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Evolution of detonation wave and parameters of its attenuation when passing along a porous coating

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ABSTRACT

Usually, attenuation of a shock or detonation wave at a normal or tangential impact to the surface of technological structures can be carried out using porous coatings. In the present work the processes of decay of a detonation wave in a hydrogen–air mixture during propagation along a porous surface were considered. We investigated how the replacement of the porous layer on the inner walls of the channel can affect the amplitude of a shock wave and the impulse of pressure generated by the passing detonation wave. We have shown how a shape of the flame front and the porous surface changes, and how these can affect the pressure beneath the porous layer. As characteristic materials, we considered porous materials with open pores (polyurethane foam, steel wool) and also with a gas-impermeable tape. Propagation and evolution of the shock wave and flame front were investigated in a rectangular cross-section channel, with a porous polyurethane, polypropylene tape or steel wool coating. Experiments were carried out in a hydrogen–air mixture undiluted by inert gas at atmospheric pressure. A stationary detonation wave was formed before entering the section with the porous walls. The dynamics of the flame front and shock waves were registered using a high-sensitivity digital camera and a Schlieren system. Pressure beneath the porous coating was measured by piezoelectric pressure transducers.

1. Introduction

At present, hydrogen is considered as a promising environmentally friendly fuel. However, due to the wide concentration limits of ignition, low density and high speed of sound, the use of hydrogen is associated with a high probability of spontaneous explosions and structural damage. On the one hand, it is a gas capable of escaping from the room in a short time. On the other hand, the molecular-kinetic properties of hydrogen allow it to ignite over the widest concentration range with minimum ignition delay. In those cases where the presence of a ventilation system and an active safety system may not be sufficient to prevent ignition or quenching in enclosed spaces, passive safety systems that prevent the formation of detonation of hydrogen–air or hydrogen–oxygen mixtures must be developed. For example, a porous coating can be used as a passive safety system. The most urgent task is to ensure safety from explosion at nuclear facilities, where forced ventilation of process rooms has significant limitations.

When considering the problem of reducing the shock-wave effect on a structural material, the motion of the shock wave and the mass of compressed gas directed along the direction normal to the surface under investigation is often studied. For example, an interaction between an air shock wave and a rigid wall covered by a porous screen has been investigated [1] numerically and experimentally. It was shown that the degree of amplification in a porous medium can be greater than for a consolidated medium. The degree of amplification is dependent on the thickness, the structure and the grain size of the porous medium.

Of special interest is the study of the propagation of the detonation wave along a porous coating. In the case when the shock wave moves along the surface of the porous coating, the intensity of the shock action also decreases.

The effect of a porous wall on detonation propagation has been considered [2]. Using a material of porosity 40–50%, covering the walls made it possible to double the deflagration-to-detonation distance form 19.1–25.4 cm for plain steel walls to 38–51 cm for fine liners (diameter of the pores 0.04 mm), and to 51–64 cm for coarse liners (0.07 mm). By *Babkin and Korzhavin* [3] an attempt was made to combine information on the propagation of combustion and detonation waves in systems with resistance for the purpose of controlling deflagration-to-detonation transition. It was based only on the resistance parameter, instead of the blocking ratio, hydraulic resistance and turbulence coefficient, etc.

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Nomenclature

ER equivalence ratio, coefficient of molar excess of hydrogen

It was shown that the resistance can accelerate the combustion of the mixture by rendering it turbulent or by increasing the surface area of its front. On the other hand, the resistance decelerates the flow, leading to blocking of the pore channels. The influence of different wall roughness generated by a Shchelkin spiral on the detonation limits in hydrogen–oxygen mixture was investigated by *Zhang* [4]. When the ratio of wire diameter to pitch of the Shchelkin spiral is larger than 0.333, this can lower the propagation velocity of the detonation and has a negative effective on the detonation propagation limits. The physical mechanism of the weakening of detonation waves in channels with acoustically absorbing porous walls was considered by *Sharypov and Pirogov* [5]. When the reflection coefficient in the calculations is set equal to zero, the trajectories of the triple points moving from the walls completely vanish.

Since the front of the detonation wave has a cellular structure formed by the motion of transverse waves, the presence of a porous coating leads to a weakening in the intensity of these waves, and to a decrease in the detonation wave intensity and hence to its decay. The essential role of transverse waves in the propagation of detonation has been demonstrated [6]. On the basis of experimental data, the authors presented graphical limits of detonation or deflagration combustion, depending on the thickness of the porous layer (porosity 0.56) and the ratio of the diameter of the plexiglass tube to the detonation cell size. Data were given for four mixtures: $H_2/0.5O_2$, $C_2H_2/4O_2$, $C_2H_4/3O_2$ and $C_3H_8/5O_2$. It has been shown in detail [7,8] that the failure of typical hydrocarbon detonations in porous wall tubes is attributed to the attenuation of their transverse wave structure. It was established that open cell flexible materials such as fibreglass wool ($\rho = 37\,kg/m^3$), polyurethane foam ($\rho = 30\,kg/m^3$) are more effective in detonation attenuation of stoichiometric oxy-hydrogen mixtures than are closed-cell polyurethane foams ($\rho = 20\,kg/m^3$) and rigid porous materials (porosity 30%) [7]. As has been shown [8], the smallest critical distance between porous walls in a square-section tube is about four times the detonation cell size.

The importance of the transverse wave instability for typical hydrocarbon mixtures in critical conditions, such as at the critical tube diameter, has been demonstrated [9]. The graphs of the critical pressure were given dependent on the dimensionless ratio of the length of the porous section to its transverse dimension. A stability analysis was carried out considering slightly porous walls in an idealised detonation confined in a circular pipe [10]. It was found that the slight porosity (1×10^{-5}–3×10^{-4}) attenuates or dampens the growth rate of perturbations for different radii.

Subsequently, various devices to suppress detonation were compared [11]. It was concluded that steel wool is only marginally more effective in attenuating transverse waves in detonations than the woven mesh used: ~8% in pressure deficit for hydrogen and ~16% in pressure for hydrocarbons. However, *Radulescu and Lee* [8] suggested that the weakening of the detonation due to the disappearance of the transverse wave only occurs for a detonable mixture with an irregular cellular structure. However, detonation weakening in mixtures with a regular cellular structure occurs for another reasons; namely, due to the mass divergence into the porous material. This has been investigated in detail [9]. The authors considered the detonation transition from a tube into an open space. The experiments of *Vasil'ev* [12] showed that materials with a porous structure (porolon, felt, sintepon) are the most efficient for quenching the transverse waves. It has been shown [13] that it is difficult for a silicone-rubber-walled tube to reduce the intensity of the detonation wave. For stoichiometric hydrogen–air mixtures, reductions of 5% in the propagation velocity and 12% in the pressure peak were recorded in comparison with those parameters in a smooth stainless tube.

Aluminium silicate wool, which is a type of a fibroid porous material with a high specific surface area, can decrease the outlet flame speed and attenuate drastically the explosion overpressure [14]. However, for that non-detonation combustion, the critical length of the porous tube was found. If the length of the porous material is less than 0.4 m, the acceleration effect dominates. At lengths greater than 0.4 m, the deceleration effect is gradually preponderant.

It is worth noting that in some cases the presence of a rigid porous coating can lead to acceleration of the flame front and to re-initiation of detonation. Combustion in a horizontal channel partially filled with a porous media has been investigated [15,16]. When the flame front achieves a velocity in the order of the speed of sound in the combustion products, and the gap height is greater than the mixture detonation cell size, the deflagration-to-detonation transition occurs in the gap [15]. The propagation mechanism is governed by the interaction of transverse pressure waves with the turbulent flame brush [16].

The effect of the pore size on the propagation of slow combustion has been studied [17,18]. It has been that the pore size can significantly affect the dynamics of the slow flame. Slow flame propagation (< 12 m/s) was investigated in a methane–air mixture with nickel foam meshes of different pore sizes (20–100 ppi) and porosities (85–95%) [17]. A 33–47% reduction in the overpressure was shown when the metal foam was used. The flame propagation (< 140 m/s) in a stoichiometric hydrogen–air mixture was investigated when stainless steel was used (line diameter 0.060–0.104 mm, bore diameter 0.193–0.528 mm) [18]. The attenuation of the pressure reached approximately 78.6%. Detonation propagations in stoichiometric hydrogen–oxygen mixtures diluted with argon and nitrogen were experimentally investigated in both smooth and porous tubes by *Wang* et al. [19]. It was shown that in the porous tube the detonation decays to deflagration with a velocity of 0.4–0.5 times the theoretical value of the Chapman-Jouguet detonation velocity.

The attenuation and re-initiation mechanism of detonations transmitted through a porous section consisting of a two-dimensional array of staggered cylinders was investigated experimentally and numerically by *Radulescu and Maxwell* for acetylene–oxygen mixtures [20]. For the equimolar mixture of acetylene and oxygen the critical pore size dimension was between 30 and 60 half-reaction lengths. The re-initiation of the detonation for two explosive mixtures of $C_2H_2 + 2.5O_2 + 70\%$ Ar (stable detonation with regular cellular pattern) and $H_2 + N_2O$ (unstable detonation with irregular cellular structure) has been investigated [21]. Attenuation and recovery of the detonation wave after passing through acoustically absorbing sections in a hydrogen–air mixture at atmospheric pressure has been investigated [22]. It was shown that the recovery of the detonation wave after passing the porous section is possible when the velocity of the shock wave is higher than the Chapman-Jouguet acoustic velocity.

The role of diffusive turbulent mixing and transverse waves in controlling the detonation limits in channels with porous walls for propane–oxygen and hydrogen–oxygen–argon mixtures has been investigated both experimentally and numerically [23].

Analysing the cited works, it can be concluded that the mechanism of decay of the detonation wave when propagating along the porous coating is rather complicated. The decay can be caused by a number of factors, such as weakening of transverse waves, radial shear of combustion products, heat losses, interaction of the boundary layer with the combustion zone, and others. The question of the evolution of the flame moving along a porous surface during the decay of the detonation wave remains poorly understood.

In order to reduce the probability of detonation formation and to prevent the destruction caused by combustion of gas fuel mixtures, it is necessary to evaluate the possibility of decay of detonation waves at atmospheric pressure. The study of the patterns of decay or re-initiation of detonation in mixtures undiluted by inert gases is important for