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Communications

Approximations of Flammability Characteristics of Liquefied Petroleum Gas−Air Mixture with Exhaust Gas Recirculation (EGR)

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It is well-known that the most effective way of reducing nitrogen oxide (NO_x) emissions is to perform combustion at lower temperature. The addition of residual gas into combustible gas is considered to be the simplest practical method to reduce the combustion temperature; therefore, the use of exhaust gas recirculation (EGR) in engines has been promoted. The combustion temperature is well-known to have a strong effect on the burning velocity of combustible gas, which is associated with the phenomenon of flame inhibition. In addition, generally, the flame inhibition in a fuel−air mixture can be characterized by the flammability limits of the mixture, so the flammability characteristics have received continuous attention. The standardized measurements of the flammability limits are usually conducted in flammability tubes or closed vessels. It is now acknowledged that flammability limits are physicochemical constants of flammable gases and vapors of flammable liquids, which are relevant to many factors, including heat losses from the flame by conduction, convection and radiation to the apparatus walls, instabilities in the flame front resulting from buoyant convection, selective diffusion, and flame stretch, as well as radical loss or their generation on apparatus walls.[1,2] Moreover, because a spark igniter is commonly adopted in experimental measurements, it is also found that the amount of ignition energy does affect the flammability limit data.[3] There is a large array of experimental data on flammability limits for ternary gaseous mixtures of fuel, air, and diluent; however, the diluent gases considered therein were nitrogen gas (N_2), carbon dioxide (CO_2), or their mixture, which are different from the practical residual gas in the combustion chamber. It should be proven of value to conduct fundamental researches on flammability characteristics of fuel−air mixtures with EGR, for the practical engineering uses. Because it would take time to operate experimental measurements and experiments are expensive, in practice, insufficient knowledge of the phenomena at the limits has called forth the idea of choosing the most reliable criterion for rapid estimating the flammability limits. A commonly accepted view is that flames fail to propagate as the burning velocity becomes too low to overcome the dissipation processes during combustion.[2] Burgess and Hertzberg[4] emphasized that at least the burning velocity at the lean limit approaches approximately the same value for many fuels. Lovachev et al.[1] predicted that 5−7 cm/s is the minimum possible flame speed for lean limit hydrocarbon flames, and Huang et al.[5] found that the laminar flame speed at the maximum diluent level is on the order of 1−2 cm/s. Blint[6] calculated laminar burning flame speeds for adiabatic one-dimensional propane/air flames over a range of pressures, initial temperatures, and diluent levels. In his work, an arbitrary flame speed (10 cm/s) is defined to approximately determine the flammability limits.

The objective of this work is to provide an approximation in estimating the flammability characteristics of liquefied petroleum gas (LPG)−air−exhaust gas over ranges of pressure, temperature, and dilution representative of engine EGR operations. Because the burning velocities are quite available in the open literature for fuel−air−diluent mixtures, the flammability limits can be evaluated using flame speed cutoff criteria.

The empirical relation of burning velocities for LPG−air−diluent flames is derived from the data of Liao et al.[7] Therein, the burning velocity (u_l) has been explicitly formulated as a function of initial pressure (p_u), initial temperature (T_u), the equivalence ratio (ϕ), and the diluent ratio (ϕ_r); this parameter is simplified as $u_l = f(P_u,T_u,\phi,\phi_r)$. Hence, for given values of ϕ_r, p_u, and T_u, the equivalence ratios at the flammability limits—ϕ_{UFL} and ϕ_{LFL}, corresponding to the upper flammability limit (UFL) and the lower flammability limit (LFL), respectively can be deduced by resolving the equation $u_{l,cr} = f(P_u,T_u,\phi,\phi_r)$, where $u_{l,cr}$ is the critical burning velocity, based on the assumption that the flame cannot propagate at lesser values.

To validate the empirical estimation of the flammability limits, experimental measurements also have been con-

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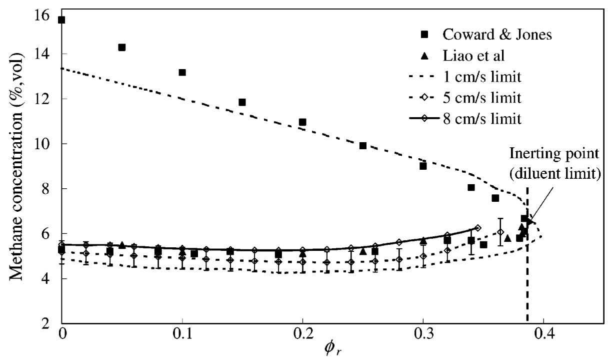

Figure 1. Flammable region of a methane−air−nitrogen mixture at 300 K and atmospheric pressure, where the burning velocity formula for diluting methane−air flames is $u_l = (-150.84\phi^3 + 287.6\phi^2 - 96.327\phi - 1.2924) \times (1 - 1.208\phi_r^{0.803})$, derived from those of Law[11] and Stone et al.[12]

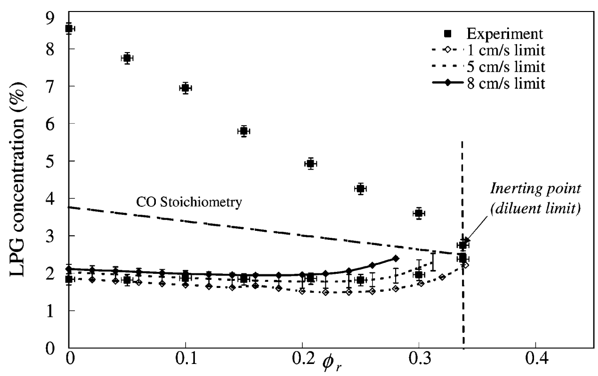

Figure 2. Flammable characteristics of a liquefied petroleum gas (LPG)−air−diluent mixture at 300 K and atmospheric pressure, where $u_l = (4.407\phi^3 - 150.69\phi^2 + 308.62\phi - 122.7) \times (3.4092\phi_r^2 - 3.8178\phi_r + 0.9864) \times (T/300)^{3.0\phi^2-6.3\phi+4.98} \times (P/0.1)^{-0.75\phi^2+1.6\phi-1.3}$.[7]

ducted in a constant combustion bomb, and the detailed description about this bomb can be obtained in ref 7. Visual observation of the flame kernel development is used to distinguish combustion and noncombustion, as proposed in standardized tests.[8]

It is known that the dependence of the flammability limits of various fuels on a diluent concentration in a combustible mixture can be presented as a typical curve, which restricts the flammability region of ternary gaseous mixtures (fuel, oxidizer, and diluent) in the form of peninsula, as shown in Figures 1 and 2. There are three burning velocity cutoff criteria, i.e., 1, 5, and 8 cm/s, those are defined to determine the flammability region. Figure 1 shows the flammability characteristics of methane−air−nitrogen flames. The figure shows that the experiments[9,10] are well within the predicted cutoff values of 1 and 8 cm/s, and a value of 1 cm/s exhibits good performance in estimating the diluent limit. In addition, it is obvious that the best agreement can be obtained for a value of 5 cm/s, because all of the measurement points are within a deviation of ±10% of the prediction. The volume diluent limit of the 5 cm/s cutoff velocity is 0.364, which shows only 5.2% different from the value of the experimental measurement (0.384). However, for a rich flame, the prediction method would narrow the flammability region, even using a value of 1 cm/s, as shown in Figure 1. The results of LPG−air flames with EGR are presented in Figure 2. Similarly, cutoff burning velocities of 1, 5, and 8 cm/s also are used. It also reveals that a value of 5 cm/s is a suitable cutoff velocity to define

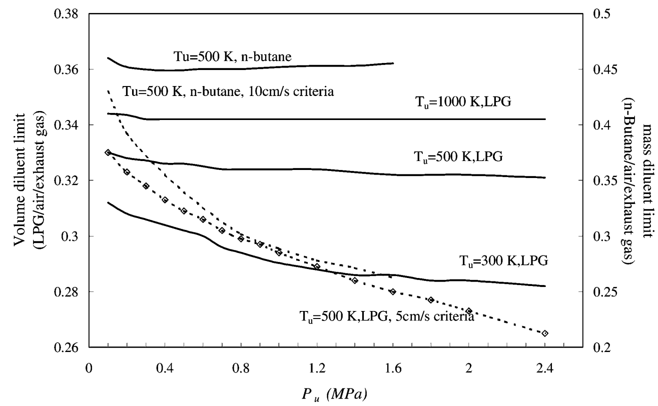

Figure 3. Computed diluent limit of EGR LPG−air mixture at various initial temperatures and pressures; dashed curves are derived from fixed flame speed criteria and solid curves are derived from pressure dependence criteria. Note that the results for *n*-butane involve mass diluent limits.[5]

the flammability limit. In this figure, it seems that the diluent limit lies just at the CO stoichiometric curve, which also gives an approximate justification of our work.[2] For the method of critical burning velocity, the advantage is that one can approximately estimate the inerting point without an excessive amount of experiments when the necessary burning velocities have been in existence. In principle, the pressure and temperature dependences of the flammability characteristics on temperature and pressure could be well-established. As reviewed by Lovachev et al.,[1] the dependence of burning velocity at the flammability limit on pressure P can be simplified as $u_{l,\mathrm{lim}} \approx u_{l,0}P^{-1/3}$, where the subscript 0 denotes the reference conditions (300 K and 0.1 MPa). Figure 3 presents the inerting EGR rate for various initial pressures and temperatures. As expected, the inerting value increases as the initial temperature increases. The limits obtained by a predicted fixed 5 cm/s cutoff velocity and pressure dependence criteria are presented; this information shows that the difference of diluent limits between these two criteria becomes more obvious with increasing pressure. Similarly, the analogous analysis[5] for n-butane−air−residual gas flames (mass diluent limit) is reproduced, and a comparable phenomenon can be observed. However, note that a flame speed of 5 cm/s may be too low and only related to the lowest loads or idle conditions of EGR engines. Because the causes of extinction at the limits are very complex, it is believed that the further research and discussions would be needed and useful for a better understanding of the thermodynamics and chemical kinetics of flammability limits and better improvements for EGR applications in engines.

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