The conditions for the implementation of the convective mode of combustion for granular mixtures of Ti + xC

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Abstract. An experimental-theoretical method is proposed for calculating the burning velocity of Ti + xC granulated mixtures in a convective mode. The quadratic dependence of the burning velocity on the gas flow rate is shown. The behavior of the burning velocity in the convective mode was studied on the governing parameters and the gas flow rates are calculated, at which the convective mode of combustion replaces the conductive one. The transition between the combustion modes of a granulated mixture of Ti + 0.5C was experimentally realized, and a good agreement between the gas flow rate at the boundary of modes and the calculated value in the transition point was shown. The results can be used to explain and predict fast forest fires, since the fast convective combustion mode is realized with large gas flow rates (high wind speed) and low ignition temperatures typical of forests during the drought period.

1. Introduction

In the experimental works [1, 2], the existence of the convective mode of combustion of fast-burning granulated mixtures Ti + xC (0.5 ≤ x ≤ 1) with pressure drops below 1 ÷ 2 atm was established. The notion "convective mode" is used here for the designation of a combustion process in which the flow of active gas ignites granules from the surface, providing a higher velocity of the combustion front than it follows from estimates on the theory of filtration combustion (conductive mode) [3] and higher velocity than in the inert gas flow. However, the regularities of combustion in this mode were not investigated, and the parametric regions of the implementation of various modes were not established. Known from the literature, numerical calculations have not established the criteria for the transition from the conductive mechanism of combustion to the convective one [4, 5].

In this work, a theoretical answer is derived to the question of the region of the convective combustion mode realization and the nature of the dependence of the burning velocity in this mode on the gas flow rate for Ti + xC mixtures, taking into account the results of work [2]. For a mixture of Ti + 0.5C, experimental confirmation of the transition of the combustion regime from conducting to convective is obtained, and the parameters of this transition are determined.

2. Calculation of combustion velocity dependence on gas flow rate

In [2], for the granular composition of Ti + C, under the assumption of the existence of a convective mode, the heat transfer coefficient of the granules with filtered nitrogen was calculated. In the calculation, we used the values of the effective combustion temperature and the ignition temperature of a mixture of Ti + C and the experimental ignition time of the granule. Then, assuming that the heat transfer coefficient remains the same as for the Ti + C mixture, the combustion temperatures for the Ti
+ 0.5C and Ti + 0.75C mixtures were calculated. The present work used this approach to solve the inverse problem — using the known heat rate coefficients the ignition time for different gas flow rates was calculated, and hence the velocity of the ignition wave was obtained. The velocity of the ignition is considered to be equal to the burning velocity of the mixture in a convective mode. Let us demonstrate the method of calculating the dependence of the burning velocity in a convective mode on the gas flow rate using the example of a mixture of Ti + C.

The velocity of the ignition wave is determined by the formula:

\[ u = \frac{d}{t}, \]

where \( d \) is the characteristic size of the granules (\( d = 1 \) mm), \( t \) is the ignition time of the granule.

Taking into account the high burning rate, the time of the granule ignition by the filtering gas \( t \), as in [2], can be determined from the expressions for heating a semi-infinite body under boundary conditions of the third kind [6]:

\[ \frac{T_{ig} - T_0}{T_s - T_0} = 1 - \varphi(\omega), \]

where \( T_{ig} \) is the combustion temperature of a mixture, \( T_0 \) is the initial temperature of the granulated mixture, \( T_{ig} \) is the surface temperature of the granule at the instant of ignition, the table additional error function \( \varphi(\omega) = \exp(\omega^2) \cdot (1 - \text{erf}(\omega)) \), and the argument \( \omega \) of the table function is \( \omega = \alpha^*(Q) \sqrt{a t} / \lambda \).

Here \( \alpha^*(Q) \) is the coefficient of interphase heat transfer depending on the gas flow rate \( Q \), \( \lambda \) is mean thermal conductivity (\( \lambda = 1 \) W/(m·K) [7]), \( a \) is heat diffusivity of granules (\( a = 10^{-2} \) m²/s [8]). Given (1), the velocity of the ignition wave \( u \) is expressed as follows:

\[ u(Q) = \left[ \alpha^*(Q)/\omega \right] \lambda \frac{d}{a} \]

(2)

The value of \( T_{ig} \) is equal to the temperature \( \alpha \to \beta \) transition in titanium (1155 K) when burning in a stream of nitrogen and the melting point of titanium (1933 K) when burning in a stream of argon [1,2]. Thus, to calculate the dependence of the burning velocity on the gas flow rate, it is necessary to establish the dependence of the heat transfer coefficient of the granules with the gas \( \alpha^* \) on the gas flow rate \( Q \).

To calculate the heat transfer coefficient of a porous substance with a gas flow \( \alpha \) we will use the formula obtained by transposing the criterion expression from [9]:

\[ \alpha = \rho_g \frac{Q \cdot c_g \cdot Pr^{-\frac{2}{3}} \cdot (1-\varepsilon)^{-1} \cdot \Psi(\varepsilon)}{4s}, \]

\[ \Psi(\varepsilon) = 0.508 - 0.56 \cdot (1 - \varepsilon), \quad \varepsilon < 0.4, \]

\[ \Psi(\varepsilon) = 1 - 1.164 \cdot (1 - \varepsilon)^{2/3}, \quad \varepsilon > 0.4. \]

(3)

Here \( Pr \) is the Prandtl number, \( 0 < \varepsilon < 1 \) is the open porosity of condensed matter, \( \rho_g \) is the gas density (\( \rho_N \) nitrogen, \( \rho_{Ar} \) argon), \( c_g \) is the gas heat capacity (\( c_N \) nitrogen, \( c_{Ar} \) argon), \( Q \) is the gas flow (vol), \( s = 2 \) cm² is the sample cross section area, \( d = 1 \) mm.

We note the directly proportional dependence of \( \alpha \) on the gas flow rate, its density and heat capacity in expression (3). To calculate the values of \( \alpha, \varepsilon \) was taken to be 0.5, which corresponds to the data of [2], Prandtl number for nitrogen was taken to be 0.8. The results of the calculations are given in table 1.

Compare the value of the heat transfer coefficient in the convective mode \( \alpha = 262 \) W/(m²K) at \( Q = 800 \) l/h, \( \Delta p = 1 \) atm (table 1) and the value calculated in [2] based on experimental data: \( \alpha^* = 2711 \) W/(m²K). The heat transfer coefficient \( \alpha^* \) is 10.4 times the theoretical value \( \alpha \) calculated by formulas (3). Such a strong difference in the heat transfer rate of gas with granules may be due to the roughness of the surface and the random nature of laying the granules of the mixture, which ensures rapid heating of the surface layer with a hot gas flow and ignition of the granule [10, 11].

Assuming that formulae (3) correctly reflect the dependence of the heat transfer coefficient on the gas flow rate, the values of the effective heat transfer coefficients for other gas flow rates \( \alpha^* \) were calculated by multiplying \( \alpha_0 \) from the table 1 to 10.4. The results of calculations \( \alpha^* \) are given in table 1.

In [2] it was shown that the convective mode is realized by combustion Ti + xC (0.5 ≤ x ≤ 1) mixtures in nitrogen. If we assume that a convective regime is also possible in the argon flow, it is necessary to use the heat transfer coefficients \( \alpha_{Ar^*} \) for argon in the estimates of the combustion velocity. To obtain
them, the values of $\alpha^*$, calculated for nitrogen, should be multiplied in accordance with the expression (3) by the ratio $\rho_{Ar}/(\rho_{N})$, and the Prandtl number for argon should be used (take 0.6).

**Table 1.** Heat transfer coefficients of Ti + C granulated mixture for different gas flow rates.

| $Q$, l/h | $\alpha$, Wm$^{-2}$K$^{-1}$ nitrogen | $\alpha^*$, Wm$^{-2}$K$^{-1}$ nitrogen | $\alpha_{Ar}^*$, Wm$^{-2}$K$^{-1}$ argon |
|---------|-------------------------------|----------------------------|----------------------------|
| 50      | 16                            | 169                        | 125                        |
| 195     | 64                            | 661                        | 489                        |
| 420     | 138                           | 1423                       | 1053                       |
| 600     | 196                           | 2033                       | 1504                       |
| 800     | 262                           | 2711                       | 2006                       |
| 942     | 308                           | 3192                       | 2362                       |
| 1100    | 360                           | 3728                       | 2758                       |

The results of calculating the effective heat transfer coefficients for a mixture of Ti + C in nitrogen and argon are applicable to mixtures of Ti + 0.5C and Ti + 0.75C at the same gas flow rates, since expression (3) does not contain thermal characteristics of mixtures. The values of the temperatures $T_g$, $T_0$, $T_{ig}$ used in estimation $\omega$ for mixtures Ti + xC in nitrogen and argon gas flows as well as the obtained values of $\omega$ are given in table 2. For each meaning of the flow rate $Q$, formula (2) calculates the burning velocity values in the convective mode in nitrogen and argon. The calculation of the velocities gives quadratic dependences, which is a consequence of the quadratic dependence of the burning velocity on the heat transfer coefficient $\alpha^*$ (expression 2), which in turn is linearly dependent on $Q$ (formula (3)).

**Table 2.** The results of calculations of $\omega$ and $u$ for mixtures Ti + xC.

| Gas    | $T_0$, K | $T(0, t_{ign})$, K | $\omega$, $u$, mm/s | $\omega$, $u$, mm/s | $\omega$, $u$, mm/s |
|--------|----------|---------------------|----------------------|----------------------|----------------------|
| Nitrogen | 300 K    | 1155 K              | 0.35 $9\cdot10^{-5}Q^2$ | 0.38 $8\cdot10^{-5}Q^2$ | 0.51 $4\cdot10^{-5}Q^2$ |
| Argon  | 300 K    | 1933 K              | 0.90 $8\cdot10^{-6}Q^2$ | 1.03 $6\cdot10^{-6}Q^2$ | 1.71 $2\cdot10^{-6}Q^2$ |

Figure 1 shows the calculated dependences of the burning velocity $u$ on the nitrogen flow rate in the convective mode at a permanent ignition temperature $T_{ig}$ for different values $T_g$ of the igniting gas temperature, corresponding to the mixtures from table 2 (curves 1, 3, 5). For these mixtures, the figure also shows the dependences of the burning velocity $u_f$ on the nitrogen flow rate (straight lines 2, 4, 6) calculated according to the theory of filtration combustion [3], in which the values of the burning velocity at $Q = 0$ are taken from [2].

From physical reason, it is clear that when the mixture is burned in a stream of nitrogen, the regime which provides a higher velocity of the front propagation is realized. Therefore, the intersection points of curves 1 and 2 (for the mixture of Ti + C), 3 and 4 (for the mixture of Ti + 0.75C), 5 and 6 (for the mixture of Ti + 0.5C) in figure 1 determine the calculated boundary of the transition from convective to convective mode of combustion in a co-current flow of nitrogen. For the burning velocity of Ti + xC mixtures in argon in the convective mode, the factors at $Q^2$ are an order of magnitude lower than for combustion in nitrogen (table 2), whereas the calculations according to the theory of filtration combustion give velocities close to velocities of combustion in nitrogen [2]. Consequently, the realization of the convective mode at gas flow rates at the experimental conditions [2] in the argon is impossible. This coincides with the conclusions of [2], made on the basis of a comparison of the ignition time of the granule in the argon flow and the time of its heating.
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Figure 1. The dependences of the burning velocity $u$ (lines 1, 3, 5) on the nitrogen flow rate $Q$ in the convective mode for mixtures of Ti + C, Ti + 0.75C, Ti + 0.5C (see parameters in table 2) and the velocities $u_f$ calculated for these mixtures according to the theory of filtration combustion (strait lines 2, 4, 6), correspondingly.

3. Discussion of theoretical results and comparison with experiment

The cause of a stronger dependence of the burning velocity in the convective mode on nitrogen flow rates (a larger multiplier at $Q^2$) with the raising in the soot content in the mixture is an increase in the combustion temperature and, accordingly, the gas temperature $T_g$, which leads to a decrease in $\omega$ in expression (1). Nitrogen flow rates on the boundary between combustion modes (in figure 1, the intersection points of curves 1 and 2, 3 and 4, 5 and 6) increase with raising content of soot $x$ from $x = 0.5$ to $x = 1$, which is a consequence of the growth of the burning velocity of mixtures Ti + $x$C with increasing $x$ in the absence of a gas stream. Therefore, the region of the conductive regime existence expands with increasing the content of soot $x$ in the mixture.

Let us analyze how the change in the ignition temperature of the granulated mixture $T_{ig}$ affects the velocity of combustion in a convective mode. Figure 2 shows the calculated dependence of the burning velocity $u$ on the nitrogen flow rate at $T_g = 3300$ K for different values of $T_{ig}$. To demonstrate the effect of $T_{ig}$ on the boundary of the conductive combustion mode in figure 2 (curve 5) we present the results of calculating the dependence of the burning velocity in nitrogen $u_f$ on gas flow rate using the theory of filtration combustion for a mixture of Ti + C. Note that, in accordance with the theory of filtration combustion, the burning velocity does not depend on the ignition temperature $T_{ig}$, therefore, as $T_{ig}$ varies, the dependence of the burning velocity on the gas flow rates does not change.

As can be seen from figure 2, the higher the ignition temperature of the granule, the higher values of the gas flow rate for the convective combustion mode realization. The dependences of the burning velocity in the convective mode on the nitrogen flow rate at different ignition temperatures $T(0, t_{ig})$ are quadratic, but with increasing $T_{ig}$ the multiplier value at $Q^2$ decreases (see table 2), which leads to the expansion of the implementation region of the conductive mode. Experimental verification of the proposed method of determining the boundary of the transition between the conducting and convective modes of combustion was carried out for a granular mixture of Ti + 0.5C in nitrogen. The experimental setup, starting materials and the method of preparation of the granules were identical to those described in [2], except that the mixture was made in a “drunk barrel” mixer using steel balls.
Figure 2. The dependence of the burning velocity on the nitrogen flow rate $Q$ in the convective mode at $T_g = 3300$ K for different values of $T_{ig}$: 1 - 1155 K, 2 – 1400 K, 3 - 1600 K, 4 – 2000 K. Straight line 5 shows a dependence of the combustion velocity of a mixture of Ti + C in nitrogen in the conductive mode.

The experimental dependence of the burning velocity of the Ti + 0.5C mixture on the nitrogen flow rate is shown in figure 3. Bold line in figure 3 shows the calculated curve, which consists of two parts: at flow rates below $Q = 779$ l/h, the conductive mode (calculated according to the theory of filtration combustion), above, the convective mode. The experimental value of the mode boundary was estimated from the coordinates of the point of intersection of the straight lines corresponding to a linear extrapolation of the left and right branches of the experimental curve, and was found to be 732 l/h. From figure 3, it can be seen that the proposed calculation method leads to a complete qualitative coincidence of the theoretical and experimental dependences of the burning velocity on nitrogen consumption and a good quantitative coincidence of gas consumption at the mode boundary.

Thus, a simple approximate method is proposed for calculating the burning velocity of granulated mixtures in the convective mode. It is shown that in this mode the dependence of the velocity on the flow rate of the filtering gas is quadratic. The regions of nitrogen flow rates are determined where the convective mode of combustion in granular mixtures Ti + xC (0.5 ≤ x ≤ 1) is realized. The impossibility of the convective mode is shown when burning granulated mixtures Ti + xC in the argon in the range of gas flow rates used in the calculations ($Q ≤ 1100$ l/h). It was concluded that the main factors contributing to the transition of combustion of granulated mixtures into a convective mode are an increase in the gas flow rate and a decrease in the ignition temperature of the granules. When burning a granulated mixture of Ti + 0.5C in a co-current stream of nitrogen, the value of the nitrogen flow rate at the boundary of the conductive and convective modes of combustion was experimentally determined, which well coincides with the results of calculations. The results obtained in this work can be used to explain and predict fast forest fires. Indeed, a fast convective mode of combustion occurs at high gas flows (high wind speed) and low ignition temperatures typical of forests during the drought period [12, 13].
Figure 3. Comparison of the experimental dependence of the burning velocity $u$ of the Ti + 0.5C mixture on the nitrogen flow rates $Q$ (curve 1) with calculations based on the theory of filtration combustion (curve 2) and on the model of the convective mode (curve 3).

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