California Institute of Technology

Ae104c Final Report:

Combustion in Porous Media

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Abstract

A 2.8-liter tube-shaped combustion vessel was constructed to study flame propagation and quenching in porous media. For this experiment, hydrogen-air flames propagating horizontally into a bed of 6 mm diameter glass beads were studied. Measurements of pressure and temperature along the length of the tube were used to observe flame propagation of quenching. The critical hydrogen concentration for H₂-air mixtures was found to be 11.5%, corresponding to a critical Peclet number of $Pe^* = 37$. This value is substantially less than the value of $Pe^* = 65$ quoted in the literature, for example Babkin et al. (1991). It is hypothesized that buoyancy and a dependence of Pe^* on the Lewis number account for the discrepancy between these two results.

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1.0 Introduction

1.1 Motivation

Decontamination and decommissioning of nuclear facilities are tasks which will need to be carried out with increasing frequency in the near future. To ensure the public's safety, it is necessary to evaluate and minimize the risks involved. Waste storage tanks pose both a significant safety hazard and a significant challenge in making an accurate risk assessment. Due to the heat released from the nuclear waste, flammable gases such as hydrogen and nitrous oxide are continuously being generated. Thus, a combustion event arising from ignition during maintenance or inspection is a possible accident scenario. In some waste tanks, the waste is found in the form of a salt cake, which resembles a porous material. At present, there is large uncertainty in estimated flame propagation regimes in these porous materials. In the laboratory, we seek to find criteria which can be used to predict flame propagation regimes for the types of flammable gas mixtures found in waste storage tanks. Such criteria would be useful in making a more accurate safety assessment for waste storage facilities than currently available data permit.

1.2 Scope of the Present Work

A combustion vessel was constructed to be able to study flame propagation for arbitrary mixtures and arbitrary porous media. For this experiment, one mixture and one medium were considered for the purpose of validating the experiment design and providing a result, critical Peclet number, that could be compared with values published in the literature. A bed of 6 mm glass beads was used to simulate an inert porous medium. Lean hydrogen-air mixtures were studied since these are two gases found in nuclear waste storage tanks and there is also a wealth of data on laminar hydrogen-air flames. In this experiment, a search was made for the critical H_2 concentration. Using data in the literature from Kumar and Koroll (1992) for laminar burning velocity, the critical Peclet number was determined for the H_2 -air mixture.

2.0 Theory

2.1 Combustion in a Porous Medium

Generally, there are two types of combustion: a low speed flame, or deflagration, and high speed detonation. In this work, only flames are studied. For combustion in inert porous media, the distinction between deflagration and detonation is blurred. Previous work by Babkin et. al. (1991) identified five combustion modes based on wave velocities. The combustion regimes are listed in Table 1.

Table 1: Steady-state combustion regimes for gas combustion in inert porous media.

Regime	Wave velocity [m/s]	Flame Propagation Mechanism
Low velocities (LVR)	0 - 10 ⁻⁴	heat conductivity, interphase heat exchange
High Velocities (HVR)	0.1 - 100	convective, uniform pressure
Sound velocities (SVR)	100 - 300	convective, pressure gradient
Low velocity detonation (LVD)	500-1000	self-ignition under shock wave interaction
Normal detonation (ND)	1500-2000	detonation under heat and pulse losses

Heat transfer from the combustion zone to the porous bed is very effective due to the large surface area between them. For laboratory studies, ceramic pebbles, ceramic foams, metal foils, and metal balls have been used as porous media. The porosity ε of the porous medium is defined by:

$$\varepsilon = \frac{\text{volume of pores}}{\text{total volume}}$$

For an uncompacted bed of spherical beads, the porosity is typically in the range of 0.36 to 0.45 independent of pebble diameter δ . Lower values of ε can be achieved for compacted beds. Typically the porosity in nuclear waste storage tanks varies within the waste. The average porosity can be estimated by removing a salt cake sample from the waste. For the purpose of this laboratory experiment, one size of bead diameter was chosen to give a roughly uniform porosity. The specific surface area a per unit volume of the porous medium depends on the bead size, shape, and packing fraction. In a packed bed of spheres of diameter δ , for example,

$$a = \frac{6(1-\varepsilon)}{\delta}$$

The hydraulic diameter d_h of the pores for a bed of packed spheres is:

$$d_h = \frac{\varepsilon \delta}{3(1-\varepsilon)}$$

In this experiment, the choice of lean hydrogen-air mixtures and a bed of 6 mm glass beads gives rise to flames that propagate in the HVR regime (0.1 - 100 m/s). Since the pressure wave propagates at a higher velocity than the flame speed, the pressure rise in the vessel is essentially uniform, whereas the temperature profile experiences a jump corresponding to arrival of the flame front.

2.2 Mechanism for Flame Propagation

Flame propagation has been experimentally studied by several researchers such as Korzhavin et al. (1982), Lyamin and Pinaev (1986) and Babkin et al. (1991). Their experiments consisted of tubes filled with a porous material and a homogeneous fuel-oxidizer mixture. The mixtures that have been studied have typically been hydrocarbon-air mixtures such as methane-air or propane-air, as the motivation for much of the research has been to improve burner technology. For example, see Trimis and Durst (1996). The main result of the previous work was that of Babkin et al. (1991), where five of the six steady combustion regimes in Table 1 were identified. In that paper, the following flame propagation mechanism for the HVR regime was proposed:

"A positive feedback between flame acceleration and turbulence production (the flame acceleration causes turbulence, which leads to flame acceleration) is damped by local quenching of the chemical reaction due to intense heat exchange in the turbulent zone. If the characteristic time of thermal relaxation becomes less than that of chemical conversion the flame will be quenched. since turbulent flow contains a spectrum of instantaneous gas velocities, those parts of the flame moving with maximum velocities will be quenched, resulting in a stable velocity of flame propagation."

Flame propagation data are usually presented in terms of the Peclet number for a porous material:

$$Pe = \frac{S_u d_m c_p \rho}{k}$$

where S_u is the laminar burning velocity, d_m the equivalent porous cavity diameter, c_p the specific heat capacity, ρ the density, and k the heat conductivity of the unburned gas. d_m/S_u is proportional to the characteristic time of chemical conversion, and $c_p \rho d_m^2 / k$ is proportional to the time of thermal relaxation. For flame propagation through a porous material, the critical Peclet number of $Pe^* = 65$ has been found (Trimis and Durst 1996). Thus, $Pe \leq Pe^*$ for quenching, and $Pe \geq Pe^*$ for flame propagation. In the work of Lyamin and Pinaev (1986), the pore hydraulic diameter d_h was found not be a suitable parameter for d_h . Instead, the correlation $d_h \approx \delta / 2.77$ was obtained.

The laminar burning velocity for hydrogen-air mixtures as a function of hydrogen concentration has been measured and published by Kumar and Koroll (1992). Their data was used in calculating the Peclet numbers for this experiment.

3.0 Apparatus

3.1 Combustion Vessel

The combustion vessel that was constructed consists of a 3 inch inner diameter aluminum tube with a wall thickness of 0.75 inches and a length of 24 inches. On one side of the tube there are holes for thermocouple probe compression fittings which use a 1/8" pipe thread. The pressure transducers use a 10-32 thread. A pipe thread is not necessary since each pressure transducer has its own small O-ring. Inside the tube, two stainless steel screens are fastened with silver solder to stainless steel inserts which slide inside the tube. These screens hold the glass beads in place and provide a space at each end of the tube for flame front formation and re-establishment after propagating through the porous bed.

To each end of the tube an aluminum end cap is fastened with 1/4-20 screws. The aluminum end cap has a 0.1 inch extension which centers the cap inside the tube. Each end cap was drilled and tapped for a pipe thread, which connects to the gas supply system via SwageLok connections. An automotive spark plug screws into a Teflon insert which is fastened through one of the end caps. The CAD drawings for the machining of the combustion vessel, end caps, and Teflon and steel inserts, are reproduced in the Appendix. A schematic of the combustion vessel is shown in Figure 1.

Figure 1: Schematic of combustion vessel.

A 16 inch long bed of glass beads sits inside the combustion vessel. The beads are held in place by stainless steel screen with square holes of length 1.9 mm. The screen is fastened to stainless steel inserts with silver solder. The inserts fit inside the tube and are held in place against the end caps. Since there is one pressure transducer and one thermocouple probe located in the space on either side of the beads, the steel insert is drilled with a 1/2 inch hole to expose the pressure transducer and allow the thermocouple probe to reach into the center of the tube.

3.2 Instrumentation

Along the length of the tube there are six Omega Type K thermocouples. The thermocouple wires pass through a 1/8" diameter ceramic rod which is held in place by compression fittings. Teflon ferrules are used inside the compression fittings to make a seal and to avoid breaking the ceramic rod with a stainless steel ferrule. Each thermocouple probe is sealed by placing a small amount of epoxy on the exposed end of the ceramic rod. It is necessary for the thermocouple

bead to protrude at least 1 mm past the epoxy so the response time of the instrument is not degraded. The thermocouples are connected to a Trigtek instrumentation amplifier using a BNC connector. A voltage offset is produced at the junction between the thermocouple wire and the BNC connector due to the joining of dissimilar metals. This offset is corrected for with amplifier offset to give a reading of zero volts at room temperature.

The four pressure transducers are Endevco Model Model 8530B-200 piezoresistive transducers. They require a 10 volt DC power source which is provided by a GALCIT shop-built power supply. Each transducer has its own internal bridge circuit, so it is only necessary to supply power and amplify the voltage differential which is output from the bridge. The amplifiers used are Preston 8300 XWB Differential Amplifiers with a gain setting of 20. Table 2 gives descriptions and specifications of the other equipment that was used for this experiment.

Function	Description
Gas line pressure gauge	HEISE 0-250 kPa Model 901A pressure gauge (SN: S9-20077) with digital pressure indicator
High voltage power supply	General Electric 10 kV supply
Capacitor	Maxwell 0.5 μ F high voltage capacitor
Amplifier	Preston 8300 XWB serial numbers AGW238, EAA1485, AGX121, AWG248 for channels 0, 1, 2 and 3
Amplifier	Trigtek Model 205B ID #354
Mixing pump	MagneTek 115V 60 Hz 1.6A 3000 RPM 1/25 HP SN: 49F83985R
Thermocouples	OMEGA type K, 24.13 K/mV
Pressure transducers	Channel 0: #10217, 40.5 bar/V Channel 1: #10317, 55.1 bar/V Channel 2: #10329, 48.2 bar/V Channel 3: #10344, 43.6 bar/V

Table 2: Description and specifications of equipment used.

The pressure and temperature signals from the amplifier outputs connect to a National Instruments AT-MIO-16E-1 data acquisition board for analog input. The board has 16 channels with 12 bit resolution and a maximum sampling rate of 1 MHz. The acquisition is triggered in the software analog mode using the pressure signal closest to the spark plug as a trigger source. The sampling rate used in this experiment was 2000 Hz. For each run, 14000 samples (7 seconds) of data were captured with 2000 pre-trigger scans.

3.3 Gas Supply System

The combustion vessel is connected to the gas supply system in the GALCIT Explosion Dynamics Lab. The gas supply system provides connections, through a series of valves and piping, to the gas storage bottles and a vacuum line. Figure 2 shows a schematic of the connections.

Figure 2: Schematic of gas supply system.

An important feature of the apparatus is that the vacuum line is connected to the gas supply line, instead of being directly connected to the vessel. When filling the vessel with a mixture of gases, this allows the gas line to be evacuated before filling with a different gas. A mixing pump is also connected to the vessel. After the vessel has been filled with the desired gases, the pump is used to mix the gases together.

3.4 Ignition System

An automotive spark plug is used initiate the flame. The spark plug gap was pried open to 4 mm to give a more energetic spark. The spark plug is connected to a 0.5 μF high voltage capacitor, which is charged with a 10 kV power supply. The spark plug discharges at a voltage of 6.5 kV, giving a spark with approximately 10 J of energy. The spark plug is threaded into a Teflon insert, which is then bolted in to one of the vessel end caps. There is an O-ring seal between the Teflon insert and the aluminum cap, and an O-ring between the spark plug and the Teflon insert. The purpose of the Teflon insert is to insulate the spark plug and prevent a discharge from the plug to the aluminum tube. The tube is not grounded, so if there were no insulation, there would

be a possible safety hazard if the tube was charged to a high voltage by the power supply. A schematic of the ignition system and high voltage circuit is shown in Figure 3.

Figure 3: Schematic of ignition system.

4.0 Procedure

4.1 Preparation

The glass beads can be added or removed by disconnecting the tube from the gas lines and removing one end cap. The tube can be stood vertically on one end. After removing the thermocouple probe which protrudes through the steel insert, the insert can be removed and the beads can be changed or removed. When filling the tube with beads, they should be poured in slowly with the tube standing vertically. Then the tube should be shaken vigorously to make sure the beads settle and that there are no empty spaces in the bed. When the insert is replaced, it should slide in 0.1 inches past the face of the tube, since the aluminum end cap has a 0.1 inch extension which centers the cap inside the tube.

The basic steps in the procedure are evacuation, filling, mixing, and firing. A detailed checklist of the procedure steps is included in the Appendix. The data acquisition is started just prior to firing, and the evacuation step is repeated after firing.

4.2 Run Conditions

For this experiment, all runs were done using lean hydrogen-air mixtures with an initial pressure of 1 bar and a bed of 6 mm beads. The hydrogen molar concentration was varied from 10% to 29.6%, where 29.6% corresponds to a stoichiometric mixture. The concentration was determined using the method of partial pressures when filling the vessel. Table 3 shows the run numbers and conditions.

Run Number	H ₂ %	Air %	Equiv. Ratio	St. m/s	Density kg/m ³	C _p kJ/kgK
4	29.6	70.4	1.00	2.6	1.173	1.379
5	10.0	90.0	0.26	0.25	1.196	1.103
6	20.0	80.0	0.60	1.6	1.186	1.228
7	15.0	85.0	0.42	0.7	1.191	1.162
8	12.5	87.5	0.34	0.5	1.194	1.132
9	10.0	90.0	0.26	0.25	1.196	1.103
10	11.0	89.0	0.29	0.3	1.195	1.114
11	12.0	88.0	0.32	0.4	1.194	1.126
12	11.5	88.5	0.31	0.35	1.195	1.120

Table 3: Summary of run conditions for experiment.

5.0 Results

5.1 Run Data

Flame propagation was observed for hydrogen concentrations higher than 11.5%. Quenching was observed for hydrogen concentrations of 10% and 11%. The Peclet number corresponding to the critical concentration of 11.5% is $Pe^* = 37$. Table 4 summarizes the results from all the runs that were performed. In Figure 4, the maximum temperature downstream of the beads is plotted versus hydrogen concentration.

Run Number	H ₂ %	Air %	Equiv. Ratio	Pe	+ propagation - quenching
4	29.6	70.4	1.00	304	+
5	10.0	90.0	0.26	27	-
6	20.0	80.0	0.60	178	+
7	15.0	85.0	0.42	76	+
8	12.5	87.5	0.34	54	+
9	10.0	90.0	0.26	27	-
10	11.0	89.0	0.29	32	-
11	12.0	88.0	0.32	43	+
12	11.5	88.5	0.31	37	+

Table 4: Summary of flame propagation results.

5.2 Pressure and Temperature Traces

Figures 5 and 6 show typical pressure and temperature traces for a run where flame quenching was observed. Figures 7 and 8 show typical pressure and temperature traces for a run where flame propagation was observed. The pressure signals from the four transducers are shown superimposed in Figures 5 and 7, as are the six thermocouple signals in Figures 6 and 8. Figures 9, 10, 11, and 12 show the same information, except the areas of greatest rate of change have been magnified for clarity.

6.0 Discussion

6.1 Determination of Quenching/Propagation Behavior

Figures 6 and 8 illustrate how it is determined whether or not the flame propagates through the bed of beads. When the flame enters the bed, it is cooled rapidly because of the high rate of heat transfer between the flame zone and the beads. If the flame goes through the bed, then it emerges into the downstream compartment and re-establishes itself as a flame front. Thus, we see a substantial jump in peak temperature between measurements in the bed and the last measurement in the compartment (labeled "T6"). Peak temperatures observed were in the range of 100 to 400 C. If the flame quenches, the temperature profile at location 6 is similar to those in the bed, with a peak temperature of about 30 C. Another characteristic of flame propagation is a second peak in the pressure signals, as shown in Figure 7. The second spike is caused by the rapid combustion in the downstream compartment.

6.2 Interesting Features of the Data

Figures 5 and 7 shows that, on the time scale of seconds, the pressure throughout the tube essentially rises and falls uniformly. All four signals appear to be superimposed. In contrast, Figures 6 and 8 show that the temperature rise is more of a local phenomenon. The reason is that for a flame or explosion, the pressure wave propagates much faster than the flame speed whereas the temperature measurement only rises as the flame passes the thermocouple. For example, in Figure 11, we see a pressure wave going through the tube with a speed of approximately 80 m/s, whereas the flame speed is on the order of 2 m/s. This approximate flame speed confirms that the combustion is taking place in the High Velocity Regime (HVR), as was mentioned in the introduction.

In cases where the flame propagates through the bed, we see a second spike in the tube pressure which coincides with the temperature rise at the compartment downstream of the beads. What is happening is that we get a small explosion in the first chamber which produces a flame front. The flame front propagates through the bed and then ignites the mixture in the second compartment, producing a second explosion. The peak temperature downstream of the bed is typically higher than the peak temperature upstream of the bed. The reason for this might be due to the production of turbulence as the flame travels through the bed, resulting in a faster chemical reaction and higher peak temperature than for the laminar flame upstream of the bed.

6.3 Comparison with Published Values ($Pe^* = 65$)

The critical Peclet number of 37 which was found for lean hydrogen-air mixtures is considerably less than the value of 65 quoted in the literature. One potential explanation of the difference is that the results published in the literature are for hydrocarbon fuels such as methane, propane, and acetylene. Hydrogen has a much higher mass diffusivity than the hydrocarbon fuels, which should make it more difficult to quench a hydrogen-air flame than a hydrocarbon-air flame. Thus we would find a lower critical Peclet number for hydrogen-air mixtures, i.e. the flame propagation can withstand lower flame speeds or small diameter pore sizes. If mass diffusion

plays a significant role in quenching behavior, in addition to the thermal diffusion, then we should expect the critical Peclet number to depend on the Lewis number.

Another explanation of the discrepancy is due to the effects of buoyancy. The results in the literature are for downwards propagating flames, i.e. for a vertical tube with ignition at the top end of the tube. In this experiment a horizontal tube was used. For downwards propagating flames, the buoyant force would act to retard the flame propagation. Thus, a flame should propagate more easily in the horizontal direction, and again we would expect a lower critical Peclet number.

7.0 Conclusions and Future Work

For lean hydrogen-air mixtures, the critical Peclet number for flame propagation was found to be 37, which is considerably less than the value of 65 quoted in the literature. The difference is probably due to the different chemistry of the fuels used (hydrogen in this experiment vs. hydrocarbons in the literature) and buoyancy (horizontal tube in this experiment vs. vertical tube in the literature). For future work, the tube could be rotated into the vertical position to reproduce the conditions as used in the literature. This would give some indication of how strongly the flame propagation behavior depends on the effects of buoyancy. Also, the experiment could be repeated with hydrocarbon fuels to examine the role of mass diffusion in flame quenching and quantify the dependence of critical Peclet number on the Lewis number.

8.0 References

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Fig. 4: Peak temperature downstream of bed vs. H₂ concentration

Appendix

Detailed Checklist for Experiment Operation (example given for 15% H₂-air mixture)

1. Open necessary bottles in bottle farm.
2. Turn on vacuum pump.
3. Turn on Heise pressure gauge, 10 volt power supply, and amplifiers.
4. Close vent valve.
5. Open isolation, circulation, KS1, and vacuum valves and wait for 50 mTorr vacuum.
6. Zero the Heise gauge and amplifiers.
7. Close vacuum valve.
8. Open the air valve on the diluent line.
9. Fill Gas #1 (air) to 85.0 kPa (use needle valve for precision).
10. Close isolation valve.
11. Open vacuum valve and wait for vacuum.
12. Close vacuum valve.
13. Turn on gas switch and warning light switch.
14. Fill gas line with Gas #2 (H₂) with 90 to 100 kPa pressure
15. Open isolation valve.
16. Fill with Gas #2 to 100.0 kPa
17. Turn off gas switch.
18. Close isolation valve.
19. Turn on mixing pump for at least 5 minutes.
20. Close Heise valve.
21. Turn off Heise gauge.
22. Run LabVIEW test program (testp.vi) - pressure signals should be between 0.4 and 0.5 volts, thermocouple signals should be zero volts.
23. Open LabVIEW program (cbv.vi) and set desired sample rate, trigger level, number of pre-trigger and post-trigger samples, and output filename.
24. Turn off mixing pump.
25. Close circulation valves.
26. Turn on the ignition Power and Arm switches on the Convol panel.
27. Start the data acquisition program.
28. Turn on high voltage power supply.
29. Slowly increase voltage until spark plug discharges (should occur at 6.5 kV).
30. Turn voltage dial back to zero and turn off high voltage power supply.
31. Using the shorting wire with the insulating handles, touch one end to the negative end of the spark plug (the one with the alligator clip attachment) and then touch the other end to the metal bar on the capacitor.
32. Open vacuum valve.
33. Open isolation valve and circulation valves.
34. Turn off ignition Arm and Power switches.
35. Turn off warning light.
36. Open Heise valve.
37. Close vacuum valve.

38. Open vent valve.
39. Close KS1 valve.
40. Turn off amplifiers and power supply.
41. Shut off vacuum pump.
42. Close bottles in bottle farm.

Drill and tap
1/4-20
BC dia 3.800"
1.5" deep
8 Plcs