Commonalities and otherwise across various combustion systems

- General behavior of premixed and diffusion-limited flames
- Turbulence and its role in premixed flames, diffusion flames and in complex flows.
- Droplet combustion physics
- Injection systems diesel engines and direct injection gasoline engines, monopropellant liquid thrusters, bipropellant liquid engines.
- Role of chemistry in ignition, steady combustion and extinction

Behavior of Premixed and Diffusion flames



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flammability limits, flash back and blow off and

guench distance



- or O/F) for stoichiometry controls the flame standoff. Since O/F is large as is true for most hydrocarbons the flux demand leads to flame stand-off several times the fuel size.
- Flame temperature is adiabatic flame temperature affected mildly by stretch and other effects

Role of chemistry in ignition, steady combustion and extinction

- Steady premixed combustion in multi dimensions depends on chemistry much as it does for onedimensional case.
- In one-dimensional case, burning velocity can be taken as representative of chemistry. When stretch and turbulence effects are accounted, most observations can be understood within this framework.
- Burning velocity-justified-single-step-chemistry with activation energy and a frequency factor would be good choice for computations. This is in fact the strategy for modeling solid propellant combustion. It would be adequate for other premixed flame situations as well.
- Unsteady or unstable premixed combustion near limits of flammability can be dealt with using additional features of fluid mechanics as in flame blow off or flash back.
- Diffusive combustion near limits of extinction or ignition need chemistry. This chemistry whether reasonably substantive (meaning a fair number of species and a large number of steps) is not necessarily identical to what is used for premixed chemistry. There may not be enough demand for clarifying the differences yet.
- Steady diffusion limited combustion for determining heat release and burn rates can be taken to relatively independent of the details of chemistry
- Auto-ignition and Ignition in practical systems need to account for conduction of heat or diffusion of species and need to treat both diffusion and reaction processes

Premixed flames - 1







- The velocity normal to a steady 1 d flame of the premixed reactants is called the <u>burning velocity</u>
- There are several techniques to measure the burning velocity. It is a function of equivalence ratio, pressure and initial temperature of the reactants.
- The variation of the reactants and temperature through the flame has been obtained.
- Typical flame thickness is 0.5 mm for CH_4 -air, ambient pressure and temperature flame.
- Efforts to get equivalent single step chemistry parameters show that it can be approximate. The activation parameter, $\beta = E/RT_{ad}$, that is taken as infinity in asymptotic analyses is 6.3 for stoichiometric case and it is much lower for hydrogen-air flames.



Fig. 1. Heat release rates with full chemistry and single step reaction for CH_4 -air system.

$$h_r / h_{r, \max} = (1 - \tau) \left(\frac{1}{\phi} - \tau \right) \exp(-E/RT)$$
$$E = \frac{\left(1 + \frac{1}{\phi} - 2\tau_m \right)}{\left(\frac{1}{\phi} - \tau_m \right) (1 - \tau_m)} \frac{R_g T_m^2}{(T_{ad} - T_0)}$$
(18)

where $\tau_m = (T_m - T_0)/(T_{ad} - T_0)$, T_m being the temperature at maximum reaction rate.

The parameters for the lean case are $T_{ad} = 1481$ K, $\beta = 15.3$, and Le nearly unity. For the stoichiometric case, $T_{ad} = 2224.0$ K, $\beta = 6.3$,



Premixed flames – 2



 $\dot{m}^{\mu} \frac{\mathrm{d}Y_F}{\mathrm{d}Y_F} = \dot{m}'' = \rho u$ 3

And so $\rho u / \delta_f \sim \omega$. This gives $\rho u \sim \omega \delta_f$ ($\delta_f \sim \delta_L^0$)

Diffusion- reaction balance gives $\rho D(1-0)/\delta_f^2 \sim \omega$; Therefore, $\rho u \delta_f = \rho D \text{ or } k/c_p \text{ or } \mu$, taking Pr = Le = 1 $\rho u = \sqrt{\rho D \omega} = \sqrt{k/c_p} \omega \sim \sqrt{k/c_p} p^{n/2} \exp(-E/2RT_{ad})$ Further, $\rho u \delta_f = \mu$ implies that flame Reynolds No = Re_f = $\rho u \delta_f / \mu = 1$

This result can also be obtained through more rigorous analysis. But it is to be realized that since the frequency factor is never known to any order of magnitude for equivalent single step reactions, this expression can be used for scaling pressure and initial temperature effects, but the measured value of the burning velocity is a true result of significance

An interlude... Mathematics of premixed flames

The conservation equations and burning velocity as an eigenvalue

- Differential equations (as well matrix equations) where non-trivial solutions are obtained only for specific parametric choices are termed eigenvalue problems. These parameters are called eigenvalues.
- Vibrations of spring-mass systems where non-trivial solution is obtained for specific values of frequency (called natural frequencies) is a eigenvalue problem.
- So is the problem of determining the burning velocity of a premixed fuel-air mixture.

Further,

For the case of normal diffusion (Lewis number = $\delta = 1$) $p \frac{dp}{d\tau} - p = -\lambda \phi(\tau), \quad \phi(\tau) = (n+1)(n+2)(1-\tau)\tau^{n}$ n ~ E/RTD, large n ~ large activation parameter this problem was discussed and solved by several researches in the nineteen seventies using high activation energy to asymptotics - Singular particular theory (as different form regular fert, them) If we take RHS to be zero everywhere, we get poly-p=0. This give p=T as the solution This satisfies p(T=0) =0 But it does not pakely p(T=1) =0. This is because we Laye have igned the reacher nate term there which is dominant near T=1.

If we integrable the equation from Too to 1, we get $\frac{1}{2}\int \frac{dp^{2}}{dt}dt - \int p dt = -\lambda \int \phi(t).$ $\frac{1}{2}p^2 \int -\int p d\tau = -\lambda \int \phi(\tau) d\tau$ ^obecause $p(\tau=0, \tau=1) = 0$. We therefore have $\chi = \frac{\int p d\tau}{\int d\tau}$. If we take as a $f(\tau) d\tau$ fust approximation $\int_{0}^{1} \theta(\tau) d\tau$ $p = \tau$, we put $\lambda = \frac{1}{2}$. This gives a result $\int \frac{1}{9ct} dt$ (G= Q_{n}S_{n}) $\frac{k}{c_{p}} \frac{\chi + m_{p}}{\chi (t_{b}, \tau_{w})} \frac{1}{(R_{u}S_{u})^{2}} = \frac{1}{\int_{u}^{t} \phi(\tau) d\tau}.$ $(S_{u}S_{u}) = \int_{-\infty}^{\infty} 2\frac{\kappa}{c_{p}} \cdot \tilde{m}_{f}^{n} \int \phi(\tau) d\tau$ This result is the same as obtained from Simple analysis except that the variation of reaction rate with temperature is accounted.

In canonical flames....

1 - D flame is unstrained or un-stretched Any curved moving flame will have \pm flame stretch ~ (+ or - du_s/ds)

and – for inward. Axisymmetric Bunsen flame at the axis has negative stretch. Swirling premixed flames have

Values of δ_0 and S_u^0 of Fuel Oxidizer Mixtures Used in This Study

| Fuel/Oxidizer | φ | S_u^0 (cm/s) | δ ₀ (mm) |
|----------------------------------|-------|-------------------|------------------------|
| $CH_4/Air, P = 1$ atm | 0.6 | 10.1 | 0.23 |
| | 1.0 | 39.6 | 0.053 |
| | 1.5 | 8.2 | 0.25 |
| C_3H_8/Air , $P = 1$ atm | 0.775 | 30.5 | 0.073 |
| | 1.0 | 47.5 | 0.0442 |
| | 1.5 | 16.1 | 0.124 |
| $H_2/Air; P = 1$ atm | 0.513 | 64.1 | 0.0536 |
| | 1.65 | 330 | 0.0167 |
| | 3.27 | 238.3 | 0.0303 |
| $H_2/N_2/O_2, P = 3 \text{ atm}$ | 1.0 | 87.2 | 0.0138 |
| $O_2/(O_2 + N_2) = 0.125$ | 1.41 | 150.3 | 0.0091 |
| | 1.8 | 155.7 | 0.0097 |
| | 2.78 | 118 | 0.0155 |
| | 3.27 | 101 | 0.0195 |
| | | | |

FIGURE 4.2.4

Relation between flame speed $V_{\rm f}$ and maximum tangential velocity $V_{\theta \max}$ in the vortex ring combustion. (From Ishizuka, S., Murakami, T., Hamasaki, T., Koumura, K., and Hasegawa, R., Combust. Flame, 113, 542, 1998.)

Turbulent premixed flame behavior

- When the scale of turbulence

 A is large compared to the
 unstrained flame thickness
 the flame is wrinkled by
 turbulence.
- The flame surface area change is taken proportional to turbulent velocity fluctuation, u'
- Because of temperature jump across the flame, viscosity increases and the flow may even become laminar locally.
- Under strong turbulence, the flame structure itself is altered
- Based on these considerations, various correlations are developed.

$$\frac{S_{\rm T}}{S_{\rm L}} = \frac{A_{\rm L}}{A_{\rm T}}, \qquad A_{\rm L}/A_{\rm T} = 1 + u'/S_{\rm L}, \qquad S_{\rm T} = S_{\rm L} + u',$$

$$S_{\rm L} = \frac{1}{\varrho_0} \left(\frac{kw}{C_{\rm p}}\right)_{\rm L}^{1/2}, \qquad S_{\rm T} = \frac{1}{\varrho_0} \left(\frac{kw}{C_{\rm p}}\right)_{\rm T}^{1/2}, \qquad S_{\rm T}/S_{\rm L} = (v_{\rm T}/v)^{1/2},$$

 $v_{\rm T} \sim u' l, \qquad S_{\rm T}/S_{\rm L} \sim R_l^{1/2}.$

Koolmogorov scale based Re, Taylor scale based Re and inertial scale based Re

 $R_{\rm k}^4 \approx R_{\lambda}^2 \approx R_1$

 $D_{\rm a} = lS_{\rm L}/\delta_{\rm L}u'$

Data On Turbulent Premixed mixtures

A comparison of turbulent flame speed correlations for hydrocarbon fuels at elevated pressures, GT2016 – 57804 by Burke, E M, Guthe, F Monaghan, R F D

Figure 5 Turbulence and flame conditions for the data displayed in Table 3 plotted on a Borghi diagram modified by Peters [17].

Figure 11 Predicted trends for Flame D (CH₄ with T = 300 K, P = 0.1 MPa) with u' = 1.89 using correlation parameter to minimize

Figure 6 Predicted trends for Flame J (CH₄ with T = 300 K, P = 0.1 MPa) with Φ = 0.7 using correlation parameter to minimize MAPE for DG 1

Figure 7 Predicted trends for Flame J (CH4 with T = 300 K, P = 0.1 MPa) with Φ = 1.0 using correlation parameter to minimize MAPE for DG 1

The conclusion of several authors is that the correlations for turbulent flame speed are not satisfactory. Modeling of the role of turbulence needs improvement.

For complex premixed flows, a simple approach is to use BML model in which the local temperature of an averaged combination of temperatures at unburnt condition and fully burnt condition, the averaging procedure evolved through conservation equations. It is turbulence that controls the averaging process.

Laminar Diffusion flames

 Y_{Ox}

 Y_{Ox}

Y_{Ox}

In an actual flow field with chemical heat release.....

FIGURE 7.2.12

FIGURE 7.2.11

Diagram and photograph of a model gas turbine combustor operating

on CH,/air at atmospheric pressure. Fuel is injected from an annulus

separating two swirling air streams. (From Meier, W., Duan, X.R., and Weigand, P., Combust. Flame, 144, 225, 2006. With permission.) Scatter plots of temperature and CH₄ mole fraction versus mixture fraction in a model gas turbine combustor. (From Meier, W., Duan, X.R., and Weigand, P., *Combust. Flame*, 144, 225, 2006. With permission.)

In a turbulent flow at large Re, the flow structures will involve curved flames and local vortical structures of partially premixed fuel-oxidant as well diffusion flame structures. Such a flow involves local temporal extinction and re-ignition. These imply that at any station where one would expect fuel, one would expect varying degrees of completion of reaction. With laminar flow and intense turbulent flows, the plots will be as above.

FIGURE 7.2.5

Temporal sequence of OH-LIF measurements captures a localized extinction event in a turbulent nonpremixed $CH_4/H_2/N_2$ jet flame ($Re \sim 20,000$) as a vortex perturbs the reaction zone. The time between frames is 125μ s. The velocity field from PIV measurements is superimposed on the second frame and has the mean vertical velocity of 9 m/s subtracted. (From Hult, J. et al., Paper No. 26-2, in 10th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, 2000. With permission.)

FIGURE 7.2.4

Scatter plots of temperature at x/d = 15 in turbulent CH₄/air jet flames with Reynolds numbers of 13,400 (Flame C) and 44,800 (Flame F). The stoichiometric mixture fraction is $\xi_{st} = 0.351$. The line shows the results of a laminar counterflow-flame calculation with a strain parameter of $a = 100 \text{ s}^{-1}$ and is included as a visual guide. (From Barlow, R.S. and Frank, J.H., *Proc. Combust. Inst.*, 27, 1087, 1998. With permission.)

Turbulence, and diffusion limited flows

- There are many perceptions of difference between laminar and turbulent flows.
- It is commonly understood that pipe flows are turbulent beyond a Reynolds number, Re (= $\rho ud/\mu$) - typically 2300, where as the correct statement would be that turbulence cannot be sustained below a certain Re, say 2300.
- Any unsteady flow with fluctuations is not a turbulent flow. It could simply be an unsteady laminar flow.
- A flow with fluctuations like white noise fluctuations with the same amplitude at all frequencies is not a turbulent flow.
- A flow in which the fluctuations have a power spectrum (variation of the square of fluctuating velocity with frequency) involving all frequencies (not simply connected to any specific geometrical feature) is turbulent.
- In a turbulent flow, the fluctuating velocity draws energy from the mean field and dissipates it through fluctuations until the final dissipation occurs through viscosity.
- A buoyancy driven flow field (like buoyant jets) can also be turbulent. Here the convective motion gets sustained buoyancy.

Turbulence, and diffusion limited flows

- Turbulence is characterized by intensity and scale. Intensity is u' and scale can be a spatial correlation distance. There are several ways of defining it.
- The first one is integral scale typically the size of the flow duct or a characteristic length of the system. The small scale is obtained by requiring the energy dissipation occurs to the smallest viscous scale. This is given by $\varepsilon \sim u^2/(L/u) \sim u^3/L$. The length scale formed of the dissipation rate and viscosity is $\eta = [v^3/(u^3/L)]^{(1/4)}$. This is the Kolmogorov length scale.
- The ratio of the largest to smallest length scale is $L/\eta = (UL/v)^{(3/4)} = Re^{3/4}$. This quantity is much discussed number when computational strategies for high Reynolds numbers are discussed it is noted that if complete resolution of all scales up to Kolmogorov scales has to be achieved for high enough Re, then the number of grid points in a 3-d flow increases so much that the current computational resources are inadequate unless a modeling of fine scales is done as in large eddy simulation and similar strategies.
- By similar arguments we get the time scales: large time scale $t_L \sim (L/u)$; small time scale can be formed as $t_\eta \sim (v/\epsilon)^{(1/2)}$
- The ratio of the time scales becomes: $t_L/t_\eta \sim Re^{1/2}$. This result is unsurprising in view of the scales involved.
- We get Taylor micro-scale as $\Lambda \sim u' t_{\eta}$ and Reynolds number based on Taylor micro-scale as $Re_{\Lambda} = u' \Lambda/v$.
- For scalars, one has other scales to define mass and energy diffusion. For calculating turbulent diffusive combustion flows, the most important scale is Scalar dissipation. Reaction occurs wherever scalar dissipation is high. The simplest approach is to treat the reaction rate as the same as turbulent mixing rate.

Droplet Burning behavior

Flame is treated as a thin sheet. Reactions occur no where else excepting at this sheet. Rates are represented by Dirac delta function. The mass and heat flux balance at the surface of the fuel and the think flame lead to the solution to the problem

 $\dot{m}_{F} = \frac{4\pi k_{g} r_{s}}{c_{pg}} \ln(1 + B_{o,q}).$ $The d^{2} law: d^{2} = d_{0}^{2} - K t$ $t_{b} = d_{0}^{2}/K$ $d_{0} = \text{drop diameter}$ $K = \frac{8k_{g}}{\rho_{l}c_{pg}} \ln(1 + B_{o,q}).$ $K = \frac{8k_{g}}{\rho_{l}c_{pg}} \ln(1 + B_{o,q}).$ $K = \frac{8k_{g}}{\rho_{l}c_{pg}} \ln(1 + B_{o,q}).$ $The d^{2} law: d^{2} = d_{0}^{2} - K t$ $t_{b} = d_{0}^{2}/K$ $d_{0} = \text{drop diameter}$ K = Burning constant $A 100 \ \mu\text{m droplet will take}$ 5 to 10 ms to burn; $A 20 \ \mu\text{m drop will take}$ $200 \text{ to 400 } \mu\text{s to burn}$

Figure 4.5 Burning-rate constants for hydrocarbons and some light commercial fuels burning in air at elevated temperature (a) cetane, (b) diesel fuel (DERV), (c) aviation kerosine, (d) n-heptane, and (e) benzene.

From Stephen Turns book....

C. The dimensionless flame radius can be calculated from (Eqn. 10.70):

$$\frac{r_f}{r_s} = \frac{\ln[1+B_{o,q}]}{\ln[(\nu+1)/\nu]} = \frac{\ln[1+8.473]}{\ln(16.08/15.08)}$$
$$\boxed{\frac{r_f}{r_s} = 35}.$$

Experimental values of dimensionless flame radii (~ 10) are considerably smaller than that calculated above. Law [15] indicates that fuel-vapor accumulation effects account for the difference. In spite of the shortcomings of the theory, useful estimates of burning rates and droplet lifetimes are obtained.

15. Law, C. K., "Recent Advances in Droplet Vaporization and Combustion," Progress in Energy and Combustion Science, 8: 171-201 (1982).

TABLE 2

| | Comparison of Various Approximations in the Analysis ($Le_1 = Le_2 = 1.0$) | | | | |
|--|--|-------------------------|-------------------------|-------------------------|--|
| | λ constant ^a | λ variable | λ constant | λ variable | |
| | c _p constant ^b | c _p constant | c _p variable | c _p variable | |
| $ \begin{array}{l} K \;(\mathrm{mm}^2/\mathrm{sec}) \\ \frac{d_f}{d_s} \\ T_f \;(^\circ K) \end{array} $ | 0.7193 | 1.1102 | 0.5431 | 0.7239 | |
| | 28.303 | 23.868 | 20.910 | 15.359 | |
| | 2548 | 2548 | 2506 | 2506 | |

^a constant $\lambda = 1.2 \times 10^{-4}$ chosen such that the SQST predicts realistic K.

b constant cp = 0.304 chosen such that the SQST correctly predicts adiabatic flame temperature.

and needed corrections

From: COMBUSTION AND FLAME 30,71-84 (1977)

The Problem of Liquid Droplet Combustion-A Reexamination

B. N. RAGHUNANDAN and H. S. MUKUNDA

They used a variable property analysis and obtained

$$\frac{\dot{m}}{4\pi r} = J(\eta)$$
 where $J(\eta) = \int_{\eta}^{1} \frac{\lambda}{c_p} \frac{d\eta}{\eta}$.

Thus we have

$$r/r_s \approx J(\eta_s)/J(\eta)$$
,

$$d_f/d_s = J(\eta_s)/J(\eta_f); \quad K = \frac{8}{\rho_c} J(\eta_s) .$$

Fig. 6. Variations of T, c_p , λ and λ/c_p with η (Le₁ = Le₂ = 1.0)-variable property analysis

Other influences on droplet combustion

- There are other effects on droplet combustion in real environments
- Forced convection effects in disperse environment

 $K = (8/\rho_d)(\lambda/c_p)\ln(1+B) \qquad K = K^0(1+0.276\text{Re}^{1/2}\text{Pr}^{1/3})$

- Spray combustion of a drop size distribution Group combustion dynamics
- Effects of turbulence on fine droplet combustion behavior
- In view of the complex flow behavior due to the above effects and even if experimental data on burn rate constants under quiescent burning are considered appropriate, validation in real combustion systems are required in view of a variety of detailed models under development.

Some fuels are more easy to ignite.....is it?, if so why?

Figure 8–5. Dependence of autoignition temperature upon carbon chain length for normal alkanes, C_NH_{2N+2} , at atmospheric pressure [26].

Methane has the highest T_{ign} followed by higher alkanes. Why so?

Larger molecules decompose more readily into reactive fragments than smaller ones. Hydrogen, the high reactive molecule is more difficult to auto-ignite compared to several liquid hydrocarbons!

All these mean that chemistry matters with regard to ignition. It is not entirely short duration high energy inspired reaction chemistry either. There are energy extraction processes due to flow including turbulence - a dynamic energy balance deeply influenced by chemistry.

Easier ignition does not mean faster combustion. Burning velocity of premixed hydro-gen-air mixture is about 5 times more than straight chain hydrocarbon. Different mechanisms are at play - early time dependent breakdown vs. steady back diffusion of reactive intermediates.

| Fuel | T _{auto-ign} , K |
|----------|---------------------------|
| Gasoline | 516 - 550 |
| Diesel | 483 |
| Carbon | 973 |
| Benzene | 771 |
| Methane | 853 |
| Ethane | 790 |
| Heptane | 477 |
| Hydrogen | 773 |

 $\tau = 1.37 \times P^{-1.06} \times e^{5130/T}.$

Spray Physics and Characterization

View of the typical conventional CI-engine spray targeting from the bottom. The images of the nonevaporative spray were obtained in an engine with a transparent piston top, using a fast camera and a pulsed laser for illuminating the sprays from the same side as the camera. (From Cronhjort, A. and Wählin, F., *Appl. Opt.*, 43(32), 5971, 2004. With permission.)

(6) Mean diameter of spray: The Sauter mean diameter X_{SMD} is the most popular mean diameter. The definition is;

$$X_{SMD} = \frac{\sum_{i} n_{i} X_{i}^{3}}{\sum_{i} n_{i} X_{i}^{2}}$$
(1)

where n_i is numbers of X_i diameter droplet. The Sauter mean diameter is a representative diameter corresponding to equivalent surface of spray and could show the average evaporation characteristics of a spray. Typical empirical equations of the Sauter mean diameter of diesel spray was as follows [11].

$$\frac{x_{SMD}}{D_n} = MAX \left[\frac{x_{SMD}^{LS}}{D_n}, \frac{x_{SMD}^{HS}}{D_n} \right]$$
(2)

$$\frac{x_{SMD}^{LS}}{D_n} = 4.12 \cdot Re^{0.12} \cdot We^{-0.75} \cdot \left(\frac{\mu_l}{\mu_a}\right)^{0.54} \cdot \left(\frac{\rho_l}{\rho_a}\right)^{0.18}$$
(3)

$$Re = \rho_l U_l D/\mu_l$$
(4)

$$\frac{x_{SMD}^{HS}}{D_n} = 0.38 \cdot Re^{0.25} \cdot We^{-0.32} \cdot \left(\frac{\mu_l}{\mu_a}\right)^{0.37} \cdot \left(\frac{\rho_l}{\rho_a}\right)^{-0.47}$$
(4)

$$We = \rho_l U_l^2 D/c$$

Where, MAX[A,B] means the larger value of the two. μ is viscosity of liquid (*l*) and air(*a*), and ρ is density. Positive index of *Re* (Reynolds number) and negative index of *We* (Weber number) meant that both of shear force in a nozzle and jet stability were dominant factors on X_{SMD} . However, applicable range of nozzle diameter D_n was unclear and it was one of fundamental issues of liquid atomization. X_{SMD} of a traditional type diesel spray was ranging into 25µm-35µm, and that of 10µm-20µm) was attained with a high-pressure injection.

Figure 14 Breakup model of diesel fuel jet (modified from ref. [22])

| Breakup Form | d10/di | V6/VI | Range in We No. |
|-------------------------------|--------|-------|--------------------|
| 1 non-breakup (into film) | | | We<80 |
| I large breakup | 0.3 | 0.3 | 80 <u>≤</u> We<600 |
| III small breakup | 0.1 | 0.5 | We≥ 600 |

Figure 17 Fuel film breakup model for impinging diesel spray [29][31]

From: Arai, Physics behind diesel sprays, ICLASS 2012, 12th triennial int. conf. liq. atomization and spray systems

Ultra high pressure spray

6) Ultra-high pressure injection

To meet the demand of clean diesel combustion, injection pressure of common rail injection system tended to increase. Shock wave generation around diesel spray was reported [55][56], but not so much attention was paid on this fact. When a diesel spray is injected by injection pressure of 300MPa into a combustion chamber, injection velocity may increase up to 750m/s and it might be far faster than the sound velocity. Hiroyasu [57] and Nishida et al.[58] reported an early study on ultra-high injection pressure diesel spray. Using Schlieren optical observation system, they reported the Mach wave around diesel spray as shown in Fig.36. It means that there might be other breakup and spray tip penetration processes, even though many research reports supported the empirical equation of Eq.11 for diesel spray of which injection pressure was beyond 200MPa.

$$0 < t \leq t_{b}$$

$$S = 0.39 \sqrt{\frac{2\Delta P}{\rho_{l}}} \cdot t \quad (8)$$

$$t_{b} = 28.7 \frac{\rho_{l} D_{n}}{\sqrt{\rho_{a} \Delta P}} \quad (9) \qquad L_{b} = 15.8 \sqrt{\frac{\rho_{l}}{\rho_{a}}} \cdot D_{n}$$

$$t_{b} < t$$

$$S = 2.95 \left(\frac{\Delta P}{\rho_{a}}\right)^{0.25} \cdot \sqrt{D_{n} t} \quad (11)$$

D 20 40 60 80 mm Figure 36 Schlieren photographs of a diesel spray and Mach wave around the spray, P_{inj}=275MPa, D_n=0.25mm, P_a=1.2MPa, T_a=298K [58]

Images From Diesel Combustion

First occurrence of luminous flame (1.0 ms after start of injection)

(0.13 ms after ignition)

(0.93 ms after ignition)

End of injection (2.67 ms after ignition)

5.33 ms after ignition

Spray characteristics – general features

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FIGURE 6.40

Influence of ambient air pressure on radial fuel distribution. (From Ortman, J., and Lefebvre, A.H., Journal of Propulsion and Power, 1(1), 11–15, 1985. With permission.)

- SMD is the actual spray volume to spray surface area. Mean drop sizes are close to 30 microns.
- Drop size distribution describes the fractional volume in a small diameter range.
- The amount of liquid distribution across the face shows that it is double peak matching with the influence of the swirl.
- The combustion process is largely governed by drop vaporization. Chemical kinetics of combustion
 will be dominant at outer limits high altitudes (12 13 km) and moderate speeds (M~0.85) when
 the pressure in the combustion chamber will be low ~ 2 to 5 atm.

Gas turbine spray aspects

FIGURE 1.2

(a) Pressure atomizers, (b) rotary atomizers, and (c) twin-fluid atomizers.

- There are a number of correlations provided in the book by Lefebvre and McDonell Atomization and Sprays, 2017 many of them specific to the design.
- One can notice that the dependence on Weber number is different in the two cases.
- Generally, the features are that the air velocity has a strong influence on the drop size.
- Unless a new design has identical geometry, one can use these expressions and determine the constants specifically.
- Modern day gas turbine engines attempt to use high shear injectors to ensure better atomization over a range of conditions that the engine has to experience.

Figure 5. High Shear swirler

- The fuel gets sprayed because of centrifugal force.
- Atomization is dependent on the rotational speed.
- As can be seen, unless the speeds are high
 ~ 40000 rpm + atomization is poor.
- The injection hole diameter is important, but not much since the centrifugal action naturally creates a thin layer of the film attached to the forward part of the rotating nozzle

Results...From: 2002 Dahm et al, AIAA 2002-3183

(a) Linear axes.

- At the comparatively low values of Oh relevant to practical fuel slingers for small gas turbines, the liquid breakup process becomes essentially independent of Oh.
- The Oh-independence indicates that viscous effects are largely negligible, and therefore the breakup process becomes largely independent of the liquid-to-gas viscosity ratio m as well.
- At We values relevant to practical fuel slingers, the primary liquid breakup process will occur near the transition between the liquid column mode and the bag mode.

4.3.3. Practical We and Oh values for fuel slingers

For the "typical" fuel slinger noted in §§4.1 and 4.2, with $R \approx 5$ cm and $\Omega \approx 3000$ rad/sec, the corresponding crossflow velocity $U_c \equiv R\Omega \approx 150$ m/sec. With the liquid properties noted earlier for Jet-A fuel, this gives the Weber number based on the nominally uniform film thickness *t* as

$$We_t \equiv \left[\frac{\rho_G U_c t}{\sigma_L}\right] \approx 0.075 \quad , \tag{4.14 a}$$

and the Weber number based on the diameter d as

$$We_d \equiv \left[\frac{\rho_G U_c d}{\sigma_L}\right] \approx 7.5 \quad . \tag{4.14 b}$$

The corresponding Ohnesorge number based on the film thickness *t* for the "typical slinger" is

$$Oh_{t} \equiv \left[\frac{\mu_{L}}{\left(\rho_{L}\sigma_{L} t\right)^{1/2}}\right] \approx 0.14 \quad , \qquad (4.15 a)$$

and the Ohnesorge number based on the channel diameter d is

$$Oh_d = \left[\frac{\mu_L}{\left(\rho_L \sigma_L d\right)^{1/2}}\right] \approx 0.014 \quad . \tag{4.15 b}$$

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