

ME 471: Turbulent Combustion, Spring 2012
Stanford University
Midterm Exam
Tuesday, May 15.

Closed books, closed notes, no calculator allowed

Guidelines: Please turn in a *neat* and *clean* exam solution. Answers should be written in the blank spaces provided in these exam sheets. Vector quantities are denoted in **bold** letters in what follows.

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Question 1 (50 pts)

- a) Explain the concept of "separation of scales" (Peters, 2000) in turbulent combustion taught in class, and outline what does it entail for turbulent-combustion modeling.

+ 20 / 20

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- b) Draw the premixed turbulent-combustion diagram in terms of the ratio of the large turnover velocity u' to the flame propagation speed S_L^0 versus the ratio of the integral length scale ℓ to flame thickness δ_L^0 . Identify the mean nondimensional parameters and give a brief description of each of the burning regimes in the diagram (use back of the page if needed).

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+ 16 DIAGRAM
+ 6 PARAMETERS
+ 8 REGIMES

+ 30 / 30

Question 2 (50 pts)

Select true (T) or false (F) for each of the statements in the list provided for each question. A complementary and *brief* mathematical proof / sketch of your answer on the back of the page would be welcome, but it is **not** needed in order to get full credit.

= MEANS CORRECT ANSWER → +50/30 EACH

3.1 In $\text{CH}_4 - \text{O}_2$ laminar premixed flames,

- a) there exists a fuel-consumption (inner) layer on the fuel side in which H_2 and CO are oxidized to H_2O and CO_2 respectively (T/F) F
- b) there exists an oxidation layer on the oxidizer side in which H_2 and CO are oxidized to H_2O and CO_2 respectively (T/F) F
- c) there exists a thin fuel-consumption (inner) layer in which the fuel is attacked by H atoms to form H_2 and CO in chain-breaking reactions; this layer has a thickness $\delta \sim 0.1\delta_L^0$, with δ_L^0 the preheat thickness (T/F) F
- d) the typical crossover temperatures are much lower than in hydrogen combustion (T/F) F.

3.2 The thermal production of NO_x in premixed burners

- a) is minimum for stoichiometric flames (T/F) F
NEAR MAX BECAUSE TEMPERATURE IS HIGH FOR $\phi \sim 1$
- b) decreases with increasing flame temperature; this is why engineers from aeronautical companies design jet-engine combustors in which the flame temperature is as high as possible (T/F) F
- c) is beneficial because it generates ground-level O_3 , which protects us from the Van Allen radiation belt (T/F) F
- d) decreases as the mixture becomes leaner or richer (T/F) F → T DECREASES

3.3 For single-step chemistry flames in the limit of large activation energies,

- a) the propagation speed of a planar laminar diffusion flame scales as $\sqrt{D/t_F}$, where D is the fuel mass diffusivity and t_F is the flame-transit time or characteristic residence time within the preheat region (T/F) F
DIFFUSION FLAMES DO NOT HAVE A PROPAGATION VELOCITY
- b) If both the diffusivity of the deficient reactant and the thermal diffusivity are multiplied by a factor 5 and the flame transit time is multiplied by a factor 5, then, according to large activation-energy scalings in laminar premixed flames, ⇒ $Le = \text{CONSTANT}$, $D_T = 5D_T$, $t_F = 5t_F$ ⇒ $S_L \sim (D_T/t_F)^{1/2}$, $S_L \sim (D_T/t_F)^{1/2}$
 - b1) the flame would become thinner by a factor 5 but the planar flame propagation speed would remain the same (T/F) F
 - b2) the flame would become thicker by a factor 5 but the planar flame propagation speed would remain the same (T/F) F
 - b3) the flame thickness remains the same but the planar flame propagation speed is larger by a factor $\sqrt{5}$ (T/F) F
- c) For flames at sufficiently small Lewis numbers, as in the case of lean hydrogen-oxygen deflagrations, the flame front remains mostly flat because of diffusive-thermal stabilizing effects (T/F) F
- d) the chemical reaction in premixed flames takes place in a layer which is much thinner than the preheat zone (T/F) F

$\delta_F \sim \frac{\delta_L^0}{\beta}$ WITH $\beta \gg 1$ (ZEL'DOVICH NUMBER)

3.4 In turbulent premixed flames,

- a) there exists an effect called "countergradient diffusion" in which the turbulent flux of reaction-progress variable c in the normal direction to the flame is directed towards regions of decreasing c , that is why it is called "countergradient" (T/F) INCREASING
- b) direct numerical simulations and experiments show that the countergradient diffusion effect is likely to be important in regions of high turbulent intensity and, in particular, in regions in which the Kolmogorov eddies are able to penetrate in the reaction zones (T/F) LOW
- c) according to the Bray-Moss-Libby model, the differences between Reynolds-averaged and Favre-averaged variables tend to increase with increasing thermal expansion (T/F)
- d) Lewis number effects are irrelevant for the propagation of turbulent premixed flames because molecular diffusion is typically neglected in RANS codes (T/F) → Le HAS A STRONG DEPENDENCE ON Le

3.5 In the modeling of turbulent premixed flames,

- a) the eddy break up (EBU) model is a turbulent combustion model for the infinitely-fast chemistry limit (T/F)
- b) the level set approach is used to track the propagation dynamics of turbulent diffusion flames (T/F)
- c) the flame surface-density transport equation has a production term related to the generation of flame surface by curvature and a depletion term related to the destruction of flame surface by tangential strain-rate (T/F) JUST THE CONTRARY
- d) the Bray-Moss-Libby model describes the crossing frequency of thick flames (T/F)

3.6 In wrinkled premixed flames,

- a) flame instabilities induced by gravity occur typically at small wavelengths (of the same order as the flame thickness) (T/F) LONG
- b) there exists a diffusive thermal instability for Lewis numbers smaller than 0.5 (approximately) by which the flame front develops a cellular shape (T/F)
- c) if thermal expansion is negligible, the flame is neutrally stable to Darrieus-Landau instabilities (T/F)
- d) diffusive thermal instabilities can stabilize the Darrieus-Landau instability at small wavelengths (T/F)

3.7 In the mixing of two reactants in a turbulent flow,

- a) the scalar dissipation rate is always a source in the scalar variance equation (T/F) SINK
- b) the scalar dissipation rate is maximum in zones where only one of the reactants exists (T/F)
- e) for order-unity Schmidt numbers, the molecular mixing of two reactants typically occurs in time scales which are much longer than the integral time scale (T/F) SHORTER
- f) macroscopic mixing or stirring is sufficient for having chemical reaction between reactants (T/F)