Optimal Control of Moving Heat Source During Doping of Quartz Preforms for Optical Fiber Production

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***Abstract*— the present paper examines the problem of optimal control of the moving heat source in the MCVD (modified chemical vapor deposition) doping process. The basis of the optimal control problem is the mathematical model of a quartz tube heated by the moving heat source. The objective of the control is to stabilize the temperature field on the surface of the heated quartz tube in accordance with the set optimality criterion.**

***Keywords*— optimal control; distributed systems; moving heat source; MCVD process**

I. Introduction

The analysis of the thermal process, which occurs in the heat zone, and the synthesis of the automatic control system, which is based on the comparison between the set temperature field and the measured one, is a prospective direction for the MCVD technology development. Designing of that system sets additional requirements to observability of the object of control and requires taking into account its properties. Regarding the process of thermal field control on the surface of the quartz tube in the MCVD process as a system with distributed parameters focuses our attention on a relatively new class of control systems – systems with moving impact source. Figure 1 demonstrates a pictorial circuit of the MCVD doping process.

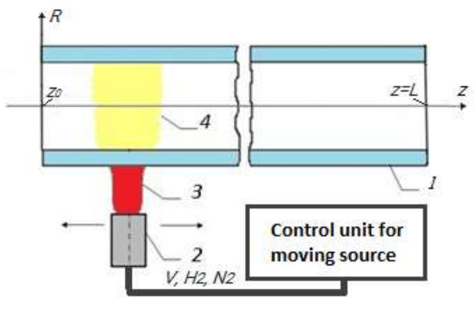

Fig. 1. Pictorial circuit of the MCVD process

1 – quartz tube; 2 – moving burner (arrows show the direction of movement); 3 – burner flame; 4 – reaction zone

II. Description of the Object of Control and Problem Definition

Papers [10, 11] present a mathematical model for heating of a quartz tube with a moving source of exposure, which has the following thermal conductivity formula:

$$\frac{\partial T(t,z)}{\partial t} - a\frac{\partial^2 T(t,z)}{\partial z^2} + \alpha T(t,z) + \beta T^4(t,z) = F(u,t,z) \qquad (1)$$

where t – time; z – coordinate; u – control; T – quartz temperature; a – thermal diffusivity coefficient; α and β – some coefficients.

The first part (1) depends on the heat flow. Heat flow's energy is spent on the heating of the quartz tube, heat exchange with the vapour-gas mixture and on the emission and the heat exchange with the environment. In this formulation, the F function is as follows:

$$\mathrm{F}(u,t,z) = \frac{S_R}{\rho c V} q(z,t) + \frac{S_R \alpha_c}{\rho c V} T_c + \frac{S_R \alpha_c \beta}{\rho c V} T^4{}_c + \frac{S_{r_0} \alpha_z}{\rho c V} T_z \qquad (2)$$

where ρ, c, λ – density, specific heat capacity and thermal conductivity of quartz; a_r and a_c – coefficients for the heat exchange with the gas and the environment; S_R and S_{r0} – area of the outer and inner cylindrical surfaces; V – volume of hollow cylinder T_z and T_c – gas temperature and environment temperature;

A differential equation in partial second-order derivatives with a nonlinear operator of (1) is solved when initial and boundary conditions are set [10].

Let us assume that the programmed movement (state) is known, i.e. the functions $\Delta T(t,z)$ и $\Delta u(t,z)$ are known. However, the real (true) state of the system will always be different from the programmed one. Therefore, we can put:

$$T(t,z) = T^*(t,z) + \Delta T(t,z) \qquad (3)$$

$$u(t,z) = u^*(t,z) + \Delta u(t,z) \qquad (4)$$

where $T(t,z)$ и $u(t,z)$ – is the real state of the system; $\Delta T(t,z)$ and $\Delta u(t,z)$ – disturbance (deviation of the programmed state from the real one).

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In the paper [11] a linearized thermal conductivity equation for $\Delta T(t,z)$ disturbances is derived and has the following formulation:

$$\frac{\partial \Delta T}{\partial t} - a\frac{\partial^2 \Delta T}{\partial z^2} + \alpha\frac{\partial \Delta T}{\partial z} + \beta\Delta T = \gamma\Delta u \tag{5}$$

The moving heat source – the $q(z,t)$ heat flow from the burner is defined by the Gaussian function, which has the following formula [10]

$$q(t,z) = q_{\max} \cdot e^{-\left(\frac{z - \int_0^t v(\xi)d\xi}{H}\right)^2} \tag{6}$$

where $v(\xi)$ – is the movement speed of the burner, H – dispersion (width of the shape of the heat source), q_{max} – burner capacity.

The research of the mathematical model for the moving source is presented in the paper [12].

The goal of the optimal stabilizing control is to select the parameters of the burner such as: burner capacity, shape of the flame and movement speed which allow

$$\left| \Delta T(t,z) \right| \to 0 \tag{7}$$

In the present paper the control function of $\Delta u(t,z)$ is the burner capacity q_{max} and the objective functional for the optimal control problem has the following formula [10]

$$F(u,\Delta T) = \int_0^\tau\int_0^L \Delta T^2 dzdt + \sigma\int_0^\tau\int_0^L \Delta u^2 dzdt \tag{8}$$

where τ – control time, L – length of the quartz tube, σ– some parameter which defines the cost of control.

Then, according to the paper [11], the optimality system, which consists of differential equations for the $\Delta T(t,z)$ functions and auxiliary function $p(t,z)$ associated with it, has the following formulation:

$$\begin{cases} \dfrac{\partial \Delta T}{\partial t} - a\dfrac{\partial^2 \Delta T}{\partial z^2} + \alpha\dfrac{\partial \Delta T}{\partial z} + \beta\Delta T = -\dfrac{\gamma^2 p}{\sigma}, \\ \dfrac{\partial p}{\partial t} + a\dfrac{\partial^2 p}{\partial z^2} + \alpha\dfrac{\partial p}{\partial z} - \beta p = -\Delta T, \\ \Delta T\big|_{t=0} = T_0(z), p\big|_{t=\tau} = 0, \\ \Delta T\big|_{z=0} = T_1(z), p\big|_{z=0} = 0, \\ \dfrac{\partial \Delta T}{\partial z}\Big|_{z=L} = T_2(z), \dfrac{\partial p}{\partial z}\Big|_{z=L} = 0. \end{cases} \tag{9}$$

Auxiliary $p(t,z)$ function and the $\Delta u(t,z)$ control function are related by the following ratio:

$$\Delta u(t,z) = -\frac{\gamma^2 p(t,z)}{\sigma} \tag{10}$$

It is important to note that the key feature of the problem defined is to get an approximate solution of the system (9) in an analytical form, which makes it possible to use it in real time in automated control systems.

It is worth noting separately that the movement speed control of the burner and the flow of the nitrogen to blow over the burner in the control system in question is conducted in accordance with the programmed law.

III. Designing the Optimal Stabilizing Regulator

Below we will be explaining the operating principle of the control system in question, which is depicted in the Fig. 2.

Let us suppose that the *MCVD* process duration equals *Tn*. The process, in this case, is to be understood as the passing of the burner from z=0 to z=L in the direction in which the vapour-gas mixture is supplied. Then, for every t out of [0, *Tn*] we know the $T^*(t,z)$ temperature distribution and the respective $u^*(t,z)$ control. Let us assume that the temperature control is conducted through a scanning pyrometer in equal time intervals, which equal τ. Then, the solution of the problem of optimal stabilizing control of the heat source will be carried out in the $[0,\tau]$ time interval. Additionally, with $t1$=0 ($t1 \in [0,\tau]$) we know the following values

$$\Delta T(0,z) = T(0,z) - T^*(0,z) \tag{11}$$

where $T(0,z)= T(t,z)$ – actual temperature received from the scanning pyrometer readings at the t moment. Assuming that $\Delta T(0,z)$ is taken as an initial condition, and the boundary conditions for $\Delta T(t,z)$ equals zero, we can calculate the $\Delta T^*(t,z)$ temperature and the change of the heat flow over time (control) of $\Delta u^*(t,z)$. This control is effective only within the $[0,\tau]$ time interval and after it elapses, a new temperature measurement occurs, we calculate the $\Delta T(0,z)$ etc.

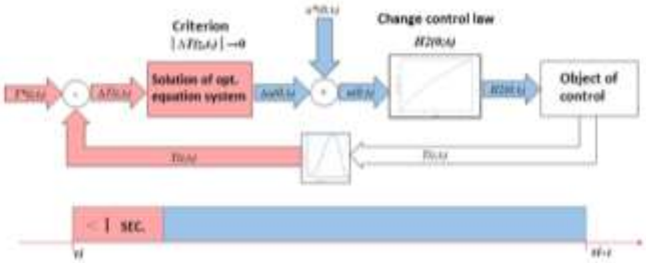

Fig. 2. Operating principle of the control system

IV. Conclusion

This paper has examined the problem of optimal control of the moving heat source during the *MCVD* process. The suggested means of control is based on the mathematical model of the quartz pipe being heated by the moving heat source.

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