QUENCHING MECHANISMS OF GASEOUS HYDROCARBON-AIR FLAMES IN PACKED BEDS

T.A. Mihalik and J.H.S. Lee Department of Mechanical Engineering McGill University, Montreal, Canada

G. Continillo Department of Engineering Università del Sannio, Benevento, Italy e-mail: continillo@unisannio.it

F. S. Marra Istituto di Ricerche sulla Combustione, CNR, Naples, Italy

Introduction

The history of the development of flame-arresting devices began with the pioneering work of Sir Humphrey Davy in 1814, who studied experimentally the problem of preventing mine explosions caused by natural pockets of firedamp ignited by a miner's lamp [1]. He used tubes, concentric circular canals, and other devices to separate the flame from the outside explosive environment. His work was the first to indicate that flames can be quenched when they encounter small apertures or openings. This led to the concept of quenching distance, a parameter first defined by Holm [2] in 1932. Subsequently, a number of experimental investigations have been carried out to obtain data on the quenching distances of a wide variety of combustible mixtures. Under simple geometrical configurations, a thermal theory of laminar flame quenching based on an energy balance between the rate of heat generation of the flame and the heat absorbed by the quenching surface, leads to correlate the quenching distance D to the Peclet number $Pe = SD/\alpha$, where S and α are the burning velocity and thermal diffusivity of the mixture [3]. This correlation is confirmed by experimental data [4]. In the presence of more complex fluid mechanics, like those induced by the tortuous paths encountered by the flow through a packed bed, this simple thermal theory might not work. In fact, flame stretch might either increase the flame surface area and thus the burning rate, or increase heat losses to the fresh gas mixture and contribute to flame extinction, while heat losses to the solid walls always act in favor of flame quenching.

Packed beds of spheres are simple and inexpensive designs for flame-arresting devices. Fabrication is simple and cleaning is essentially replacement of the packed bed itself. However, few data are available on flame propagation and limits of combustible mixtures in packed beds of spherical particles. Furthermore, the basic mechanisms of flame propagation and extinction in a packed bed are not well established. Babkin [5] studied flame speed through packed beds, but no attempt was made to correlate propagation limits with parameters of the packed bed (i.e. sphere material, bead size, etc.). Experimental data indicate that quenching distances are somewhat dependent on channel geometry [6] and, subsequently, correlations to relate the quenching effects of different geometries have been obtained and verified experimentally [7]. However, for the complex geometry of a packed bed, the open channels for flame propagation are non-uniform and only an average dimension can be defined. Thus, the objective of the present study is to investigate the phenomenon of flame quenching in a packed bed of spheres, both experimentally and through detailed numerical modeling. The quenching limits are determined experimentally as a function of the packed bed parameters, and the dependency is studied to elucidate the mechanisms of flame quenching in a packed bed of spherical particles. The effect of heat losses on the extinction of gas flames in a packed bed is assessed and compared to the effect of flame stretch induced by the flow. Numerical simulations are also used to separately test, via "ideal" experiments, the influence of each sub-mechanism.

Experimental Setup

The experiments were carried out in a 1.8-m long transparent Plexiglas tube of 5-cm internal diameter. The tube was constructed to match the standard flammability apparatus of Coward and Jones, to permit a direct comparison of data [8]. The combustible mixture was prepared by a continuous flow method where the concentrations of fuel and oxidizer (air) were monitored using calibrated flow meters. The fuel and air streams were mixed in a chamber and the resulting mixture was flowed through the flame tube for sufficient time to allow the displacement of ten tube volumes. Prior to ignition, the ignition end of the tube was opened to the atmosphere while the downstream end remained closed. Thus, in all experiments the flame propagated from the open end to the closed end of the tube. The mixture was ignited with a 5 mm spark. The igniter was located at the top of the tube for downward flame propagation and at the bottom for upward flame propagation. Methaneair and propane-air mixtures were used in the present study.

The packed bed of solid spheres was supported on a wire screen located 0.9 m from the end of the tube. A range of materials were tested (i.e. glass, stainless steel, and brass). The thermal properties of these different materials vary by two orders of magnitude. The sphere diameters varied between 9.53 mm and 25.4 mm. Experimental results were found to be independent of the height of the packed bed section for column heights greater than approximately one tube diameter. Thus, all experiments were conducted with a one-tube diameter height of spheres. Failure or successful transmission of the flame through the packed bed was determined by visual inspection, following the standard procedure used in flammability tests. To assess the effect of the non-uniform cross-sectional area of the channels of a packed bed on flame propagation, experiments were also conducted with a flame-arresting element consisting of a series of thin, evenly-spaced, parallel steel plates connected by four thin needles and soldered to form a rigid structure. The planes of the plates were set parallel to the tube axis to form a series of planar channels for flame propagation. A range of channel widths between 4 mm and 7 mm was tested. The spacing between plates was accurate to ± 0.1 mm. Both arrangements are shown in Fig. 1.



Fig. 1 Two different arrangements used for the flame-arresting device

Numerical Model

The development of flames through gas mixtures in enclosures represents perhaps the most studied class of transient gas combustion phenomena in laminar flow. Classical configurations include spherical vessels, rectangular and cylindrical tubes, as well as more complex geometries. There is evidence of the occurrence of strong and complex interactions between flame chemistry and thermodynamics, and fluid mechanics. Even when starting from rest, fluid flow is initiated and driven by the reaction, and, depending on the geometry of the confinement, the flow interacts with the flame and determines its developing structure. The structure of the flame in turn determines the overall burning rate. The flow can get very complicated and rapidly evolving with time. In fact, inviscid and viscous flow regions coexist, the first essentially determined by the flame acting as a volume source, and the second primarily located near the confining walls.

The present model is based on the classic Navier-Stokes equations for reacting flows. For a mixture of ideal gases not electrically charged, the Navier-Stokes equations can be written as:

Species

$$\frac{\partial}{\partial t} \boldsymbol{\rho}_{k} = -\nabla \cdot (\boldsymbol{\rho}_{k} \mathbf{v} + \mathbf{j}_{k}) + r_{k} \qquad k = 1, ..., N$$

Momentum

$$\frac{\partial}{\partial t}\rho\mathbf{v} = -\nabla \cdot (\rho\mathbf{v}\mathbf{v} + \boldsymbol{\pi}) + \rho\mathbf{g}$$

Energy $\frac{\partial}{\partial t}\rho e = -\nabla \cdot (\rho e \mathbf{v} + \mathbf{q} + \boldsymbol{\pi} \cdot \mathbf{v})$ where $\rho = \sum_{k=1}^{N} \rho_k$, and the total energy is defined in the usual way as $e = u + \frac{1}{2}v^2 + \Phi$. In the equations t is the time coordinate, ρ the density, v the velocity vector, j the diffusive flux, r the reaction rate, π the stress tensor, g the gravity vector, q the heat flux, u the internal energy, Φ the potential energy, p the pressure, T the temperature. Subscript k refers to the chemical species. The equations are closed with proper initial and boundary conditions, and a set of constitutive equations. Transport coefficients are evaluated as in [9]. Dufour and Soret effects are neglected. Radiation is not considered. A single step, global reaction mechanism with Arrhenius-type kinetic law is adopted for the modeling of the combustion of a hydrocarbon. A low-Mach number formulation is adopted, and an elliptic equation is derived for the pressure correction, and closed with proper boundary conditions. The numerical discretization is conducted by means of a control-volume formulation. The computational grid (that gets as large as 50×400 square cells) is chosen with constant-width space steps, to avoid the presence of numerically preferred directions of evolution. The mesh size is the same as that used in [10]. This enabled the authors to reportedly maintain the error on the flame speed within an excellent 0.3%. The computational procedure is summarized as follows: composition and temperature are computed first by explicitly solving species and energy balance, then density is obtained directly from the gas state equation. The pressure gradients are computed from the elliptic equation. The velocity field can then be updated through the momentum balance equation.

The model is applied to a downward propagating flame entering a tube, in an axisymmetric cylindrical configuration. The base case consists of a downward propagating flame in a near-limit mixture of propane-air. Each simulation requires 48 hours of CPU time on a Digital Alpha Station 466MHz.

Results and Discussion

As a preliminary assessment of the procedure, results were verified to agree, both quantitatively and qualitatively, with previous experimental observations of upward and downward laminar flame propagation in an open tube (i.e., without the packed bed section). For example, the upward lean flammability limit for CH_4 -air is found to be 5.35%, in accord with the value of 5.3% given in [8]. A downward limit of 5.98% for CH_4 -air is obtained which agrees well with the value of 5.85% reported in [11]. In addition, the results show the effect of buoyancy: flammability limits for upward flame propagation are wider than those for downward flames.

Propagation and quenching of the flame in the packed bed can be observed when the packed bed is transparent (i.e., glass spheres) and, of course, from a side view in the case of the array of parallel plates. Visual observations of the structure, propagation, and extinction of the flames are in good agreement with previous optical studies of near-limit flame phenomena [12, 13]. For example, a typical downward flame is planar in shape, with the edges curved slightly upwards. At left in Fig. 2 are sequential photographs of the extinction process of a downward propagating methane-air flame through one of the parallel channels in the arrangement shown in the right frame of Fig. 1. Numerical simulations of a downward propagating propane-air flame, shown in the right frame of Fig. 2, indicate a remarkable qualitative agreement with the experiment.

The thermal conductivities of the packed beds were chosen to vary over several orders of magnitude (i.e., glass, stainless steel, and brass). Intuitively, it is expected that a material with high thermal conductivity will have narrower flame propagation limits. Experimental results, however, clearly indicate that the extinction limits are



Fig. 2 Qualitative comparison of experimental (left) and numerical (right) evolution of the quenching of a near-limit, downward propagating hydrocarbon-air flame. Time intervals and lengths not to scale.



Fig. 3 Overall burning rate (top) and flame location (bottom) for a near-limit propane-air flame propagating downward and entering a tube, as computed in numerical simulations.

insensitive to the material of the solid spheres (see for example [14]). This result is in accordance with flame quenching experiments in small tubes where the tube wall material has been found to play a small role in the flame quenching distance [2]. Despite these results, conduction is not excluded as a means of heat transfer in the packed bed. First of all, as noted in [14], given the time scale of the passing flame front (of the order of 10 ms), the temperature of the sphere surface cannot significantly increase from the initial value, regardless of the sphere material. Flame temperatures for gaseous hydrocarbon-air flames are an order of magnitude higher than the ambient condition in the present experiments. As a consequence, steep temperature gradients are present at the sphere surfaces and their magnitudes are insensitive to the sphere material.

The numerical experiments provide further confirmation that heat transfer to the wall is the dominant mechanism of flame quenching. Figure 3 reports the overall burning rate (on top) and the flame location, measured downward, for a near-limit propane-air flame propagating and entering a tube having a diameter of 20 mm. The tube entrance is located at 0.02 m from the top of the computational domain. The simulations are conducted under three different conditions: the "real" one (both fluid-mechanics and heat transfer to the wall are considered), the "free-slip" one (free-slip condition at the wall, i.e. strongly reduced flame strain), and the "adiabatic" one (full strain but no heat transfer to the wall). It is seen that the flame is quenched in the real and in the free-slip cases, with slight quantitative differences, while it propagates throughout the tube if the heat transfer to the wall is eliminated from the scene.

Finally, by estimating the average channel dimension between the closely packed spheres as a characteristic quenching distance, extinction limits determined in packed beds can be reported in the same chart along with those determined for parallel plates. The average channel dimension in a close-packed bed of spherical particles is $0.3d_s$, where d_s is the sphere size [16]. It is seen that the experimental results obtained are in fairly good agreement with the published data. Figure 4 reports the quenching distances as determined for methane-air and propane-air mixtures as a function of the equivalence ratio. It is seen that the extinction limits in a packed bed are well correlated to the quenching distance of the mixture.

It can be concluded that the quenching mechanisms in a packed bed are governed by those responsible for more traditional flame quenching experiments with straight narrow channels. The dominant flame quenching mechanism in a packed bed of spherical particles is thus heat loss to the sphere surfaces by conduction.



Fig. 4 Characteristic quenching distance as a function of methane (left) and propane (right) concentration in air for packed beds and parallel plates. Published quenching distance data obtained from [6] and [15].

References

- 1. Davy, H., "On the Fire-Damp of Coal Mines, and the Methods of Lighting the Mines so as to prevent Explosions," *Phil. Trans. Roy. Soc.*, 1816, pp. 1-22, 23-24, 115-119, *Phil. Mag.*, 1816, Vol. 48, pp. 51-59, 197-200.
- 2. Holm, J.M., "On the Initiation of Gaseous Explosions by Small Flames," *Phil. Mag.*,1932, Vol. 14, pp. 51-59, 197-200.
- 3. Friedman, R., "The Quenching of Laminar Oxyhydrogen Flames by Solid Surfaces," *Third Symposium on Combustion, Flame and Explosion Phenomena*, 1949, pp. 110-120.
- 4. Putnam, A.A., Jensen, R.A., "Application of Dimensionless Numbers to Flash-Back and Other Combustion Phenomena," *Third Symposium on Combustion, Flame and Explosion Phenomena*, 1949, pp. 89-98.
- 5. Babkin, V.S., "Propagation of Premixed Gaseous Explosion Flames in Porous Media," *Combustion and Flame*, 1991, Vol. 87, pp. 182-190.
- 6. Harris, M.E., Grumer, J., von Elbe, G., Lewis, B., "Burning Velocities, Quenching, and Stability Data on Nonturbulent Flames of Methane and Propane with Oxygen and Nitrogen," *Third Symposium on Combustion, Flame and Explosion Phenomena*, 1949, pp. 80-89.
- 7. Berlad, A.L., Potter, A.E., "Prediction of the Quenching Effect of Various Surface Geometries," *Fifth Symposium (International) on Combustion*, 1967, pp. 728-735.
- 8. Coward, H.F., and Jones, G.W., Limits of Flammability of Gases and Vapors. U.S. Bureau of Mines Bulletin, 1952, No. 503.
- 9. Marra, F.S., Continillo, G., "Numerical Study of Laminar Flame Propagation in a Closed Tube with a Full Navier-Stokes Approach," *Proceedings of the Combustion Institute, 1996, Vol. 26, p.* 907.
- 10. Lee, S. T., Tsai, C. H., Combustion and Flame, 1994, Vol. 99, pp. 484-490.
- 11. Jarosinski, J. and Strehlow, R.A., "Lean Limit Flammability Study of Methane-Air Mixtures." *Archivum Combustionis*, 1981, Vol. 1, No. 3-4, pp. 203-215.
- 12. Levy, A., "An optical study of Flammability Limits," Proc. Roy. Soc. London., 1965, Vol. A-283, pp. 1549-1557.
- 13. Jarozinski, J., Strehlow, R.A., Azarbarzin, A., "The Mechanisms of Lean Limit Extinguishment of an Upward and Downward Propagating Flame in a Standard Flammability Tube," *Nineteenth Symposium (International) on Combustion*, 1982, pp. 1549-1557.
- di Mare, L., Mihalik, T.A., Continillo, G., Lee, J.H.S., "Experimental and Numerical Study of Flammability Limits of Gaseous Mixtures in Porous Media," *Experimental Thermal and Fluid Science*, 2000, Vol. 21 (1-3), pp. 117-123.
- 15. Jarozinski, J., "Flame Quenching by a Cold Wall," Combustion and Flame, 1983, Vol. 50, pp. 167-175.
- 16. Lee, J.J., Detonation Mechanisms in a Condensed-Phase Porous Explosive. PhD thesis, University of Sherbrooke, Sherbrooke, Quebec, Canada, 1997.