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Clearing of ventilating emissions in low temperature environment of plasma

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Abstract. The method of high-temperature processing of streams of the ventilating air which is a subject clearing from organic pollutions is developed. Data about its efficiency, including on a number of economic parameters are obtained. Results of work are recommended for use, first of all, by development clearing plasma-thermal reactors (CPTR) for clearing air, especially from toxic substances, and also for large technological clearing installations, containing organic ventilating emissions (OVE). It is created experimental CPTR. Laws of the expiration of a plasma jet in stream of OVE limited by cylindrical walls, water-cooled channel are experimentally investigated. Dependences of a trajectory and long-range the plasma jet blown radially in stream of OVE are received. Heat exchange of stream of OVE with walls of CPTR after blowing a plasma jet is experimentally investigated; dependences of distribution of temperatures on length of a reactor and a thermal stream in a wall of channel of CPTR are received. Are investigated chemical compound of OVE after plasma-thermal clearing, some experimental data by formation of oxides of nitrogen and mono-oxide of carbon during clearing are received.

1. Introduction

For oil refining, paint and varnish, pharmaceutical, etc. manufactures by a characteristic problem the choice of an effective method of clearing deleted ventilating air containing organic emissions (OVE) with the purpose of protection of an atmosphere from organic pollutions. The technologies of clearing based on application of low temperature plasma (LTP) are perspective [1]. Their feature consists that there is an opportunity of transfer of substance in an overactive condition. It allows to accelerate processes of clearing, to increase a degree of chemical transformations, to reduce weight and dimensions of the equipment. Greater speeds of mixture of OVE stream both jets LTP and short duration of chemical reactions are preconditions to creation small-sized, high-efficiency clearing plasma-thermal reactors (CPTR).

2. Experimental research and experimental installation of CPTR

Scheme of CPTR is presented on Figure 1 [2]. Experimental installation consists from:

1. Air plasma-thermal reactor direct current PD-1 5 with power of 45 kW with system of electrosupply and system of submission of compressed air;

2. Flowing reactor in the form of pipe $D=100$ mm, consisting from: chambers of mixture 4, 150 mm length; eight calorimetric sections 6-10, 12 (50; 100; 200 mm length); reception section 2 (200 mm length), with a window 1 for visual supervision; metal turbulence grid 3, with the size of a cell 0,5x0,5 mm;
3 Ventilation system 15 consisting from: the fan 18, confusor 16 and diffusor 14 for connection with a reactor, a throttle-valve 17;
4 Systems of submission of aerosols;
5 The general system of water cooling of plasma-thermal reactor;
6 Systems of selection of gas tests;
7 Water refrigerator, for cooling gas tests;
8 Complex of measuring gauges and the equipment;
9 Ten gauges of temperature installed on system of water cooling of plasma-thermal reactor.

3. Technique of experimental researches

Intensity of hashing of a jet with a taking downstream in a reactor depends on following major factors:
1) Corner of attack ($\gamma_0$) of jet in relation to taking down stream of OVE;
2) Relation of high-speed pressures of a jet and a stream:

$$J=(\rho_{jet}V_{jet}^2)(\rho_{str}V_{str}^2)^{1/3}$$

Where: $V_{jet}$ - speed of a plasma jet, m/s;
$V_{str}$ - speed of a stream, m/s;
$\rho_{jet}$ - density of a jet calculated on average-mass temperature of plasma jet $T_{jet}$, kg/m$^3$;
$\rho_{str}$ - density of a stream calculated on average-mass temperature of plasma stream $T_{str}$, kg/m$^3$;
3) Ratio between diameters of reactor $D$ and nozzle of jet $d$.

Research of current of a plasma jet in one-jet plasma-chemical reactor consist in an experimental research of various operating modes of plasma-chemical reactor. Data about operating modes are resulted in Table 1 [3].
Table 1. Parameters of the investigated operating modes of a reactor.

| Mode | $V_{str}$ | $V_{jet}$ | $T_{str}$ | $T_{jet}$ | $J$   |
|------|----------|----------|----------|----------|-------|
| 1    | 7.0      | 92       | 293      | 5350     | 9.5   |
| 2    | 10.9     | 87       | 283      | 5050     | 3.5   |
| 3    | 13.6     | 90       | 293      | 5230     | 2.4   |
| 4    | 9.6      | 89       | 286      | 5130     | 4.8   |

4. Processing of results of experiments

For each control section, it has been lead nine experiences. The measuring module was installed in position $\varphi = 0^\circ$, results were fixed by digital Walt meter. Similarly experiment repeated, for the given section and the given position of the measuring module three times. Further the measuring module turned about the axis in subsequent positions $\varphi = 60^\circ$, and $\varphi = 300^\circ$, installation joined, and procedure of carrying out of experiments repeated for each position. Thus, seven series of parallel experiences which number is equal to number of investigated sections are lead, and for each series is lead on nine experiences, at a preset value of parameter $J$.

For each series of parallel experiences average arithmetic value $I$ on dependence is calculated:

$$
\overline{I}_j = \frac{1}{k} \sum_{i=1}^{k} I_{ji}, \quad (j = 1, \ldots, M),
$$

where $k$ - number of the parallel experiences lead at identical $j$ and in same section; $M$ - number of parallel series.

Then the estimation of a dispersion for each series of parallel experiences was spent:

$$
S_j^2 = \frac{1}{k-1} \sum_{i=1}^{k} (I_{ji} - \overline{I}_j)^2
$$

For check of reproducibility of experiences the relation of greatest of estimations of dispersions to the sum of all estimations of dispersions by Kohren’s criterion is calculated:

$$
K_{cal} = \frac{\max(S_j^2)}{\sum_{j=1}^{M} S_j^2}. \quad (4)
$$

Settlement value $K_{cal} = 0.335$. Tabulared $K_{tab} = 0.382$. As $K_{cal} < K_{tab}$ that experiences are considered reproduced, and estimations of dispersions - homogeneous.

5. The analysis of results of experiments

On Figures 2-5 structures of temperatures on investigated sections of a reactor are presented. From figures current of the plasma jet blown into the channel is visible, that, has a complex spatial appearance. At $J = 9.5$ structures of temperatures have two strongly pronounced maxima, and greater is located closer to an opposite surface of input of a jet. It is possible to explain it to that the jet gets deep into a stream, not being laid on spreading surface of the channel (Figure, $J=9.5$). In an initial site of deviating jet there is a kernel of constant full pressure. Deformation of section of a jet speaks character of its interaction with a stream. At once after an output of a plasma jet from nozzle owing to intensive hashing with a taking down stream of air the turbulent layer of mixture is formed. The peripheral particles of a jet having smaller speed, than particles of a kernel, deviate a taking downstream an initial direction more strongly, move on more curved to trajectories.
At $J = 2.4$ structures of temperatures have a unique maximum that is connected by effect of laying of jets on spreading surface in initial sections (Figure 5, $J = 2.4$ at $X/D = 0.75$). The jet develops downstream the channel as unlimited. 

At $J = 3.5$ structures of temperatures also have a unique maximum, but not so strongly pronounced as at $J = 2.4$. The temperature border of a jet extends deep into a reactor. In it also as well as at $J = 2.4$ pair whirlwinds are not formed.

Hence, it is possible to draw a conclusion that there is such mode of mixture of a plasma jet with a stream when the jet will not be laid in initial sections on surfaces of walls of the channel. Thus, intensity of promotion of pair whirlwinds in stream will be maximal as a result of a flow of a jet from different directions and by that the most intensive mixture of a plasma jet with a taking down ventilating stream will be achieved.

Figure 2. Structures of temperatures at $J = 9.5$.

Figure 3. Structures of temperatures at $J = 4.8$. 
On Figure 6 trajectories $Y/D$ of the maximal temperatures of a gas-air stream of investigated sections of CPTR, depending on coordinate $X/D$, for the investigated modes are represented. The temperature trajectory of a jet was determined on coordinates of the maximal temperature in investigated sections.
On Figure 6 it is visible, that with increase $J$ depth of penetration of a jet $h = (Y/D)_{\text{max}}$ increases. At $J = 2.4$ the jet develops as unlimited walls of the channel in a taking downstream. In the determining parameter, influencing a temperature trajectory of a jet, is $J$. The jet has a flat trajectory, not testing essential influence of a surface of the channel located above a jet. The range $h$ of the jet achieves on significant distance $X/D = 4.25$ from a place of its input.

Than it is more $J$, especially the high pressure is created in a taking downstream at an opposite surface and the more so the jet has an abrupt trajectory.

At $J = 9.5$ the effect of laying of the jet (Figure 6 $X/D > 3.25$) was observed. Laying occurs on a surface of the channel, the jet located opposite to input. The jet, having unwrapped on a stream on short enough distance $X/D = 1.5$ and having got thus further axes of the channel ($Y/D > 0.6$), nestles a taking downstream on a surface of the channel. Therefore, the further increase in coordinate $Y/D$, it is possible to explain of laying effect of the jet on a surface of the channel located opposite to a place of its input.

At $J = 3.5$ the laying effect of the jet on walls of the channel it is not observed. Value $h$ a jet achieves on shorter distance ($X/D = 3.25$) from input of a jet, than at $J = 9.5$ and $J = 2.4$. The range $h$ a jet thus is about $0.5D$.

On the basis of processing and studying of experimental data about a temperature trajectory it is possible to draw a conclusion that an effective mode of hashing of a plasma jet with an air stream in investigated one-jet CPTR is that at which $h = 0.5D$ i.e. when the plasma jet is unwrapped by a taking downstream near to an axis of the channel.

For reception of the approached dependence of a trajectory of a plasma jet, from determining parameters the known technique of generalization of skilled data [4] is used. The researches resulted in [5-8], have shown, that the trajectory of the jet developing in the taking downstream is determined, mainly, by the relation of impulses of a blown jet and basic stream $J$. 

$$Y/D = AJ^m \cdot (X/D)^n.$$  
(5)

For definition of parameters $m$, $n$ and $A$ the program in which the sum of square-law deviations of function (5) from experimental value $Y/D$ was minimized is made, thus the parameter $m$ varied in an interval $[0..1]$ with step 0.01, parameter $n$ in an interval $[0..1]$ with step 0.01, and $A$ in an interval $[0..2]$ with step 0.01. Thus, the trajectory of a plasma jet in a taking downstream limited by a cylindrical wall can be described by the formula:

$$Y/D = 0.25J^{0.39} \cdot (X/D)^{0.18}.$$  
(6)

It is experimentally established, that maximal range of the jet achieves on distance $X/D = 2.3$ (see Figure 6) from a place of input of a jet, accepting in the equation (6) $Y = h$, we shall receive:

$$h/D = 0.29J^{0.39}.$$  
(7)

As it is constructive $D = 5.6d$ for $h/d$ it is had:

$$h/d = 1.69J^{0.39}.$$  
(8)

In Table 2 results of calculation jet range under the formula (8) and according to, received by other researchers are compared. From Table 2 it is visible, that dependence (8) received at processing experimental data will well be coordinated with dependences of other authors received in similar conditions.
Table 2. The comparative characteristic of settlement data by definition of jet range with data of other authors.

| J  | $h/d$, [9] | $h/d$, [10] | $h/d$, (8), [3] |
|----|------------|-------------|------------------|
|    | Round jet, stream in the cylindrical channel | Round jet, stream in the cylindrical channel | Round jet, stream in the cylindrical channel |
| 5  | 4.65       | 3.77        | 3.17             |
| 10 | 5.13       | 4.51        | 4.15             |
| 20 | 5.72       | 5.40        | 5.44             |

6. Conclusions
As a result of the lead researches are investigated the thermal physical processes proceeding at plasma-thermal clearing of organic ventilating air by reactor method, and providing effective clearing due to optimization of hashing of a plasma jet and a stream in clearing plasma-thermal reactor.

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