Boron Particle Ignition in a Restricted Thermodynamical Equilibrium

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Abstract

PUBLISHED experimental evidence leads to the conclusion that a certain particle temperature is the most important prerequisite for boron particle ignition. For particle heating, a model concept of a hybrid gas generator is chosen. The resulting thermal state of the boron particles is characterized by a T^* temperature which is derived for a restricted thermodynamical equilibrium defined by the suppression of chemical contact between the reacting substances of the gas generator and the boron fuel, which is set to be in thermal contact only. A temperature diagram is derived with the help of an existing computer program for thermochemical calculations, in which the ignition readiness of the boron fuel is displayed in terms of a T^* temperature depending on a varied fraction of the boron fuel, which is set to be combusted in the primary process in order to achieve the temperature necessary for ignition of the remainder of the boron.

Contents

Some severe problems have prevented the realization of the full potential of elemental boron as a high-energy fuel. Extensive experimental investigations of boron particle ignition and combustion have shown them to be connected with the failure of the boron to ignite and to combust satisfactorily in practical applications.[1] In order to study the phenomena of ignition and combustion separately, a model motor consisting of a combination gas generator/ramburner seems to be well suited. The primary reactions of the gas generator provide the boron fuel in the necessary preignition state, such that ignition and combustion in air is safely attained in the course of the secondary reactions taking place in the ramburner at the ramair recovery pressure. Although a number of parameters influence the preignition state of the boron fuel, the preignition temperature seems to be of particular importance. In the proposed model application, the gas generator therefore serves to heat the boron fuel up to the well-known ignition temperature of about 1900 K. It is a characteristic feature of this gas generator process that a major part of the fuel (the inert fraction of the boron) does not take part in the chemical reactions, but rather stays in thermal contact with the reacting substances of the primary reaction. The resulting temperature is equivalent to the nonequilibrium temperature T^* introduced by Baumgartner[2] for combustion-chamber processes. Based on the T^* temperature of the primary combustion chamber, the T^* temperature of the primary exhaust may be derived under simplifying assumptions, e.g., thermal and mechanical equilibrium in the isentropic expansion of a gas particle mixture.

In our model motor, the use of a hybrid gas generator is envisaged with a fluid oxidizer sprayed onto a solid-fuel block consisting mainly of elemental boron and a hydrocarbon binder which provides the mechanical stability of the block. Assuming a complete consumption of the binder in the primary reaction, the energy required to heat the boron fuel can be expressed in terms of the fraction of the boron which has to be combusted in the primary reaction in addition to the organic binder, such that the rest of the boron attains its ignition temperature. We assume a fuel block composed of 80% boron and 20% polyethylene, which is to simulate the organic binder. The oxidizer is assumed to be redfuming nitric acid (RFNA) composed of 14% N_2O_4, 84% HNO_3, and 2% H_2O. For a varied reactive fraction of the boron, two combustion regimes of the gas generator have been investigated. In case a, the amount of RFNA is in stoichiometric proportion to the organic binder; in case b, the amount of RFNA is in stoichiometric proportion to the organic binder and the reactive boron fraction. Thus, case a is fuel rich and case b a stoichiometric combustion regime.

The computer program SP-273 by Gordon and McBride[3] has been applied for the thermochemical calculations. For use of the program, the reacting substances may be in any state of aggregation. According to our model of the gas generator, the inert fraction of the boron represents the boron particles which are to be discharged into the secondary combustion chamber. For the range of temperatures under investigation, a large amount of boron would therefore appear in the solid or liquid state. Since we have to make assumptions as to the velocity of the boron particles in the course of the primary expansion, and since we plan to allow for a given thermal nonequilibrium, the inclusion of the inert boron into the SP-273 program is precluded. Therefore, only the reacting substances are dealt with in the program[3] and the T^* temperatures, which result from the presence of the inert fraction of the boron, have to be derived by additional computations. In the course of the thermochemical calculations, two options of the program[3] have been used. In the (H,p) option, the adiabatic flame temperature T_c^a is derived under the provision of a set chamber pressure p_c and a set enthalpy of the reacting substances. In our calculations, we assumed $p_c = 30$ bar. Subsequent isentropic expansion to set values of the pressure p is calculated to provide the temperatures T^a of the gas flow. In the (T,p) option, the reaction enthalpy is derived under the provision of a set pressure p and temperature T.

The fusion temperature of boron was found to be only slightly pressure dependent, whereby the specific enthalpy of boron $h_p(T)$ was taken as independent of the pressure.

The heat transferred to the inert boron from the substances which were allowed to react was determined by establishing thermal equilibrium between the reacting substances and the inert boron. Let m designate the mass of the primary reagents and M designate the mass of the inert boron which is supposed to be at an initial temperature T_0. If T_c^a designates the adiabatic flame temperature for the reacting species at the

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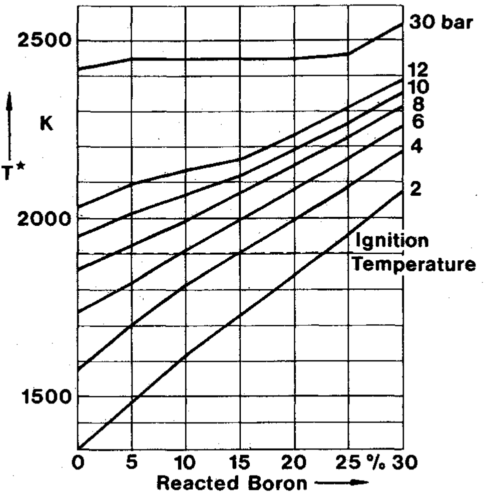

Fig. 1 T^* **temperatures for case a: amount of RFNA in stoichiometric proportion to binder.**

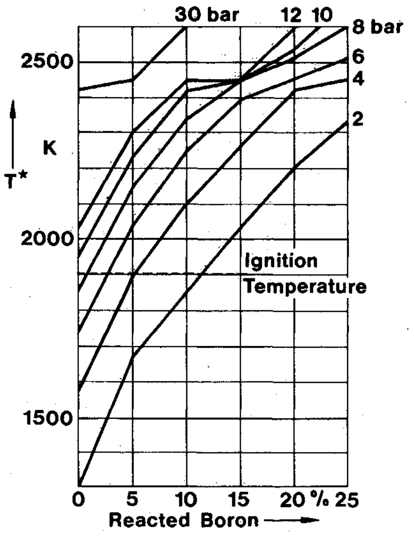

Fig. 2 T^* **temperatures for case b: amount of RFNA in stoichiometric proportion to binder and reacted boron.**

chamber pressure p_c, then the temperature T_c^* of the thermal equilibrium between the products of the primary reaction and the inert fraction of the boron may be found by iteration, such that the heat taken from the reacting substances equals the heat received by the inert boron

$$m(h_g(T_c^a;p_c) - h_g(T_c^*;p_c)) = M(h_p(T_c^*) - h_p(T_0)) \qquad (1)$$

Here, $h_g(T;p)$ designates the enthalpy of the primary reagents and $h_p(T)$ the enthalpy of the inert boron. The left-hand side of Eq. (1) is a strictly decreasing function of T_c^* for any given value of p_c, whereas the right-hand side is strictly increasing in T_c^*. Thus, for any given value of M/m there exists a unique value of T_c^* which satisfies Eq. (1). By determining $h_g(T;p)$ with the help of the (p,T) option of the computer program,[3] the effect of changing compositions and phase transitions in the reacting substances are included. The deliberations, which led to Eq. (1) under the assumption of thermal equilibrium between the reacting and inert substances, may obviously be generalized to the case of a given thermal nonequilibrium by which one might want to describe the incomplete heat transfer from the reacting substances to the inert boron.

The primary process results in a heated gas/particle mixture which is discharged into the secondary combustion chamber by expanding through a nozzle. The kinetic energy gain of the gas/particle nozzle flow derives from $h_g(T_c^*;p_c)$, as only the gaseous components are able to do expansion work. Because of the thermal contact between the boron particles and the gaseous components during the expansion, some of the particle enthalpy is converted into the kinetic energy of the flow, whereas frictional entrainment of the boron particles in the flow results in a transfer of kinetic energy from the gas to the boron particles. Thus, there are four parameters characterizing the expanding gas/particle flow at a given pressure p: gas velocity v_g, gas temperature T_g, particle velocity v_p, and particle temperature T_p. For the intended applications, it is desirable to keep the particle temperature as high as possible to facilitate ignition. This is abetted by larger particle sizes and the low thermal conductivity of the boron. It is further desired to keep the particle velocity as low as possible to facilitate complete combustion in the secondary chamber. These stipulations can be realized to a certain degree of the actual construction of the gas generator. The principle of energy conservation leads to the equation,

$$mh_g(T_c^a;p_c) + Mh_p(T_0) = m(h_g(T_g;p) + \tfrac{1}{2}v_g^2) + M(h_p(T_p) + \tfrac{1}{2}v_p^2) \qquad (2)$$

The limiting case $T_p = T_g = T^*$, $v_g = v_p$ is of special interest, as the resulting temperatures T^* represent lower bounds of the actual particle temperatures. Let W_g designate the gas velocity for a flow under equivalent conditions but with no particles present. Then W_g represents an upper bound of v_g, if one makes the usual assumption that the volume occupied by the particles is negligible. Assuming $v_g = W_g$ then furnishes

$$h_g(T_c^a;p_c) - \tfrac{1}{2}v_g^2 = h_g(T^a;p) \qquad (3)$$

Here, $h_g(T^a;p)$ represents the enthalpy of the reaction products after isentropic expansion from p_c to p with no inert boron present. W_g, $h_g(T^a;p)$ and T^a are easily derived with the help of the computer program.[3] Choosing $T_0 = 298.15$ K, one gets $h_p(T_0) = 0$, so that one derives from Eqs. (2) and (3)

$$m(h_g(T^*;p) - h_g(T^a;p)) + M(h_p(T^*) + \tfrac{1}{2}W_g^2) = 0 \qquad (4)$$

As the left side of Eq. (4) is a strictly increasing function in T^*, there exists a unique solution T^* of Eq. (4) for any given value of M/m. The derivation of Eq. (4) obviously allows for a generalization by assuming a certain thermal or kinetic nonequilibrium between the gaseous and the particulate components of the flow. T^a is an obvious upper limit of the particle temperature T_p such that one finally obtains

$$T^* < T_p < T^a \qquad (5)$$

The T^* temperatures resulting from Eq. (4) for two interesting combustion regimes are displayed in Figs. 1 and 2. Case a represents the fuel-rich combustion regime, whereas case b represents stoichiometric combustion. Curves marked with 30 bar designate the chamber temperatures T_c^*. Figures 1 and 2 show the decisive role played by the pressure p of the secondary combustion chamber when one wants to safeguard a particle temperature of 1900 K which is required for ignition. For a given secondary chamber pressure p, the concept of a hybrid gas generator allows for a simple adjustment of the amount of oxidizer. The effect of increasing the oxidizer becomes apparent by comparing Fig. 2 with Fig. 1.

References

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