Explosion propagation in inert porous media

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Porous media are often used in flame arresters because of the high surface area to volume ratio that is required for flame quenching. However, if the flame is not quenched, the flow obstruction within the porous media can promote explosion escalation, which is a well-known phenomenon in obstacle-laden channels. There are many parallels between explosion propagation through porous media and obstacle-laden channels. In both cases, the obstructions play a duel role. On the one hand, the obstruction enhances explosion propagation through an early shear-driven turbulence production mechanism and then later by shock–flame interactions that occur from lead shock reflections. On the other hand, the presence of an obstruction can suppress explosion propagation through momentum and heat losses, which both impede the unburned gas flow and extract energy from the expanding combustion products. In obstacle-laden channels, there are well-defined propagation regimes that are easily distinguished by abrupt changes in velocity. In porous media, the propagation regimes are not as distinguishable. In porous media the entire flamefront is affected, and the effects of heat loss, turbulence and compressibility are smoothly blended over most of the propagation velocity range. At low subsonic propagation speeds, heat loss to the porous media dominates, whereas at higher supersonic speeds turbulence and compressibility are important. This blending of the important phenomena results in no clear transition in propagation mechanism that is characterized by an abrupt change in propagation velocity. This is especially true for propagation velocities above the speed of sound where many experiments performed with fuel–air mixtures show a smooth increase in the propagation velocity with mixture reactivity up to the theoretical detonation wave velocity.

Keywords: porous media; flames; detonations; explosions

1. Introduction

Explosion propagation in a porous medium is governed by both the properties of the gas mixture and the geometric characteristics of the porous medium. This is a very difficult research topic because the interior of the porous medium is largely inaccessible to experimental measurement. Furthermore, numerical analysis is difficult because of the complex internal flow path structure. Porous media take on different forms depending on the application, e.g. metallic and ceramic foam, fibrous fillings, bed of sand or spheres. Porous media are typically characterized by the pore size and the porosity, which is defined as the ratio of the void volume

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and the total volume. Most porous media used in experiments are composed of spheres because of their well-defined shape. Closely packed spheres are the most dense arrangement possible that has a theoretical porosity of 0.26, whereas loose randomly packed spheres have a porosity of 0.40 [1]. Because of the complex shape of the pore cavity, it is difficult to define a pore size. In the porous media combustion literature, the effective pore size is generally taken to be equal to one-third the sphere diameter [2]. For foams, the porosity and effective pore size are specified by the manufacturer [3].

The understanding of combustion in porous media is important for explosion hazard analysis. The most common application, which is not the focus of this paper, is the use of porous media in flame arresters. Flame arresters are used in the chemical industry for explosion protection of piping and vessels where a combustible gas is present and there is a possibility of accidental ignition. The arrester material is selected based on its ability to mitigate an explosion while not introducing excessive pressure drop for flow-through systems. The medium is chosen such that the pore size is small enough to quench the flame. Combustion phenomena are not generally affected by the porous media material as the heat-transfer rate between phases is limited by the thermal conductivity of the gas. Spalding [4] showed analytically that the condition for quenching of a planar laminar flame in a smooth-walled tube corresponds to a critical Peclet number of 60.5. The Peclet number for this application is defined as

$$Pe = \frac{\rho c S_u d}{k}$$

where $S_u$ is the laminar burning velocity, $d$ the tube inner diameter, $\rho$ the density, $c$ the heat capacity and $k$ the thermal conductivity of the gas. The Peclet number is important in porous media combustion because it represents the ratio of the rate of chemical energy release in the voids and the rate of heat loss to the porous medium. Experimental flame quenching data obtained in various porous media have shown good agreement, to within $\pm 50\%$, with the above critical Peclet number, where $d$ is taken to be the effective pore diameter [2,5,6]. Deviation from the theoretical value could be attributed to many factors, including flame instabilities, unburned gas flow and non-planar flamefront across adjacent pores [2]. For conditions where the Peclet number is larger than the critical value, a range of flame and detonation-propagation phenomena are possible. This paper provides a review of the explosion propagation regimes in obstructed channels and porous media. Recent experimental results are highlighted to draw parallels between the explosion propagation in porous media and obstructed ducts.

2. Flame propagation in multi-compartment channels

There are two fundamental velocities for a propagating combustion wave: the planar laminar burning velocity and the Chapman–Jouguet (CJ) detonation velocity. For hydrocarbon fuel–air mixtures, the laminar burning velocity is of the order of 0.1 m s$^{-1}$ and the CJ detonation velocity is of the order of 2000 m s$^{-1}$. The propagation mechanism responsible for these two combustion modes is very different. The propagation of a detonation wave is governed by shock ignition, and the CJ detonation velocity is solely dependent on the energy content of
the mixture. The propagation of a laminar flame is governed by the diffusion of mass and energy, and the burning velocity depends on the rate of diffusion and chemical reaction.

The presence of obstructions in the path of the combustion wave has a dramatic effect on both combustion phenomena. For a tube with relatively low blockage obstructions, such as orifice plates or mixing tabs, a detonation wave can propagate at a velocity significantly below the CJ value, and a flame can propagate at a velocity several orders of magnitude larger than the laminar burning velocity. Porous media represent an extreme case of flow obstruction that affects the entire flamefront. The flame path through a porous medium is very complex owing to the multitude of irregular shaped pathways. As a first approximation, one can consider the flamefront to propagate through a linear series of interconnected compartments. Flame propagation studies have been carried out in a variety of such geometries, including interconnected cylindrical volumes [7] and cubic volumes [8]. An extensive research programme was carried out at McGill University in the 1980s investigating explosion front propagation in a tube filled with periodic orifice plates that can be treated as interconnected cylindrical shaped compartments [9,10]. As background knowledge for the discussion of explosions in porous media, a brief review of combustion propagation in an obstacle-laden channel is provided in §2a. A comprehensive review of the subject was published by Ciccarelli & Dorofeev [11].

(a) Flame acceleration in obstructed channel

Almost a century ago, Chapman & Wheeler [12] showed that periodic obstacles placed in a cylindrical tube result in flame acceleration to a velocity greater than $200 \, \text{m} \, \text{s}^{-1}$, even in a relatively insensitive methane–air mixture. This is more than three orders of magnitude greater than the laminar burning velocity. Shchelkin [13] used a different type of periodic obstacle to promote flame acceleration: he inserted a spiral-shaped wire in a tube to roughen the inner wall to promote flame acceleration leading to transition to detonation. The deflagration-to-detonation (DDT) run-up distance was reduced by two orders of magnitude with the spiral in place. Shchelkin pointed out the importance of the turbulence generated by the interaction of the unburned gas flow ahead of the flame and the wire. The spiral perturbs the unburned gas flow generating a non-uniform axial velocity profile across the tube cross section that distorts the oncoming flame. The spiral also generates a turbulent shear layer, originating from the inner edge of the wire, that enhances the local burning rate. Both these effects result in an increase in the volumetric burning rate and a corresponding higher unburned gas velocity. This feedback mechanism involving the volumetric burning rate and the unburned gas velocity results in very efficient flame acceleration. When the flame reaches a velocity approaching the unburned gas speed of sound compression waves form ahead of the flame that eventually coalesce to form a strong lead shock wave. Further flame acceleration is achieved by the interaction of the reflected shock waves, formed by the collision of the lead shock wave and the spiral, and the flamefront.

With the recent emergence of high-quality high-speed video cameras, much has been learned about the mechanisms involved in the different stages of flame acceleration in an obstructed channel. Experiments carried out in an optically
access, it is observed that the flow blockage ratio (BR) defined as the ratio of the open area and the channel cross-sectional area. Several images taken at the ignition end of the channel with 0.33 BR obstacles showing an accelerating flame in a stoichiometric methane–air mixture at an initial pressure of 47 kPa are shown in figure 1. Early in the flame acceleration process, a pair of vortices form in the unburned gas flow downstream of the obstacles. The subsequent entrainment of the flame into the vortices (figure 1a) results in an increase in flame area and an acceleration of the flame tip that propagates through the core of the channel. The flame tip accelerates as it propagates in the area contraction through the obstacle pair and then decelerates in the expanding flow after the obstacle pair. This is repeated at every obstacle pair producing an oscillation in the flame tip velocity with axial distance, the magnitude of which is strongly influenced by the obstacle blockage ratio. As the flame tip achieves a velocity of 100 m s$^{-1}$ (figure 1b) the vortex rings grow to become turbulent recirculation zones that fill the volume between adjacent obstacles. The recirculation zone is bounded by a strong shear layer originating at the obstacle inner edge that prevents the flame from immediately turning the corner around the obstacle into the recirculation zone. At this stage, the flame tip, which remains laminar, is driven by the turbulent combustion in the shear layer and recirculation zone.

Figure 1. Schlieren video of flame propagation in a 7.62 cm square channel with 2.54 cm high obstacles spaced at the channel height: (a) inter-frame time is 1.67 ms, (b) inter-frame time is 0.67 ms [15].
As the flame accelerates to a velocity in excess of the speed of sound, compression waves form ahead of the flame that coalesce into a strong leading shock wave. At this stage, the explosion propagation is governed by the interaction of the reflected shock waves with the trailing turbulent flame (figure 2). The reflected shock forms when the lead shock interacts with the channel top and bottom surfaces and the front face of the obstacle. The images in figure 2 are taken at 2.1 m away from the ignition end of the channel equipped with 0.33 BR obstacles. The interactions of the reflected shock waves and the flamefront result in a very large centerline flame velocity variation between obstacles. As the flame passes through the obstacle in the first few images, it accelerates to a peak centreline velocity of $1100 \text{ m s}^{-1}$ and then decays to a velocity of $750 \text{ m s}^{-1}$ just before the next obstacle. The lead shock decays from 1000 to $750 \text{ m s}^{-1}$ over the same distance. These swings in both the centreline flame and shock velocities continue down the full length of the channel. For the highest blockage ratio obstacles tested (BR = 0.67), the swings in the centreline flame velocity are between 400 and $800 \text{ m s}^{-1}$. Combustion continues in unburned gas pockets between adjacent plates well behind the flamefront propagating in the channel core. For the 0.33 BR obstacles, significant combustion continues in pockets two to three obstacles back and for the 0.67 BR obstacles combustion continues five to six obstacles back. If the mixture is reactive enough eventually transition to detonation would occur at one of the reflection surfaces [16].

(b) Steady-state propagation regimes

Experiments investigating explosion front propagation in tubes equipped with equally spaced orifice plates were performed by Lee et al. [9]. The experiments were carried out in larger diameter tubes with different fuel–air mixtures. The effect of flow obstruction was investigated by varying the orifice plate BR. It was found that after an initial acceleration phase, described in §2a, the combustion
front propagates at a constant velocity. For a given tube diameter and orifice plate blockage ratio, four propagation regimes were identified: subsonic, choking, quasi-detonation and detonation. The transition between regimes is delineated by an abrupt change in the terminal velocity.

The final steady flame velocities measured in hydrogen–air mixtures at 1 atm in different tube diameters and orifice plate blockage ratios are provided in figure 3. For mixtures near the flammability limits, after an initial flame-acceleration phase, flame quenching occurs in tests with large blockage ratio orifice plates. For very high blockage orifice plates, the pressure across the orifice plate can build quickly, approaching a value close to the adiabatic constant volume pressure. Flame propagation occurs as a result of successive explosions in adjacent compartments interconnected by the orifice plate. Ignition is caused by the mixing of the hot products issuing from one compartment with unburned gas in the adjacent compartment. Lee et al. [9] proposed that quenching occurs when the ignition fails to occur because the characteristic mixing time is shorter than the characteristic chemical reaction time. Kuznetsov et al. [17] observed quenching in less-reactive mixtures in high-blockage square cross-sectional channels. They obtained photographic evidence of quenching followed by re-ignition in less-reactive mixtures in moderate blockage channels. In this case, quenching occurred as a result of the interaction of the flame and the strong turbulent flow immediately downstream of the blockage. If quenching does not occur, a subsonic steady flame velocity of the order of $100 \, \text{m s}^{-1}$ can be achieved (e.g. BR = 0.43, $\text{H}_2 < 12\%$). This subsonic propagation regime is typically bounded by a very narrow composition range and represents a condition where the flame acceleration feedback mechanism does not take hold.

For more reactive mixtures, the flame accelerates to a supersonic velocity around 700–800 m s$^{-1}$ (figure 3). Dorofeev et al. [18] showed that the transition
between the slow subsonic and the fast supersonic regimes is governed by basic flame properties, most notably the density ratio across the flame and the Lewis number. This is consistent with the idea that the expansion ratio across the flame is the driving force behind the flame acceleration feedback mechanism. The flame velocity in this supersonic regime is close to the combustion products’ speed of sound. Lee et al. [9] proposed that the final steady velocity is governed by wall friction and heat addition, analogous to one-dimensional compressible flow choking, and referred to it as the ‘choking regime’. In the choking regime, shock flame interactions (as seen in figure 2) play an important role in the explosion front propagation. Specifically, vorticity generated from the interaction of pressure waves with the density gradient in the reaction zone results in an enhancement of the burning rate (via enhanced mixing of fresh and product gases) that is required to achieve such high front velocities. The photographic evidence obtained by Ciccarelli et al. [15] indicates that in the choking regime the final steady velocity is controlled by the interaction of the flamefront with the reflected shock waves coming off the obstacle face. For lower blockage obstacles (as in figure 2), the flame is able to propagate through the obstacle pair relatively unaffected by the converging reflected shock waves as seen in images 5–8. For higher blockage obstacles, the reflected shocks reach the channel centreline before the flame passes through the obstacle pair. The collision of the two shock waves at the channel centreline results in a rearward propagating shock wave that interacts with the flamefront. The passage of this shock wave severely decelerates the flamefront resulting in a lower average velocity measured between adjacent obstacle pairs.

A further increase in the mixture sensitivity results in DDT. In an obstacle-laden tube, transition typically occurs as a result of shock reflection, either off the tube surface or at the obstacle face, producing the condition for transition [16]. Peraldi et al. [10] showed that a necessary condition for DDT to occur is that the mixture detonation cell size must be smaller than the orifice plate inner diameter. For mixtures far from stoichiometry, the detonation propagates at a velocity well below the theoretical CJ detonation velocity (figure 3). The data show that the smaller the tube diameter, or the larger the blockage ratio, the larger the velocity deficit relative to the CJ detonation velocity. In very rough-walled tubes, i.e. tubes equipped with orifice plates, detonation velocity deficits as large as 50 per cent are observed. This is in contrast to smooth-walled tubes where the detonation velocity deficit, due to detonation front curvature, is not much larger than 15 per cent. These low-velocity detonations are referred to as ‘quasi-detonations’. The wall roughness is responsible for a very low detonation velocity but also provides a mechanism by which these low-velocity detonations can exist [19]. It has been shown that in an obstacle-filled tube, the low average detonation velocity is the result of the continuous failing and re-initiation of the detonation wave [16]. Specifically, the detonation wave fails after each orifice plate because of the sudden expansion and then re-initiates owing to shock reflection off the tube wall, or the following orifice plate face. It was determined that if the orifice plate opening can accommodate at least 13 detonation cells, the detonation propagates at a velocity very close to the CJ value. At this condition, the detonation is not influenced by the lateral boundary conditions. This is consistent with the critical tube diameter criterion that defines the condition under which a detonation wave can successfully transmit from a tube into the open [20].
3. Combustion wave propagation in porous media

For conditions where the flame Peclet number is larger than the critical value [4], rapid flame acceleration is observed in porous media leading to steady propagation. Steady-state combustion propagation regimes have been identified, similar to the propagation regimes observed in obstacle-laden channels. The propagation regimes are typically categorized based on the magnitude of the combustion front velocity, e.g. low velocity, high velocity, sound velocity, low-velocity detonation and detonation regimes [21]. The explosion front propagation mechanism for each regime is different and is governed by the relative importance of inter-phase heat-transfer, turbulence and compressibility effects.

(a) Low-velocity regime

The low-velocity regime is a special case that exists in an open-ended flow-through system, commonly referred to as filtration combustion. This type of combustion only occurs in porous media with pore sizes less than a millimetre. Early research was typically carried out with fine sand [22]. Recently, there has been a renewed interest in this mode of combustion because of the development of ceramic foam radiant heaters [3]. The low-velocity regime is not directly relevant to explosion hazard applications. However, it will be briefly discussed here since it involves phenomena that are important in the other more relevant regimes. In filtration combustion, the combustible gas mixture flows through the porous medium, and depending on the filtration velocity, as well as the properties of the gas mixture and the porous medium, the combustion wave propagates upstream (opposite direction to the filtration flow), downstream (same direction as the filtration flow) or remains stationary. Stationary combustion in porous media was studied extensively both experimentally and theoretically by Takeno & Sato [23] and will not be discussed here. For the non-stationary conditions, the combustion wave moves at a velocity of the order of 0.1 mm s$^{-1}$ relative to the porous medium [24]. A plot of the combustion wave velocity measured in hydrogen–air mixtures as a function of hydrogen composition and filtration velocity is shown in figure 4. Note that the experimental conditions are such that the Peclet number based on the laminar burning velocity is less than the critical quenching value, and thus there is a minimum filtration velocity below which the reaction is quenched. The minimum filtration velocity required to establish a stable combustion wave for all the mixtures tested was about 0.4 m s$^{-1}$. At this filtration velocity, the combustion wave velocity is negative, i.e. the wave propagates in the opposite direction to the filtration flow. As the flow velocity is increased, the wave speed increases and then decreases eventually becoming stationary. In the experiments, the maximum combustion speed occurred at a filtration velocity of roughly 1.5 m s$^{-1}$. The combustion wave is stationary at a different filtration velocity for each mixture composition. A further increase in the filtration velocity above this critical value results in a change in the combustion wave propagation direction. This can be seen for the 65 per cent hydrogen mixture in figure 4.

In this low-velocity combustion regime, heat transfer between the porous medium and the oncoming unburned gas is the driving force for the propagation of the wave. The structure of the thermal wave consists of preheat, reaction...
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and thermal relaxation zones [22]. Chemical energy is released from the gas in the reaction zone that locally heats up the porous medium. Heat is transferred forward via conduction through the porous medium carcass. In the preheat zone, the oncoming gas is heated by the porous medium to its autoignition temperature at the start of the reaction zone. Therefore, the low-velocity combustion regime is characterized by solid-phase ignition [25]. Within the reaction zone, there is a large temperature difference between the gas and the porous medium; heat transfer between the two phases continues downstream in the thermal relaxation zone. At the end of the relaxation zone, the temperatures of the two phases equilibrate. In a gas-phase flame, the adiabatic equilibrium flame temperature depends on the thermodynamic properties of the gas. In the porous media low-velocity combustion regime, the equilibrium temperature depends on additional properties, including the filtration velocity, the porous medium properties and the direction of the wave propagation relative to the filtration flow. In general, an increase in the filtration velocity results in an increase in the equilibrium temperature. If the combustion wave moves counter to the filtration flow direction, an increase in the magnitude of the wave velocity results in a decrease in the equilibrium temperature. However, if the wave moves in the same direction as the filtration flow direction, an increase in the wave velocity results in an increase in the equilibrium temperature. This is because heat released from the gas that accumulates in the porous medium is returned to the incoming unburned gas. As a result, it is possible to obtain a maximum temperature that is higher than the gas adiabatic flame temperature, referred to as ‘superadiabatic’. Babkin et al. [26] developed a one-dimensional, two-phase model that considered heat exchange between phases and heat conduction in the solid phase but not in the gas phase. The model predicts the experimentally
observed trend in the combustion wave velocity as a function of the filtration velocity and the filtration flow velocity at which the wave direction changes seen in figure 4.

\( (b) \) High-velocity regime

In filtration experiments with larger diameter porous media, where the Peclet number is above the critical quenching value, there is a transition from the low-velocity to the high-velocity regimes when the filtration velocity is lowered. This is analogous to flashback in a burner configuration [27]. In this regime, heat and mass transfer in the gas govern flame propagation and heat conduction within the porous medium is unimportant. In this regime, there is no need for a filtration flow so experiments are typically carried out in a closed channel. Babkin et al. [24] carried out experiments in a vertical 2.88 m long, 48 mm square channel filled with polished steel balls. Tests were carried out with ball diameters in the range of 1.15–4.5 mm. The flame was ignited in a small open volume at the top of the channel and propagated downwards through the porous medium at a constant velocity. The flame velocity was obtained from time-of-arrival photo-diode measurements. The flame velocity measured for different methane–air mixtures and ball diameters as a function of initial pressures is provided in figure 5. For each series of experiments, there is a minimum pressure, below which the flame is quenched. For the largest diameter balls of 2.2 mm, the maximum flame velocity recorded was about 4 m s\(^{-1}\), which is more than an order of magnitude larger than the laminar burning velocity. In general, the flame velocity increases with initial pressure, even though the laminar burning velocity decreases with pressure [28]. The experimentally observed increase in flame velocity is governed by the turbulent nature of the flow and heat loss from the reaction zone to the porous medium.

The thickness of a laminar flame in the open, largely composed of a preheat zone, for hydrocarbon–air mixtures at atmospheric pressure is between 0.1 and 1 mm. For most mixtures, the laminar flame thickness varies inversely with pressure [28]. The thickness of a propagating flame in a porous medium consisting of 6 mm steel balls was measured by Korzhavin et al. [29]. The apparatus used to make the measurements is identical to the one used by Babkin et al. [24] discussed earlier. The experiments were carried out with stoichiometric methane–air, and the mixture reactivity was varied via the initial pressure over the range 0.2–1.5 MPa. The thickness was estimated by measuring the duration of the light emitted from the flame. As the chemiluminescence is a function of temperature it is not clear whether the measurement represents the reaction zone length or the total flame thickness. A small diameter transverse line-of-sight channel was created in the porous medium that extended the width of the apparatus. The transverse line-of-sight channel was located roughly at the midspan position in the vertically oriented apparatus. The channel was produced by placing a 2 mm wire through the apparatus, prior to loading the spherical balls. When all the balls were in place the wire was removed. The light in the channel was recorded by a photomultiplier (sensitive in the range of 300–600 nm) located outside the apparatus. Over the pressure range of 0.5–1.5 MPa, taking into account experimental data scatter, the duration of the light pulse was in the range of 5–10 ms. For pressures below 0.5 MPa, the light duration increases to a maximum.
Figure 5. Flame velocity versus initial pressure in spherical balls with different diameters and methane–air mixtures: curve 3, 9.5% methane, $d = 2.2 \text{mm}$; curve 4, 8.5% methane, $d = 1.5 \text{mm}$; curve 5, 9.5% methane, $d = 1.15 \text{mm}$; curve 6, 8% methane, $d = 1.15 \text{mm}$; curve 7, 7.25% methane, $d = 1.15 \text{mm}$; curve 8, 7% methane, $d = 1.15 \text{mm}$; curve 9, 6.8% methane, $d = 1.15 \text{mm}$ [21].

of 45 ms for the condition just above the quenching pressure of 0.2 MPa. The flame thickness was obtained by taking the product of the light duration and the measured flame velocity. The flame thickness increased from 3 cm at a pressure of 0.2 MPa to 5 cm at 1.0 MPa. However, the scatter in the data is of the same order as the measured 2 cm change in thickness. On average 0.7 cm of this uncertainty was found to be owing to the ‘waviness’ of the flamefront. There could also be a substantial error associated with scattered light originating in pores outside the line-of-sight channel that was not quantified. Pressure measurements were used to measure the thermal relaxation period, defined as the time from when chemical reactions start to when the gas and porous medium temperatures equilibrate. The thermal relaxation time and the light emission duration were found to be of the same magnitude.

Babkin et al. [24] proposed that the flamefront can be considered to be made up of many local flame fronts propagating through the porous medium cavities. Flame propagation through each cavity is limited to a maximum velocity owing to local quenching of the reaction zone. Babkin et al. [24] argue that quenching occurs because of intense heat exchange in the turbulent flame. This is different from the Spalding quenching model [4] where heat transfer to the walls occurs solely by conduction. In this way, the overall flamefront velocity is limited to a velocity dictated by the stabilizing effect of quenching in individual cavities. The condition for quenching was obtained by matching the characteristic time for thermal relaxation of the products due to heat transfer to the solid phase and the characteristic time for chemical reaction. The time for thermal relaxation
was obtained based on a one-dimensional model of a gas flow in a constant wall temperature cylinder with the inlet gas temperature equal to the adiabatic flame temperature. The model provides the following relationship for the quenching condition, and thus the flame velocity:

\[ Re = 0.6 \left( \frac{E(T_w - T_{ad})}{RT_w^2} \right)^{-3/2} Pe^3, \]  

(3.1)

where \( E \) is the activation number, \( R \) is the gas constant, \( T_w \) is the wall temperature and \( T_{ad} \) is the adiabatic flame temperature. The Reynolds number \( (Re) \) is based on the unburned gas flow velocity (approximated as the measured flame velocity less the laminar burning velocity) and the Peclet number defined in equation (1.1) is based on the laminar burning velocity. The experimental methane–air data were fitted with the relationship \( Re = 5 \times 10^{-4} Pe^3 \). The fit has the same Peclet number dependency as that obtained from the theory (equation (3.1)). The propagation limit obtained by either decreasing the laminar burning velocity or decreasing the cavity diameter corresponds to a Peclet number of roughly 60 which is in agreement with the quenching diameter criteria [4].

For ignition at the closed-end of a channel, the expansion of the gas across the flame results in an unburned gas flow ahead of the flame. In the experiments of Babkin et al. [24], \( Re \) of the unburned gas flow is in the range of \( 10^2 – 10^4 \). The unburned gas velocity used to calculate \( Re \) is based on the difference between the measured flame velocity and the mixture laminar burning velocity. At these \( Re \)'s, the flow within the cavities is turbulent. Mickley et al. [30] reported hot-wire anemometry measurements made in the voids of a porous medium consisting of spheres. For flows with \( Re \) of 4780 and 7010, they measured turbulence intensities of about 50 per cent with respect to the local mean velocity. Parallels between vortical motion in turbulent combustion and the ‘pulsating flow’ in porous medium combustion were discussed by Dobrego & Chornyi [31]. Based on their analysis, they proposed that the turbulent combustion mode which occurs in the high-velocity regime can be located on the Borghi diagram [32]. Using data from Babkin et al. [24] and Dobrego et al. [25], their analysis showed that the turbulent combustion in this regime is characterized by a Karlovitz number of unity, which represents the boundary between the distorted-flame and the distributed-reaction zone regimes. This is a very speculative model that cannot be verified because of the difficulties in measuring the flame structure in a porous medium.

\( (c) \) Sound velocity regime

By increasing the mixture reactivity, initial pressure or pore size, there is a transition from the high-velocity regime to the so-called sound velocity combustion regime. The explosion front velocity in this regime is subsonic and approaches the speed of sound in the porous medium as the initial pressure is increased, e.g. flame velocities are between 100 and 300 ms\(^{-1}\). Owing to wave dispersion, the sound velocity in porous media depends on the wave frequency and can be significantly lower than the speed of sound in the gas alone. It is debatable whether this propagation regime is unique, as the propagation mechanism of turbulent combustion is similar to that in the high-velocity regime. The distinguishing feature in this regime is that there is a local pressure buildup ahead of the flame compared with the high-velocity regime where the pressure
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Figure 6. Flame velocity versus initial pressure in spherical balls of 2.6–3.6 mm diameter and hydrogen–air mixtures: curve 1, 20% hydrogen; curve 2, 18% hydrogen; curve 3, 17% hydrogen; curve 4, 15% hydrogen; curve 5, 10% hydrogen; curve 6, sound velocity in porous medium. HVR, high-velocity regime; SVR, sound velocity regime; LVD, low-velocity detonation. Lyamin & Pinaev [34] data plot adapted from Babkin et al. [24].

in the channel is uniform. Pinaev & Lyamin [33] proposed that the high-velocity regime (they refer to it as the rapid compression regime) be characterized by a subsonic front velocity and a front peak pressure of greater than 1.1–1.2 times the initial pressure, corresponding to a front velocity of about 20 m s\(^{-1}\).

Lyamin & Pinaev [34,35] found that in very reactive mixtures, e.g. stoichiometric acetylene–oxygen and hydrogen–oxygen mixtures, flame propagation in the sound velocity regime was not observed, even in tests performed in sand with particle sizes in the range 0.6–1.2 mm. For these very reactive mixtures, the flame either quenched upon entering the porous medium or quickly transitioned to a supersonic mode of combustion. The quenching limits for stoichiometric acetylene–oxygen and hydrogen–oxygen were found to be 0.2 atm and 1 atm, respectively. They determined that the quenching limit corresponds closely to a Peclet number of 65 that is in agreement with Spalding’s conduction heat loss quenching. It is interesting that the measured minimum velocity just above the quenching limit was around 1000 m s\(^{-1}\), well above the laminar burning velocity used in Spalding’s theory [4]. At this velocity, one would expect convective and compressibility effects should be important as discussed in flame propagation in orifice plate laden tubes [9].

For less-reactive fuel–air mixtures, they found that increasing the initial pressure for a given porous medium resulted in a transition in propagation regimes from the high-velocity to the sound velocity regime. Steady-state flame velocity measured in hydrogen–air mixtures in a porous medium consisting of 2.6–3.6 mm steel balls as a function of initial pressure is provided in figure 6 [35]. Also plotted on the graph is the measured speed of sound through the porous medium. In the experiments, the flame accelerates to a steady velocity in the range of 100 m s\(^{-1}\) in about 30 cm of propagation. For each mixture, there is a minimum pressure
below which the flame is quenched. The transition from the high-velocity to the sound velocity regime occurs at a progressively higher initial pressure for weaker mixtures. For a 10 per cent hydrogen mixture no transition was observed and flame propagation was only observed in the high-velocity regime. For 18 and 20 per cent hydrogen, there is a second transition to a higher propagation velocity above 500 m s$^{-1}$, which will be discussed in §4. It was also found that the transition pressure for a given fuel–air mixture depends on the porous medium particle size. The abrupt transition from the high-velocity to the sound velocity regime is not universal. In another study [34] performed with acetylene–air mixtures in porous media consisting of 2 and 4 mm spheres transition typically occurred from a velocity of 10 to 500 m s$^{-1}$, thereby bypassing altogether the sound velocity regime.

Using a photomultiplier and piezoelectric pressure transducer, Pinaev & Lyamin [33] established that in this regime there is a smooth rise in pressure to a maximum that occurs at the start of the reaction zone, defined by the start of light emission. The pressure then falls to a final pressure below the initial pressure due to heat loss from the products to the porous medium and condensation of the water in the products. Pinaev & Lyamin [33] showed analytically that the drop in pressure after the peak is due to the convective cooling of the combustion products. The peak overpressure was measured to be of the order of two to five times the initial pressure, which is substantially below the adiabatic constant volume explosion pressure for the mixture. Based on the pressure pulse duration and the front velocity, the axial extent of the compression region is 10–20 cm. The rate of pressure rise ahead of the reaction zone was found to correlate with the front velocity, i.e. the higher the flame velocity the steeper the pressure rise.

It is difficult to determine the structure of the reaction zone since detailed measurements in the porous medium are difficult. Visualization of a flamefront propagating at a similar velocity in an obstructed channel (figure 1) shows a coherent laminar flamefront in the channel core with a trailing transverse turbulent combustion front, as well as burning pockets far behind the front. In porous media, the effective blockage ratio is very high, so that one would expect a lot of burning in trailing pockets and that the strong turbulence that fills the core could quench the flamefront as it propagates through the constriction between pores. If the mixture is reactive enough, mixing of the hot products and the fresh mixture in the neighbouring pore can result in re-ignition. Therefore, it is possible that propagation is the result of repeated quenching and re-ignition, similar to that observed in an obstructed channel by Kuznetsov et al. [17]. As a result of this quenching and re-ignition process, there can be a considerable amount of mixture that is not consumed, explaining the low conversion reported in many porous media studies.

(d) Detonation regime

In the detonation regime, the front propagates through the porous medium at, or just below, the CJ detonation velocity. For very reactive mixtures, or large pore size media, the detonation can negotiate the tortuous pathways without locally failing, and as a result one would expect the front velocity to be close to the CJ velocity. Any velocity deficit would be the result of momentum and heat losses.
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Figure 7. Variation of normalized velocity with equivalence ratio in a porous medium consisting of 12.7 mm spheres at an initial pressure of 1 atm [37].

.to the porous medium. Experiments under these conditions were performed by Kauffman et al. [36] with stoichiometric methane–oxygen mixtures at different initial pressures in a tube filled with 19.1 mm diameter spherical steel balls. In these experiments, it was observed that the steady front velocity decreased with decreasing equivalence ratio and decreasing initial pressure. At an initial pressure greater than 5 atm, the front velocity was close to the CJ detonation velocity, whereas at an initial pressure of 1 atm, the measured front velocity was about 20 per cent lower than the CJ detonation velocity. Kauffman et al. [36] developed a one-dimensional detonation model that took into account momentum and heat losses to explain the experimentally observed effect of initial pressure on the detonation velocity.

In experiments carried out with acetylene–oxygen mixtures in a much less porous medium consisting of sieved (0.7–1.2 mm) quartz sand, Pinaev & Lyamin [33] measured a smooth reduction in the steady front velocity from the CJ value of 2500 m s\(^{-1}\) to roughly 600 m s\(^{-1}\) over the initial pressure range 10–0.1 atm. They noted that the CJ detonation velocity is attained if the effective pore size is at least 10 times the detonation cell size [34]. A comprehensive series of experiments looking at detonation propagation in porous media consisting of different size ceramic spheres and different fuel–air and fuel–oxygen mixtures was carried out by Makris et al. [37]. A summary of their results obtained for 12.7 mm spheres at an initial pressure of 1 atm is provided in figure 7. The results show that the front velocity decreases smoothly as the mixture is made leaner, or richer, relative to stoichiometric down to a velocity that is 75 per cent below the CJ detonation velocity. A front velocity at the CJ value was measured in only the most reactive mixture of acetylene–oxygen. The velocity deficit increases with decreasing mixture reactivity, with the largest deficit corresponding to the fuel–air mixtures. Makris et al. [37] proposed an empirical correlation relating the detonation velocity deficit with the ratio of the average pore size, \(d_p\), to the...
critical detonation tube diameter, \( d_c \):

\[
\frac{V}{V_{CJ}} = 1 - 0.35 \log \left( \frac{d_c}{d_p} \right).
\] (3.2)

The correlation implies that when the average pore size is equal to the critical tube diameter, the velocity deficit equals zero, i.e. \( V = V_{CJ} \). As the critical tube diameter is 13 times the detonation cell size, their findings are in line with those of Lyamin & Pinaev [34]. The correlation in equation (3.2) is consistent with detonation theory since the critical tube diameter is a measure of the transverse passage size above which the detonation wave propagates unaffected by the boundary.

Makris et al. [37] pointed out that momentum and heat losses cannot explain the very large velocity deficits; instead they proposed that the low detonation velocity is the result of the local failure and re-initiation of the detonation wave. This is similar to that observed in the quasi-detonation regime in obstacle-laden channels. Makris [38] demonstrated this in an experiment carried out in an optically accessible narrow channel with the porous media simulated by widely spaced cross-flow cylinders. For very reactive mixtures, the detonation propagates around cylinders unaffected by the expansion on the back side of the cylinder. For less-reactive mixtures, the detonation fails on the back side of the cylinder, only to re-initiate directly behind the cylinder when the uncoupled shocks collide. For even less-reactive mixtures, a turbulent flame propagates around the cylinders.

Unlike the transition between the other regimes, there is no abrupt jump in the front velocity going from the low-velocity detonation to the detonation regime. As seen in figure 7, the front velocity increases continuously with mixture sensitivity. As discussed earlier, the drop in front velocity can partly be explained by the continuous local failure and re-initiation of the detonation within the porous medium. However, at the very large velocity deficits, a detonation most probably does not form. Instead, the front most probably propagates as a result of ignition at ‘hot spots’ that permits steady propagation down to a velocity of the order of half the CJ detonation velocity. There is no direct evidence for this and would represent an important finding for future work.

4. Discussion

The most interesting, and least understood, combustion phenomena occur in explosion propagation at velocities between the sound velocity and the detonation regimes. Babkin [21] referred to this as the ‘low-velocity detonation’ regime. This is a misnomer since propagation in this regime is not restricted to detonation waves. In fact, because of the high loss environment, it is typically very difficult to discern detonation wave propagation in porous media, except in the case of the most reactive mixtures, where the wave propagates at a velocity close to CJ detonation velocity. In figure 6, the final front velocity in the low-velocity detonation regime, observed in the 18 and 20 per cent hydrogen–air mixtures, lies between 800 and 1000 m s\(^{-1}\). Pinaev [39] measured velocities in the low-velocity detonation regime as low as 500 m s\(^{-1}\) in porous media consisting of spheres with diameters in the range 2.0 mm to 11.5 mm for hydrogen–air and acetylene–air. The differentiator for this regime, compared with the sound velocity regime, is that the
front propagates at a supersonic velocity (note the position of the speed of sound curve in figure 6). Therefore, it is perhaps more accurate to refer to this more generally as the supersonic regime, where detonation propagation represents the upper limit. Brailovsky & Sivashinsky [40,41] developed a steady one-dimensional detonation theory incorporating a momentum sink term that takes into account hydraulic resistance. This simple model predicts the location of the CJ plane but does not take into account any of the complex chemical-gasdynamic phenomena that necessarily occur within the reaction zone. The model predicts the possibility for both a high-velocity and low-velocity detonation for a given amount of resistance. This paper correlates the existence of the non-unique solution with the abrupt transitions in velocity observed experimentally.

In the supersonic regime, shockwaves are expected to play an important role in the propagation of the front. At the lower velocity-end of the regime, the shock wave is not strong enough to cause direct ignition of the gas. However, the interaction of the reflected shock waves and the flamefront should play an important role in the propagation of the front, similar to that observed in the choking regime in obstructed channels described in §2. Lyamin & Pinaev [34] observed that there was a two orders of magnitude difference in the combustion light intensity for the high-velocity regime and the low-velocity detonation regime. Ciccarelli et al. [42] performed experiments in a 7.6 cm square cross-sectional channel filled with 1.76 cm diameter ceramic spheres in order to visualize the explosion front. The channel had a glass side through which high-speed video captured the light emitted from the combustion front. Ignition was at one end of the channel via an automotive capacitor discharge system. Experiments were carried out in stoichiometric hydrogen–air at an initial pressure in the range of 33–55 kPa. Over this initial pressure range, the explosion front accelerated to a stable velocity of about 700 m s\(^{-1}\) (classified as the low-velocity detonation regime) in a distance of only 0.2–0.3 m. Consecutive video frames captured at 22 500 frames per second from an experiment carried out at an initial pressure of 45 kPa are shown in figure 8. The explosion front becomes clearly visible in the third frame when intense light appears in a local spot, and then quickly spreads across the field-of-view by the fourth frame to form a planar front. Note that the channel height has seven layers of spheres; figure 8 only shows the four central layers. The sudden appearance of light indicates a changeover in propagation mechanism.

The pressure–time history recorded at four axial locations on the back wall, corresponding to P3–P6 in figure 8, is shown in figure 9. Unfortunately, it is not possible to synchronize the video frames with the pressure traces to determine the relative position of the lead shock wave and the reaction front. Experiments carried out in a similar channel partially filled with 1.27 cm spheres indicated that the lead shock wave is only about one sphere diameter ahead of the leading edge of the reaction zone, i.e. light emission zone [14]. The sudden appearance of the intense light in the third frame of figure 8 most likely corresponds to the second sudden pressure rise leading to the peak in the P4 signal in figure 9. This second pressure pulse catches up to the initial pressure rise to form a strong, abrupt pressure rise typical of a lead shock wave in the P5 signal. The pressure profile is then maintained in P6 and P7 (mounted on the top of the channel). It was shown in Ciccarelli et al. [42] that the sudden appearance of the intense combustion light coincides with the development of a strong shock front that is typical of the low-velocity detonation regime.
The leading shock wave is not strong enough to directly initiate reaction. The emitted light is produced by the adiabatically compressed combustion products processed by the reflected shock. This phenomenon was clearly observed in the obstructed channel experiments as seen in the images in figure 2. The gas at the centre of the channel is progressively illuminated in images 9–12, in figure 2, as the two obstacle-reflected shocks converge to form a single shock wave that propagates back through the channel. In the obstructed channel experiment this light emission, following the reflected shock wave, continues very far back in the channel where only combustion products are present. One can speculate that this is the same mechanism at play in figure 8 that illuminates the porous medium towards the ignition end of the channel. Light associated with this effect is superimposed with light generated in the reaction zone that is scattered backward.

For a shock velocity of 500–1000 m s\(^{-1}\) the temperature rise of the gas processed by the lead shock wave is not sufficient to initiate reaction. At these velocities, the role of the shock wave is to adiabatically heat the gas in the pore ahead of the flamefront, and to generate reflected shock waves that interact with the reaction front. Depending on the nature of the reaction front, the interaction with the reflected shock waves can produce flame instabilities (if a flame sheet exists) or
generate vorticity to promote mixing of the products and unburned gas. If the lead shock wave is of sufficient strength, the shock reflection process can produce temperatures sufficiently high to ignite the gas next to the reflecting surface. This can happen in parallel to convective flame propagation associated with the shock and trailing reaction zone discussed earlier. If the shock is of sufficient strength, i.e. for local velocities greater than 1000 m s$^{-1}$, it can also lead to autoignition of the gas in the pores. As a consequence, the front propagation velocity in this regime is governed by a combination of all three mechanisms, where the dominant mechanism depends on the strength of the lead shock wave.

Most of the research done to date on explosion propagation in porous media has centred on measuring global parameters, such as the front velocity and pressure profile. Future studies should focus more on determining the detailed structure of the front and the important phenomena at play, i.e. the interplay of shock reflection, turbulence and chemical reaction. This must involve novel measurement techniques, or testing in scaled geometries where existing experimental methods can be used. There is also a need for numerical simulation of the detailed flow structure within the porous medium that cannot easily be accessed experimentally. This is a difficult task considering the complex internal structure of porous media. It is a particularly difficult task for the higher propagation velocity regimes where both turbulence and compressibility effects play important roles.

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Figure 9. Pressure–time history recorded along a channel for initial pressure of 45 kPa [42].
(Online version in colour.)
References

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