DEVELOPMENT OF NATURAL CONVECTION IN A LIQUID HEATED BY THE FRONT OF SELF-PROPAGATING HIGH-TEMPERATURE SYNTHESIS (SHS)

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The process of development of free convection in a liquid heated by a moving combustion front is considered. The emphasis is on the dynamics of development of the process.

Self-propagating high-temperature synthesis technological processes are finding ever increasing use and seem so universal in prospect that, they can successfully replace traditional ones, especially in engineering, power engineering, automotive and aircraft industry, etc. There emerges an opportunity to obtain new materials (supersolid, superconducting, etc.) and products which are either impossible or very labor-consuming and expensive to obtain by other means. Stable SHS front velocity and other characteristics make it in a number of cases a considerably promising mobile heat source. In particular, fundamentally new schemes are possible for heat recovery in incineration and processing of a number of industrial, household and agricultural wastes and, low-calorie fuels. Selection of heat and its transmission from a SHS source to an intermediate heat transfer agent can be carried out by free or combined convection.

It is of interest to consider free convection in a liquid heated by a self-propagating combustion wave, especially in the initial period of development of free convection when a moving narrow front and heated products forming behind it in the condensed phase serve as the heat source.

SHS is highly exothermic and one of the most high-temperature processes of burning [1]. This work evaluates the development of free convection around the cylindrical source which is SHS in a thermally thin envelope of inertial material. In order to obtain a thermally thin envelope and to simplify the problem, we make use of self-propagating synthesis in a mixture of organic powders (malonic acid–piperazine) for investigation. Characteristic of this mixture [2] are: the total heat release $Q = 260$ kJ/kg, the heat capacity of the mixture $C = 2000$ J/(kg·deg), the thermal conductivity of the mixture $\lambda = 0.4$ J/(m·sec·deg), the combustion temperature $T = 155°C$, and the burning rate $V = 1$ mm/sec. The temperature growth rate for the organic powders is 50 K/sec. The problem of propagation of the combustion front of the condensed system which is in contact with the inertial medium is dealt with in the works [3-5].

From the analysis of heat conduction equations [3] it follows that the characteristic warm-up depth of the inertial material under the reaction zone in the direction perpendicular to the burning rate has the order

$$S = (a_f a_i)^{1/2}/V,$$

where $a = \lambda/\rho c$ is the thermal diffusivity; f is the index of the inertial material; i is the fuel index; V is the burning rate. The inertial material layer is thermally thin [3], when $L \ll S$ (L is the inertial material thickness). The transverse temperature distribution over this layer can be disregarded in this case.

In the case under study $L = 0.4 \times 10^{-3}$ m, $S = 1.14 \times 10^{-3}$ m, i.e., the inertial material may be considered thermally thin.

The critical thickness of the fuel layer from [3] is $H_e = 5 \cdot 10^{-3}$ m (the fuel layer thickness in the reactor in question is $19 \cdot 10^{-3}$ m).

We will evaluate the influence of the SHS front, moving in a thermally thin envelope, on the development of natural convection (Fig. 1).

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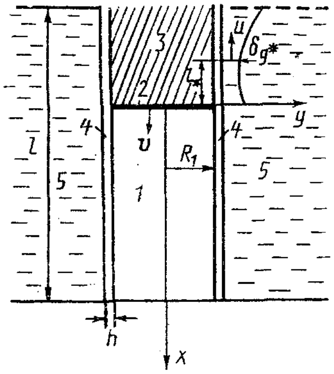

Fig. 1

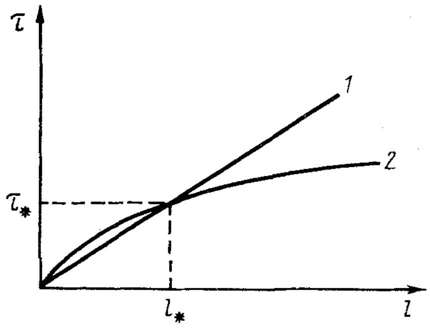

Fig. 2

Fig. 1. Scheme of investigations: 1) initial mixture; 2) zone of heat release; 3) products of reaction; 4) envelope; 5) liquid.

Fig. 2. Dependences of $\tau(\ell)$ for front motion (1) and free convection development (2).

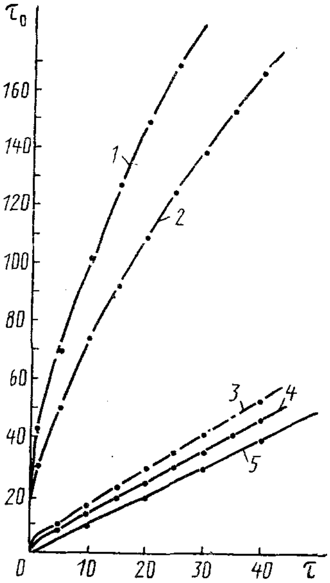

Fig. 3. Lag of free convection as the synthesis front moves: 1) glycerine, $\Delta T = 80°C$; 2) glycerine, $\Delta T = 130°C$; 3) PMS-100, $\Delta T = 120°C$; 4) PMS-100, $\Delta T = 80°C$; 5) water, $\tau = \tau_0$. τ, τ_0, sec.

When the temperature difference between the body and the surrounding medium occurs, one can distinguish three stages of heat exchange in time. At the initial instant the process is determined by heat conduction, then low-intensive convection is superimposed, and after a rather large interval developed free convection establishes.

We will write the expression for the interval, after which, according to [6], free convection is established near the heated body placed into the liquid:

$$\tau_0 = \Phi(\mathrm{Pr})\,(l/g\beta\Delta T)^{1/2},$$

TABLE 1. Scale of Convection Lag Behind the Front of Thermal and Hydrodynamic Boundary Layers vs Temperature Drop and Liquid

T, °C	Water, $Pr=7$, $Ec=10^{-9}$			Glycerine $Pr=12465$, $Ec=10^{-6}$			PMS-100 $Pr=185$, $Ec=10^{-8}$		
	l_*, mm	δ_{g*}, mm	δ_{t*}, mm	l_*, mm	δ_{g*}, mm	δ_{t*}, mm	l_*, mm	δ_{g*}, mm	δ_{t*}, mm
130	—	—	—	52	98	0,88	4,67	25,9	1,91
100	—	—	—	67	111	0,99	6,07	30	2,2
80	1,53	10,4	3,9	84	125	1,12	7,59	33,2	2,44
60	2,04	12,05	4,5	112	144	1,44	10,12	38,34	2,81

where $\Phi(\mathrm{Pr})$ is some function of the Prandtl number. In [6] it is found that the given function has the form

$$\Phi(\mathrm{Pr}) = 5{,}3\,(0{,}9 + \mathrm{Pr})^{1/2}.$$

The time of motion for the SHS front is $\tau = l/V$.

To visualize the real processes taking place as free convection develops from a moving source, we plot dependencies for the time of front motion (Fig. 2, curve 1) and for the time of development of free convection (curve 2). As is seen from Fig. 2,

there exist such l_* and τ_0^* when the velocities of motion for the synthesis front and the development of free convection are equal. In this case the convection at the given point will develop τ_0^* later, after the front has passed. In the region $l < l_*$ free convection has no time to develop. With $\tau = \tau_0$ we will obtain the expression for l_*, characterizing the scale of convection lag behind the front:

$$l_*/V = \Phi(\mathrm{Pr})\,(l_*/g\beta\Delta T)^{1/2},$$

or

$$l_* = \Phi^2(\mathrm{Pr})\,V^2/g\beta\Delta T.$$

Thus, for a moving source one can distinguish the following stages by the time of development of free convection. At the initial instant the process of heat conduction followed by the transition region is determining ($l \leq l_*$). The second one is the stage of development of free convection which is affected by the moving front. For this zone $l \cong l_*$ is characteristic and the scale of velocity which is equal to the burning rate becomes determining. The third one is the steady-state developed free convection zone when convection does not depend on the moving front $l \gg l_*$.

Figure 3 plots the time of free convection development vs the time of motion of the SHS front for several liquids.

In free convection, when motion of a liquid is totally determined by the process of heat exchange, the thermal and hydrodynamic boundary layers cannot be considered separately.

With $\mathrm{Pr} \gg 1$ the region of substantial display of molecular heat conduction is equal or smaller than that of substantial display of molecular viscosity [6]:

$$\delta_{g*}/\delta_{t*} = \mathrm{Pr}^{1/2},$$

where

$$\delta_{g*} = l_*/\mathrm{Gr}_x^{1/4}.$$

The results of numerical estimates for water, glycerine, and PMS-100 at different temperature drops are given in Table 1.

Thus, the above approach makes it possible not only to analyze the development of free convection from a heat source, i.e., self-propagating high-temperature synthesis, but also to select a liquid (on which the processes of interest can be observed) and a heat source (a specific SHS-composition).

This enables us at a qualitative level to consider a new class of convection-related problems.

NOTATION

V, velocity of front motion; U, natural convection velocity; τ, time of front motion; τ_0, time for development of natural convection; δ_g, width of hydrodynamic boundary layer; δ_{t_*}, width of thermal boundary layer.

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