

FLAMMABILITY MEASUREMENTS OF DIFLUOROMETHANE IN AIR AT 100 °C

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ABSTRACT

Difluoromethane (CH_2F_2 , or R-32) is a candidate to replace currently used ozone-depleting chlorofluorocarbon refrigerants. Because CH_2F_2 is flammable, it is necessary to assess the hazard posed by a leak in a refrigeration machine. The currently accepted method for determining flammability, ASTM E 681, has difficulty discerning the flammability boundary for weak fuels such as CH_2F_2 . This paper describes an alternative approach to identify the limits of flammability, using a twin, premixed counter-flow flame. By using the extinction of an already established flame, the point dividing flammable from non-flammable becomes unambiguous. The limiting extinction mixture changes with stretch rate, so it is convenient to report the flammability limit as the value extrapolated to a zero stretch condition. In the burner, contoured nozzles with outlet diameters of 12 mm are aligned counter to each other and spaced 12 mm apart. The lean flammability limit of CH_2F_2 in dry air at room temperature was previously reported by the authors to be a mole fraction of 0.14, using the twin counter-flow flame method. In the current study, relative humidity was not found to affect the lean limit. Increasing the temperature of the premixed fuel and air to 100 °C is shown to extend the flammability limit in the lean direction to 0.13. The rich limit of CH_2F_2 found using the counter-flow method is around 0.27. The uncertainties of the measurements are presented and the results compared to data in the literature.

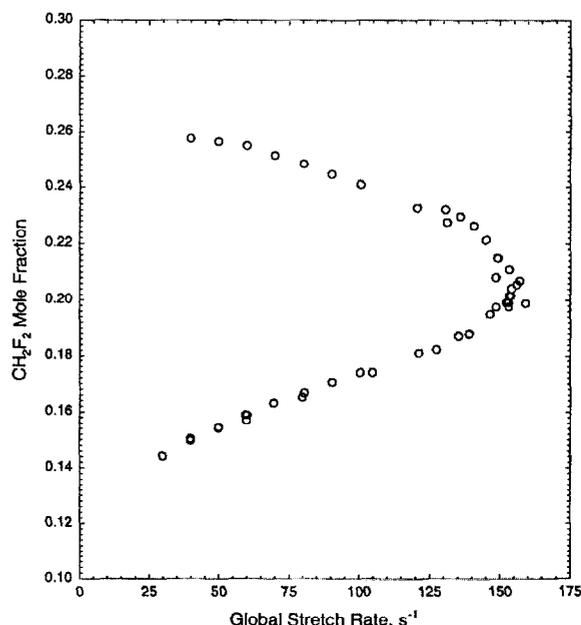


Figure A-1 Extinguishing stretch limits of CH_2F_2 in air mixtures initially at 100 °C

NOMENCLATURE

c_1	= effective activation temperature, K
c_2	= proportionality constant in eq. (3), K^2s^{-1}
ΔH_c	= enthalpy of combustion, J/kg_{fuel}
k_p	= radiative absorption coefficient, m^{-1}
K_g	= global stretch rate, s^{-1}
LFL	= lean flammability limit, mole fraction of fuel in mixture
P	= pressure, Pa
Q_{rad}	= radiative heat loss, J/kg_{fuel}
R	= ideal gas constant
$T_{ad, st}$	= adiabatic, equilibrium, stoichiometric flame temperature, K
T_{dp}	= dew point temperature, K
T_f	= flame temperature, K
$T_{f, rad}$	= flame temperature with radiative cooling, K
T_i	= mixture inlet temperature, K
X_i	= mole fraction of species i
σ	= Stefan-Boltzmann constant
τ_c	= characteristic chemical reaction time, s
τ_f	= characteristic fluid residence time, s
Φ	= fuel/air equivalence ratio
[]	= concentration of species, moles/ m^3

BACKGROUND

An accepted method for determining the flammability limits of gaseous fuels is described in ASTM Standard E 681 (1994). The minimum and maximum concentrations of the fuel in air for flame propagation are based upon the observed ignition and growth of a flame in a vessel filled with a quiescent fuel/air mixture at a specified uniform temperature and pressure. A clear distinction is sought between a mixture which creates a non-propagating flicker and a flame which has enough horizontal propagation to be hazardous. When applied to fuels like methane or propane, these tests give well-defined results. Weak fuels like difluoromethane (CH_2F_2 , or R-32), however, have a greater sensitivity to the test conditions and provide ambiguous limits (see Table 1 and references therein). The ignition energy and type (spark, match-head, heated wire), the complex geometry of the flame, and wall effects all contribute to this ambiguity.

Many of the difficulties associated with the ASTM measurements of flammability are not present in the approach suggested by Law, et al. (1986). They used a planar, twin-flame, counter-flow arrangement to determine the volume flow rate at which burning CH_4 /air and C_3H_8 /air mixtures are extinguished. By repeating the experiments at diminishing fuel concentrations, it is possible to plot the concentration versus the flow rate, and to extrapolate the results to identify the concentration corresponding to an experimentally unattainable zero-flow condition, which is an equivalent definition of flammability limit. Unlike the ASTM apparatus, the counter-flow burner method entirely avoids issues surrounding the design of an ignition mechanism, it minimizes

heat loss and wall effects, and also it is amenable to computational analysis.

A twin-flame counter-flow burner was selected by Womeldorf and Grosshandler (1999) to determine the lean flammability limit (LFL) of CH_2F_2 in dry air at ambient temperature. At the limiting lean mixture, the reaction rate is slowed to the point that the residence time in the flame (which is maintained about constant since the velocity and spacing are fixed) is insufficient for complete combustion to occur, leading to flame extinction. On the other hand, when a fixed concentration of the fuel is maintained, increasing the jet velocity forces the flames towards the stagnation plane lying equidistant between the two burner jet outlets. At a sufficiently high velocity the time through the reaction zone becomes so short that the reactants pass through faster than they can burn, decreasing the combustion efficiency to a point that not enough heat is released to propagate the flame. Again, extinction follows.

The effect of jet velocity and spacing can be combined into a single parameter called the global stretch rate, K_g , defined as the average velocity at the exit of the burner jet divided by the distance between the exit plane and the stagnation plane (i.e., half the nozzle separation). The concentration (or mole fraction) of refrigerant at extinction can be plotted against diminishing values of K_g , and linear extrapolation used to determine the minimum concentration of fuel required to propagate a flame at the zero-flow ($K_g = 0 s^{-1}$) condition. This is the LFL of the fuel for the given initial conditions (ambient temperature, pressure and relative humidity).

Difluoromethane has a molecular weight of 52 g/mol, a boiling temperature of $-51.7^\circ C$ at 101 kPa, a saturation pressure of 1.69 MPa at $25^\circ C$, a specific heat (gas phase) of $0.843 kJ/kg\cdot^\circ C$, and an enthalpy of combustion of $-9.35 MJ/kg_{fuel}$. The complete, stoichiometric combustion of CH_2F_2 in dry air is given by the following expression:



The stoichiometric mole fraction of CH_2F_2 ($X_{CH_2F_2}$) in dry air is 0.1736. The equivalence ratio, Φ , in the counter-flow burner is equal to 4.76 times the ratio of the volume flow of CH_2F_2 to the volume flow of air.

The temperature and products of combustion of difluoromethane at adiabatic, equilibrium conditions were determined by Womeldorf and Grosshandler (1999) for different values of equivalence ratio. For CH_2F_2 /dry air mixtures, initially at $25^\circ C$ and 101 kPa, the peak temperature, $1940^\circ C$, occurs when $\Phi = 1.05$. At approximately the same Φ , the CO_2 reaches a peak mole fraction of about 0.13. The mole fraction of HF at stoichiometric conditions is close to 0.30, and it continues to increase with Φ . The mole fraction of H_2O in the dry flame is over two orders-of-magnitude less than the mole fractions of HF and CO_2 .

Womeldorf and Grosshandler (1999) estimated the adiabatic, stoichiometric laminar flame speed of $\text{CH}_2\text{F}_2/\text{air}$ to be 67 mm/s. They also measured the limiting lean equivalence ratio to be 0.78 ± 0.04 , which corresponds to a lean flammability limit mole fraction of 0.14 ± 0.006 , when the air is dry and at $35^\circ\text{C} \pm 5^\circ\text{C}$.

The refrigeration industry is interested in identifying the hazard associated with a leaking refrigerant as installed in the field, where the temperature and humidity differ from the above experimental conditions. Mixtures at higher temperatures are expected to be more flammable, while the impact of changing the relative humidity is less clear. The current paper addresses these points, and describes experiments in which the temperature is increased to 100°C and the dew point of the air is set at 12°C (equivalent to 50% relative humidity at 23°C and 101 kPa). An estimate of the rich flammability limit and the global stretch rates at extinction for all mixtures between the lean and rich limits are also provided.

FACILITY DESIGN AND OPERATION

Figure 1 is a schematic of the experimental facility. The counter-flow burner is cylindrical, about 100 mm in outside diameter and 450 mm high. The critical dimensions are the nozzle separation and the nozzle diameter, both of which are fixed at $12.0 \text{ mm} \pm 0.2 \text{ mm}$. Air premixed with the fuel enters the upper and lower sections of the burner. The flow is straightened and made uniform with honeycomb, fine mesh screens, and a converging nozzle with an area contraction ratio of 44:1. Nitrogen flows in a concentric annulus to quench the reactants as they escape from the flame, to prevent the flame from stabilizing on the nozzle rim, and to reduce entrainment of air. To eliminate unwanted air currents around the burner and direct the exhaust gases upward, the entire burner is enclosed within a 300 mm dia. Plexiglas tube.

The burner flanges directly exposed to the flames are water-cooled to maintain their integrity and to minimize heat transfer back into the nozzle. Water flows through a copper tube coiled around the upper chamber of the burner to prevent the exhaust gases from preheating the upper section. Thermocouples are located on the centerline just upstream of the contraction nozzles to monitor the incoming mixture temperatures. Flammability measurements at temperatures above the ambient are conducted by heating the air/refrigerant mixtures and controlling the temperatures of the upper and lower burner sections.

The reactants are stored in individual pressurized cylinders. The air is certified to have a mole fraction of O_2 equal to 0.2110 ± 0.0002 , with water and hydrocarbon levels

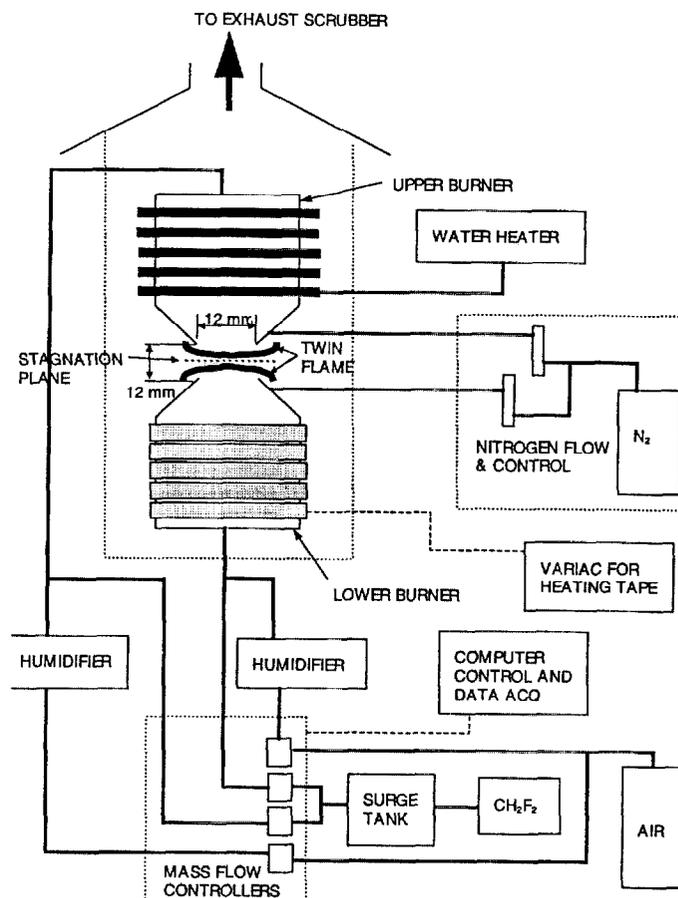


Figure 1. Block diagram of counter-flow burner experimental facility

below 10^{-6} . The remaining components (N_2 , Ar, and CO_2) are as taken from the atmosphere. The air is routed through a humidifier prior to reaching the burner. The CH_2F_2 is a liquid at room temperature and 1.69 MPa, and is claimed by the manufacturer to contain mass fractions of water and non-volatile residues of less than 10^{-5} and non-condensable contaminants of less than 1.5% by volume. The CH_2F_2 supply bottle is connected to a lower pressure expansion tank to minimize pulsation in the flow of gas. The air and the refrigerant are combined at the upper and lower sections of the burner. The concentration of gases in the mixture is maintained through electronic mass flow controllers. All flow controllers are calibrated to $\pm 2\%$ of value with the gas used during testing. Hydrofluoric acid in the exhaust stream is removed using a water spray scrubber. Complete details of the facility design can be found in the final report by Grosshandler, et al. (1998).

A computer controls the flow and monitors the inlet temperatures and pressure. Either the equivalence ratio or the global stretch rate can be chosen as the independent experimental variable. The other then becomes the dependent parameter. Before beginning an experiment, the burner is pre-heated and measurements of the air humidity are taken. An initial lighting condition is chosen which is robust enough for easy ignition, but has a flow velocity greater than the flame speed to prevent flashback into the burner. Depending on the

conditions, the luminescent region is 10 mm to 20 mm in diameter and the gap between the flames is about 4 mm or less. Once the flame has stabilized, the flow settings are changed in small increments to bring the conditions closer to extinction. Refer to Grosshandler, et al. (1998) for more operational details.

EXPERIMENTAL RESULTS

The effect of humidity on the extinction stretch rate of close to room temperature, lean CH_2F_2 flames was determined by repeating the experiments of Womeldorf and Grosshandler (1999) with air at a relative humidity of 43 %. The dot-dash line in Fig. 2 is a least-squares fit of the data (solid diamonds), with the mole fraction of CH_2F_2 in the mixture plotted versus the global stretch rate at extinction. Mole fractions above and to the left of the line are flammable; below and to the right of the line a steady flame cannot be maintained. The dashed line in the figure represents a least-squares fit of the dry air experiments (open diamonds) conducted at the same initial temperature. The difference in the intercept of the two lines is well within the experimental uncertainty, indicating that humidity does not significantly alter the lean flammability limit. This implies that even though the H/F ratio in the fuel is unity, enough water vapor is formed during the reaction that the addition of more H_2O is in excess of the minimum necessary to supply the critical H and OH chain carrying radicals.

The temperature of the mixture was increased to $100\text{ }^\circ\text{C} \pm 5\text{ }^\circ\text{C}$ and experiments were conducted to assess any impact on the lean flammability limit. The dew point was maintained between $11.6\text{ }^\circ\text{C}$ and $13.4\text{ }^\circ\text{C}$. A dew point of $12.0\text{ }^\circ\text{C}$ corresponds to a relative humidity of 50 % at standard pressure and $23\text{ }^\circ\text{C}$. The results are plotted as the circles in Fig. 2. The solid line is a linear fit through the data for global stretch rates between 30 s^{-1} and 70 s^{-1} . An extrapolation of the line to a zero stretch condition yields a lean flammability limit CH_2F_2 mole fraction of 0.131 ± 0.004 . The temperature can be seen to have a measurable impact on the LFL, decreasing the lean limit almost 7 % as the initial conditions are changed from $30\text{ }^\circ\text{C}$ to $100\text{ }^\circ\text{C}$. While the intercepts of the three curve-fits change with the temperature, the lines remain almost parallel. The slope of the extinction mole fraction versus stretch rate curves lie between 0.46 ms and 0.48 ms.

The equivalence ratio that leads to the maximum extinction stretch rate changes with the fuel. For example, Law et al. (1986) found that for methane/air mixtures, the

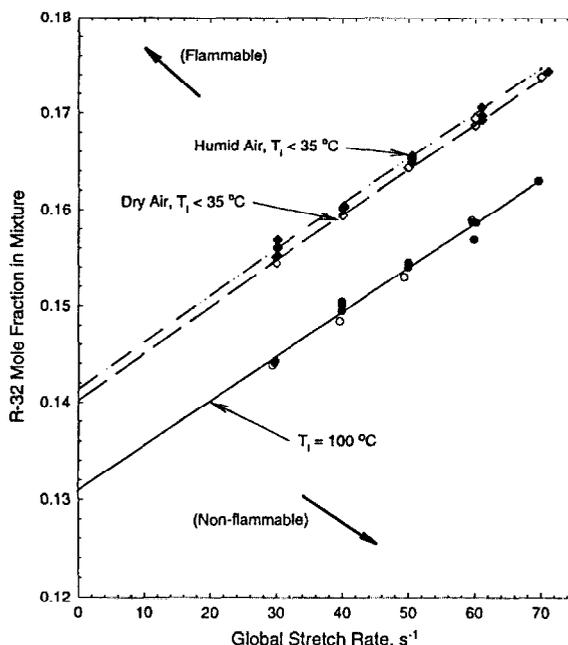


Figure 2 Lean extinction mole fraction of CH_2F_2 in air as function of global stretch rate, comparing effect of humidity and initial temperature: solid symbols, $T_{dp}=12\text{ }^\circ\text{C}$; open symbols, dry.

highest extinction stretch rate occurs for $\Phi=0.95$, while for propane/air mixtures, the most robust mixture is associated with an equivalence ratio near 1.20. To determine the mixture of CH_2F_2 in air that leads to the most difficult flame to extinguish, additional experiments were performed for stoichiometric and rich conditions.

Figure 3 is a plot of the data, taken at a nominal temperature of $100\text{ }^\circ\text{C}$ and a dew point of $12\text{ }^\circ\text{C}$. The lower portion of the curve, for K_g less than 70 s^{-1} , includes some of the same data as shown in Fig. 2. The horizontal line corresponds to $\Phi=1.0$ ($X_{\text{CH}_2\text{F}_2}=0.1736$). It is evident that the stoichiometric condition is not the most difficult to extinguish. Operating at a CH_2F_2 mole fraction of 0.202 increases the extinction stretch rate to 156 s^{-1} , compared to 102 s^{-1} for a stoichiometric flame. The peak mole fraction corresponds to an equivalence ratio of about 1.20, which is similar to the behavior of propane/air flames. The shift to fuel-rich conditions for maximum flame stability cannot be attributed to a higher temperature since at $\Phi=1.2$ the equilibrium adiabatic condition produces a temperature well below the peak, which occurs when $\Phi=1.05$. Rather, the shift can be attributed to the greater than unity Lewis numbers of propane and CH_2F_2 . (The Lewis number for methane is less than one.)

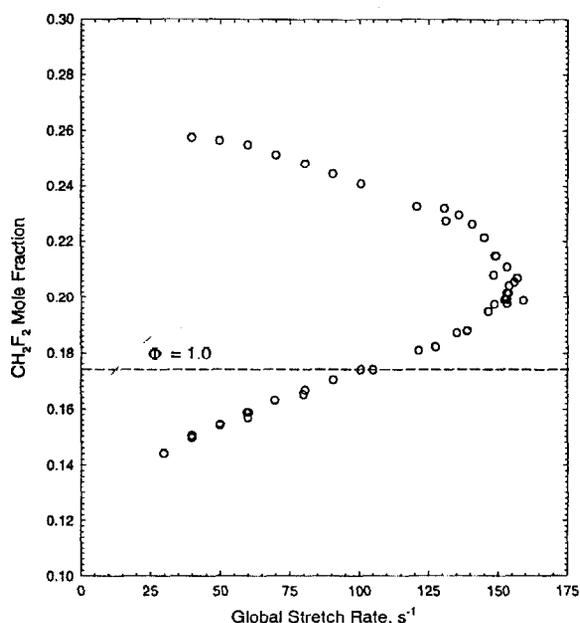


Figure 3 Extinguishing stretch limits of CH_2F_2 in air mixtures initially at 100°C and $T_{dp} = 12^\circ\text{C}$

The structure of rich flames is more complex than flames in lean mixtures because recombination reactions lead to multi-carbon species and soot, and preferential diffusion of the H-atom is enhanced among the field of larger hydrofluorocarbon molecules. Even so, inspection of the upper branch of the flammability curve in Fig. 3 suggests that a linear extrapolation to a zero-stretch condition can yield an identifiable upper limit. A straight-line fit through the data with $X_{\text{CH}_2\text{F}_2} \geq 0.24$ has a y-intercept of 0.271; excluding data with stretch rates greater than 60 s^{-1} produces a slightly lower value, 0.263. These values are less than most of those reported in the literature, which range for ambient initial conditions from 0.269 using a flame tube and fuse wire (Dekleva, et al., 1993) to 0.334 measured in the ASTM E-681 apparatus with a match ignitor (Richard and Shankland, 1992).

ANALYSIS AND DISCUSSION

The measured flammability limits are subject to uncertainties from several sources, including errors in flow measurements; variations in temperature, pressure and composition; the rate at which the extinction point is approached; changes in burner geometry; and non-linear effects near the zero stretch rate condition. Flow calibration and measurement uncertainties were examined and described in detail by Grosshandler et al. (1998). An uncertainty in mole fraction of ± 0.006 , with a 95 % confidence interval, was estimated based upon the assumed linear relation between the

LFL and stretch rate, and the dependence of each on the uncertainty in measured flows. In the current work, additional mass flow controllers have been added, which are sized to operate close to the middle of their dynamic range during most of the experiments, and to allow independent control of the upper and lower burner sections. Both of these conditions lead to less uncertainty in the flow.

The impact on the uncertainty of the results caused by variations in humidity, unknown concentrations of trace species in the reactants, and variations in inlet temperature cannot be expressed in a simple mathematical expression because of the complex relationships between these parameters and the flame chemistry. The uncertainty in dew point is about $\pm 1^\circ\text{C}$, which, based upon the measurements with and without any moisture added, is an insignificant variation. The impact of the barometric pressure, which ranges between about 98 kPa and 100 kPa, is thought to be negligible since combustion theory predicts almost no change in flame stability for such a small change in pressure. The average temperature of the reactants as they enter the burner nozzle varies less than 10°C , and the maximum difference in temperature between the upper and lower sections is approximately the same. Higher temperatures are known to stabilize the flame, but since the actual temperature at extinction varies in the experiment in a non-systematic way, the uncertainty in flammability limits caused by variations in reactant temperature can be reduced by replication. The high degree of repeatability of the extinction conditions indicate that such random errors are smaller than the uncertainty in flow.

The extinction process is dynamic and the response times of the electronic flow controllers and burner are non-zero. This means that the exact conditions at the nozzle exit and in the flame during the precise point of extinction are not measured. The uncertainty due to this behavior is reduced by ensuring that changes in flow conditions occur at a rate slower than the response time of the burner and control system, which is estimated from the volume of the burner and the typical flow rate to be about 10 s. The conditions at extinction are taken to be the readings just after the change in flow setting. The uncertainty can be estimated to be one half the increment between the previous and final step if the flow controllers do not overshoot the new set point. This value varies among tests, but is typically less than 0.5 % of the recorded stretch rate or mole fraction.

The effect of intentionally changing the burner geometry on the measured LFL has been found to be significant (Grosshandler et al., 1998). This is distinct from small changes due to imperfections in the burner or misalignment in assembly. The burner was disassembled for cleaning a number of times and physically relocated from one laboratory to another. No extraordinary care was taken to

Table 1. Lean flammability limits of CH₂F₂/air at ambient temperature (unless indicated otherwise) using different experimental methods

Author(s)	Method	Ignition	Lean Limit Equiv. Ratio	Lean Limit Mole Fract.
Dekleva et al. (1993)	5 cm tube (ICI)	hot wire	1.11	0.189
Richard and Shankland (1992)	4 liter tube	match	0.84	0.150
Dekleva et al. (1993)	ASTM E 681, 5 liter	hot wire	0.81	0.145
Grob, D. (1991)	ASTM E 681, 12 liter	hot wire	0.81	0.145
Richard and Shankland (1992)	ASTM E 681, 5 liter	hot wire	0.79	0.142
Womeldorf and Grosshandler (1999)	counter-flow twin flame, linear extrapolation	(extinction)	0.78 ± 0.04	0.141 ± 0.006
Dekleva et al. (1993)	ASTM E 681, 5 liter	hot wire	0.77	0.139
Dekleva et al. (1993)	ASTM E 681, 12 liter	match	0.77	0.139
Dekleva et al. (1993)	Autoclave, 8 liter	hot wire	0.75	0.136
Richard and Shankland (1992)	ASTM E 681, 5 liter	spark	0.74	0.134
present work (50 % RH, 100 °C)	counter-flow twin flame, linear extrapolation	(extinction)	0.72 ± 0.02	0.131 ± 0.004
Ohnishi, H. (1993)	ASTM E 681, 5 liter	paper match	0.71	0.130
Richard and Shankland (1992)	ASTM E 681, 5 liter	match	0.69	0.127

reassemble the nozzles precisely in the same manner each time. It is estimated that the nozzle spacing and centerline alignment could have varied by as much as 0.5 mm. (The measured separation distance ± 0.2 mm was always used to compute the global stretch rate.) As long as an entire test sequence was conducted without disassembling the burner, no additional uncertainty in LFL was found distinct from the random errors associated with run-to-run variations. Table 1 lists the lean flammability limit of CH₂F₂/air mixtures found in the literature using alternative techniques. Exact temperature, pressure, and humidity were not always listed in these other studies, nor were the uncertainties quantified. However, the values of the LFL reported bracket those determined in the current study.

The basis for assuming that the LFL can be obtained by a linear extrapolation of the extinction mole fraction to a zero-stretch condition is the satisfactory agreement between the experimental measurements and a straight-line fit to the global stretch rate. (An identical approach was used effectively by Wang et al. (1998) for pre-vaporized benzene/air mixtures.) Although a strong correlation is undeniable from a statistical analysis over stretch rates between about 30 s⁻¹ and 60 s⁻¹, the

critical lower stretch conditions necessary to confirm linearity are unattainable in the burner due to the presence of buoyant instabilities.

There are two major difficulties with the linear extrapolation approach: first, the global stretch rate is not equal to the local stretch rate at the flame front; and second, a recent micro-gravity study (Maruta et al., 1996) and theoretical analysis (Ju et al., 1998) indicate that the approach to a zero-stretch condition is not linear, and is affected by radiation and the fuel Lewis number. The impact on the LFL of using the global stretch rate is lessened if K_g is proportional to the local stretch rate, even if the two values differ significantly in magnitude. Kobayashi and Kitano (1991) found the proportionality to be about constant in their counter-flow burner. Preliminary LDA measurements of the axial velocity profile led to the conclusion that the seed particles have a negative impact on the low stretch CH₂F₂/air flames, causing them to extinguish prematurely. As a result, the analysis conducted in the present paper is based upon the assumption that the global stretch rate is proportional to the local stretch rate over the range of conditions examined.

The extent to which radiation heat loss affects the zero-

stretch condition can be investigated by first assuming that at extinction, the chemical reaction time (τ_c) is about equal to the residence time of the fluid in the flame front (τ_f), as done by Chung et al. (1996). The characteristic residence time scales with the inverse of K_g . If the reaction rate, which scales with the inverse of τ_c , is taken to be first order in CH_2F_2 and oxygen concentration and Arrhenius in form, then the following empirical expression can be used to model the extinction stretch rate:

reaction rate $\propto 1/\tau_c \approx 1/\tau_f \approx K_g$

$$\propto [\text{CH}_2\text{F}_2] [\text{O}_2] \exp(-c_1/T_f), \quad (1)$$

where c_1 is an effective activation temperature and T_f is the flame temperature. The mole fractions of CH_2F_2 and oxygen can be approximated by $\Phi/(\Phi + 4.76)$ and $1/(\Phi + 4.76)$, respectively, for lean to stoichiometric mixtures. The concentrations are proportional to their respective mole fractions and the molar density, which decreases with increasing inlet temperature, T_i . Thus,

$$[\text{CH}_2\text{F}_2] [\text{O}_2] \propto \Phi / (\Phi + 4.76)^2 / T_i^2, \quad (2)$$

and equation (1) can be written as

$$K_g = c_2 [\Phi / (\Phi + 4.76)^2 / T_i^2] \exp(-c_1/T_f), \quad (3)$$

where c_2 is a proportionality constant.

The equilibrium temperature of a CH_2F_2 /air flame, accounting for radiative heat loss, can be represented in terms of the stoichiometric equilibrium temperature ($T_{ad, st} = 2213 \text{ K}$), the initial temperature, the radiation loss normalized by the enthalpy of combustion ($Q_{rad}/\Delta H_c$), and Φ , assuming that the excess air acts only as a heat sink and that the specific heat of the mixture per unit mass does not change with equivalence ratio:

$$T_{f, rad} = T_i + (1 - |Q_{rad}/\Delta H_c|) (T_{ad, st} - T_i) \Phi / [\Phi + 0.726(1 - \Phi)]. \quad (4)$$

The radiation loss from a disk shaped flame, in Joules per kilogram of CH_2F_2 , can be estimated by

$$Q_{rad} = 3\tau_f \sigma k_p T_f^4 (RT_i/P) (2\Phi + 4.76) / (0.052\Phi), \quad (5)$$

where k_p , is the absorption coefficient, σ is the Stefan-Boltzmann constant, R is the ideal gas constant, and P is the pressure (Grosshandler et al., 1998). Equation (5) indicates that the radiation loss increases in an unbounded fashion directly with the flow time; hence, as K_g ($\approx 1/\tau_f$) approaches zero, the chemical reaction will be quenched. The absorption coefficient was estimated (Grosshandler et al., 1998) to be about 0.8 m^{-1} , $\Delta H_c = -9.35 \text{ MJ/kg}_{\text{CH}_2\text{F}_2}$, the initial temperature

is 373 K, and P is 101 kPa. The flame temperature accounting for radiative loss is, thus,

$$T_{f, rad} = 373 + [1 - 4.46 \times 10^{-16} (T_{f, rad}^4 / K_g) (2\Phi + 4.76) / (0.052\Phi)] \times \{1838\Phi / [\Phi + 0.726(1 - \Phi)]\}. \quad (6)$$

The constants in Eq. (3) have been calculated, using the radiation-corrected temperature, by matching the lower branch of the data in Figure 3 at K_g equals 30 s^{-1} and 102 s^{-1} , yielding $c_1 = 18300 \text{ K}$ and $c_2 = 7.35 \times 10^{13} \text{ K}^2 \text{ s}^{-1}$. Equations (3) and (6) can be solved iteratively to find the extinction equivalence ratio as a function of K_g for a flame with radiative heat loss. The dashed line in Fig. 4 shows the result (with Φ replaced by the mole fraction of CH_2F_2). Also plotted in the figure is a dash-dot line representing the extinction mole fraction for an adiabatic flame (i.e., $Q_{rad}/\Delta H_c \ll 1$). Accounting for radiative heat loss does two things; first, it shifts the extinction mole fraction curve upward, and second, it demonstrates a true lower limit, as indicated by the * in Fig. 4. No solutions are mathematically obtainable for $K_g < 2.5 \text{ s}^{-1}$. The non-adiabatic, non-linear theory predicts a lower value for LFL than the simple linear extrapolation; however,

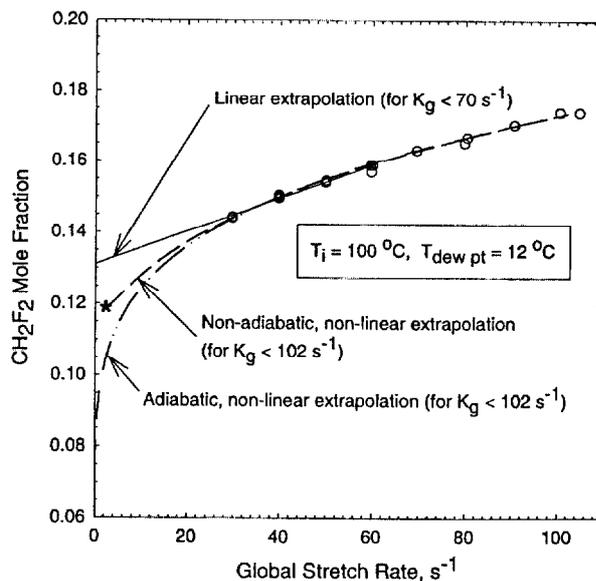


Figure 4 Non-linear extrapolation of CH_2F_2 extinction mole fraction to a zero-stretch flame

other affects such as conduction losses, preferential diffusion, and flame distortion due to buoyancy would act to move the practical LFL upward.

CONCLUSION

In this work, a counter-flow burner has been used to determine the extinction stretch limits of CH₂F₂/air flames for differing mixture inlet conditions. The following conclusions are made based upon the experimental results and analysis:

- An increase in relative humidity from zero to 50 % (based upon an air temperature of 23 °C) has no measurable effect above the experimental uncertainty on the extinction limits of lean CH₂F₂/air stretched flame.
- An increase in initial temperature from 30 °C to 100 °C widens the lean flammability limit in a measurable way. The LFL recommended for CH₂F₂/air (dew point of 12 °C ± 1 °C) mixtures is 0.13 ± 0.004 when the inlet temperature is 100 °C ± 5 °C and the pressure is 99 kPa ± 1 kPa.
- The rich flammability limit for CH₂F₂/air at 100 °C and a dew point of 12 °C is estimated to lie between 0.26 and 0.29, based on linear extrapolation of a limited amount of data to a stretch rate of zero. Additional studies are required to better understand the behavior of fuel rich flames.
- The maximum extinction global stretch rate for CH₂F₂/air flames is 156 s⁻¹ ± 10 s⁻¹ for initial mixture conditions of 100 °C and a dew point of 12 °C. This occurs when the mole fraction of CH₂F₂ is 0.202 ($\phi \approx 1.2$), a result consistent with a fuel Lewis number greater than unity.
- If a non-linear extrapolation to the zero-stretch condition is used and radiative loss is taken into account, the LFL at 100 °C is extended down to about 0.12. However, unless one is concerned about flame spread in a quiescent mixture under micro-gravity conditions, buoyancy-generated instabilities preclude the lowest stretch rates from practical consideration.

ACKNOWLEDGMENT

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