torch cooling fluid

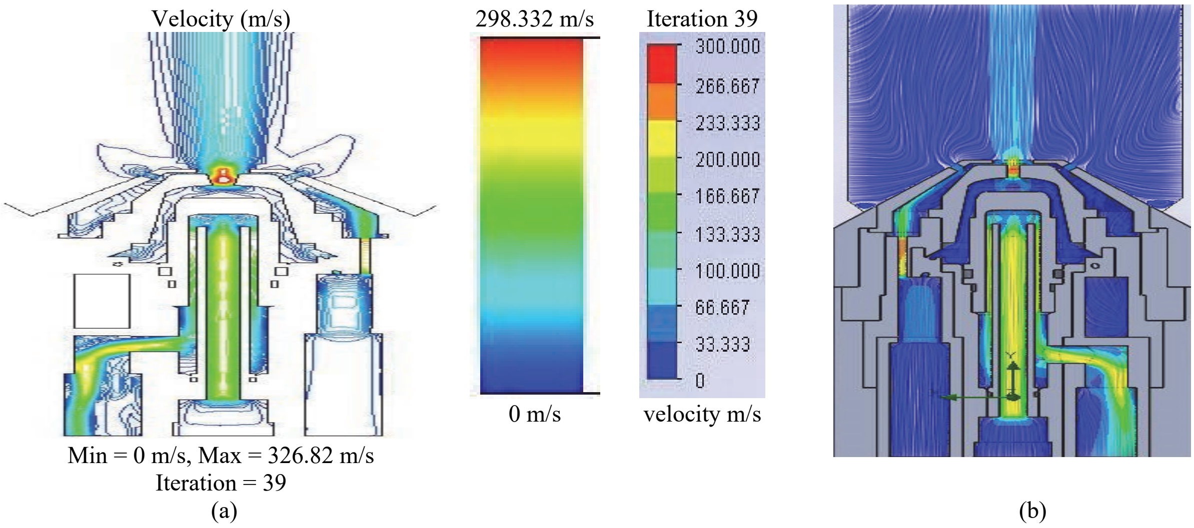

Fig. 8. Modeling in Ansys of the hydrogen torch on hydrogen nozzle diameter D=2.5 mm: (a) represent the speed the fluid mixture steam and hazardous liquids; (b) the flow of the compressed air, steam and hazardous liquids and torch cooling fluid

Following the simulations presented above, it is found that in order to obtain a plasma with very high temperature and divergent and continuous flame with nozzle diameter D = 2.5 mm, hydrogen plasmas were made with the designed constructive characteristics and were tested in an existing experimental stand in the research laboratory (Fig. 9).

3.3. Design, modeling and simulation with the Solidworks program of the constructive shape of the pump blade in the torch cooling installation

The torch cooling installation was adapted to the intense operating demands, the shape of the pump blades (Gaikwad and Sonawane, 2014) was redesigned according to the flow of the main adduction (Fig. 10). The materials used for the pump blades can be composite materials or steels on which various alloying elements are thermally deposited on the surface layer of the blade through the plasma spraying process (Avram et al., 2014a; Avram et al., 2014b), they must withstand various complex stresses (mechanical, torsional, bending and cavitation) as well as chemical and biological corrosion. Finite element analysis of the state of stress of pump blade was performed using specialized software with an preprocessor. The steps of finite element analysis are:

a) pump blade volume hydraulic modeling and determine the properties of the material of the piece, creating finite element structure of blade;

b) processing piece finite element model.

- establishing the restrictions, the contour conditions of the part and the value of the demands imposed by the operation;

- solving the FEM method and display the results for static and dynamic analysis, vibration analysis, thermal analysis, fatigue and oscillations analysis.

Finite element analysis results are presented in the whole volume of the piece and representative sections for drawing conclusions on the analyzed part identifies the most dangerous sections following that on them to carry out thorough investigations. The results of the finite element analysis are presented in the entire volume of the part and in the representative sections, in order to establish the conclusions regarding the analyzed part, the most dangerous sections are identified and detailed investigations.

FEM analysis of the pump blade was made with AutoCAD AutoFEM Analysis in Figs. 11 – 16 are presented the main analyzes performed:

- amplitude of displacements and equivalent stress (Fig. 11);
- equivalent pressure and safety coefficient of equivalent pressure (Fig. 12);
- damage to the part by equivalent stress and stress intensity (Fig. 13);
- the safety factor for equivalent stress and normal stress (Fig. 14);
- the safety factor and total operating cycle for the stress intensity (Fig. 15);
- the temperature and amplitude of the thermal flux in the part (Fig. 16).

Fig. 9. Experimentation of plasma on hydrogen nozzle diameter D=2.5 mm

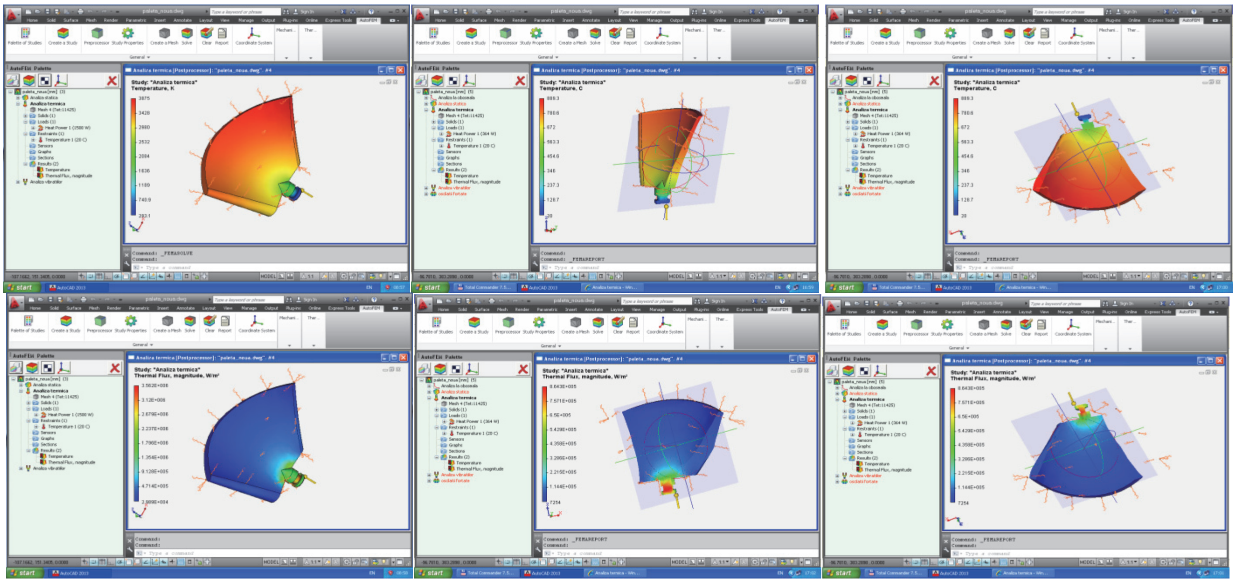

Fig. 16. Solution by MEF the temperature and amplitude of the thermal flux in the part

4. Conclusions

The paper summarizes the design and simulation of hydrogen plasma torches components used for heat treatment of hazardous industrial liquids the development of algorithms for controlling the power sources of torchs and the dimensional design and functional simulation of the pump blade that ensures the circulation of the cooling liquid (water) in the torch.

Upgrading a plasma plant that uses liquid waste as an energy source requires redesigning the hydrogen cakes that equip the reactor and the gas purification system, improving the power source control system and optimizing the pump in the cake cooling system.

The results of the scientific research presented are:

- the realization of the control algorithm for the power sources that supply the torches on hydrogen, the respective algorithms were implemented with the help of Matlab Simulink software in the control module of the sources;

- 2 types of hydrogen torches with a nozzle diameter of 1.5 mm and 2.5 mm were modeled, the speed and the flow mode inside the torch of the technological fluids were studied in Ansys;

- following the simulation of the torches operation in Ansys, the shape of the surfaces of some components of the torch was dimensionally optimized so as to obtain a uniform jet of plasma on hydrogen, without major turbulence, with a large dispersion cone and a flame continuity in time;

- the method of mixing hazardous industrial liquids and steam as well as the cooling efficiency of torches by the cooling fluid (water) was studied;

- the hydrogen plasma torchs designed by our team were physically made by a specialized company and were used in experimental research;

- the power of the sources was set so that the temperature of the gas mixture obtained was approximately 4000 ºC, for experiments on the stand made in the laboratory, the torch with a nozzle diameter of 2.5 mm was chosen because it best meets the technological requirements;

- torches cooling is very important depending on the cooling liquid flow the duration of operation of the anode and cathode varies greatly, a new type of blade was designed and simulated for the pump that drives the cooling liquid, it was checked by finite element analysis resistance to complex torsion and bending stresses, cavitation, mechanical and chemical corrosion and maximum temperature in the pump blade.

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