

1B04: COAXIAL TURBULENT JET FLAMES: SCALING RELATIONS FOR MEASURED STOICHIOMETRIC MIXING LENGTHS.

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Could the thickness of the rim separating the central jet and coflow have an influence on the scaling properties? Does the thickness of the rim have to be scaled with pressure?

Reply by S. Alexander Schumaker
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The injector post thickness (T_p) sets the size of the recirculation zone immediately behind the injector post. Also, depending on the velocity ratio (r_u), T_p can determine if the Kelvin-Helmholtz instability of the inner shear layer is replaced by a wake instability characterized by alternate rotating vortices [1]. As T_p is increased the value of the momentum flux ratio (M) where this transition occurs also increases. The recirculation zone behind the post extends no more than 1–2 T_p regardless of pressure. With the injector dimensions used in this study, the recirculation zones would extend less than half of the inner jet diameter (d_i). With nonreacting mixing lengths on the order of 3–15 d_i and reacting mixing lengths on the order of 15–55 d_i the effect of these recirculation zones are viewed as small. Also in the current work this transition point between shear and wake instabilities was not achieved. This view is based on experimental data taken by the authors in nonreacting He-air jets at atmospheric pressure which showed no difference in mixing length for T_p values of 0.89 and 0.53 mm over $r_u = 5.0$ -2.5 [2]. This is consistent with the results of Matsumoto et al. [3] who found T_p effects on mixing length to be negligible. However, the structure of these recirculation zones are of interest in the context of jet and flame base stability and a follow-up study is underway at Michigan using Particle Image Velocimetry (PIV) to investigate the structure of the flowfield directly downstream of the post.

References:

- [1] G. Buresti, P. Petagna, A. Talamelli, *Exp. Therm. Fluid Sc.* 17 (1998) 18–36.
- [2] S.A. Schumaker, J.F. Driscoll, *AIAA 43rd Joint Propulsion Conference*, Cincinnati, OH, 2007, Paper AIAA-2007-5590.
- [3] R. Matsumoto, K. Kimoto, N. Tsuchimoto, *Bull. Jpn. Soc. Mech. Eng.* 16 (1973) 529–540.

Comment by Godfrey Mungal.
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I believe that the scaling relations can be interpreted more directly via the conservation of jet momentum. Following [1, 2], we can see that $(\rho_{\text{reacting}}/\rho_{\text{nonreacting}})^{1/2}$ is the reduction in entrainment which governs flame length.

References:

- [1] Donghee Han, M.G. Mungal, *Comb. Flame* 124 (2001) 370–386.
[2] L. Muñoz, M.G. Mungal, *Comb. Flame* 126 (2001) 1402–1420.

Reply by S. Alexander Schumaker

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The authors agree that the equivalence principle of Tacina and Dahm [3,4] is not the only method to account for heat release effects in reacting shear flows. This method was chosen for the current work due to its demonstrated and well documented ability to account for decreased entrainment in reacting jets and shear layers with large heat release such as occurs with hydrogen-air.

References:

- [1] D. Han, M.G. Mungal, *Combust. Flame* 124 (2001) 370–386.
[2] L. Muniz, M.G. Mungal, *Combust. Flame* 126 (2001) 1402–1420.
[3] K. M. Tacina, W.J.A. Dahm, *J. Fluid Mech.* 415 (2000) 23–44.
[4] W.J.A. Dahm, *J. Fluid Mech.* 540 (2005) 1–19.

Comment by Sebastien Candel.

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This is an interesting and useful investigation on coaxial jet flames. The momentum flux ratio has been extensively used in cryogenic combustion studies where the density ratio is quite large [1]. This number can be used for example to express the intact length of the liquid oxygen core. It also serves to sort out the different regimes and combustion and controls the flame length. From experiments carried out with liquid oxygen and hydrogen and methane, it has been found however that this ratio does not alone correlate data and that critical values of this ratio depend on the couple of reactants being studied. This might perhaps explain why some of your data do not collapse into a single curve.

Reference:

- [1] R. Snyder, G. Herding, C. Rolon, S. Candel, *Combustion Science and Technology*. 124, (1997) 331–370

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In cryogenic combustion studies, the additional dominate parameter is the Weber number which accounts for the effect of surface tension on the liquid core breakup and does not apply to the gaseous combustion presented in this work. There is an upper and lower limit to the momentum flux scaling. The upper limit is the annular jet case where a recirculation bubble forms in the inner jet. Favre-Marinet and Camano-Schettini [2] suggest a momentum flux ratio of 50 for the start of recirculation in nonreacting coaxial jets. This is well above the maximum momentum flux ratio (M) of 12 in the current study. The second limit is associated with a change from a

shear-like or Kelvin-Helmholtz instability in the near field mixing layers to a wake like instability [3]. This limit is highly dependent on the injector post thickness; however, nonreacting work in the current configuration suggests a momentum flux ratio limit of 0.1 [4]. These limits show that the reacting cases presented in this study are well within the range where the momentum flux ratio scaling applies. The equivalence principle of Tacina and Dahm [5] accounts for differences in reactants in equilibrium temperature and molecular weight state relations. Additional effects related to the reactants such as differential diffusion and chemical kinetics are possible; however, error in the data collapse is likely due to inadequacies in the equivalence principle related to the assumptions used in the derivation. Differences in higher pressure cases versus atmospheric pressure results, which were presented at the Symposium but not included in the paper, appear to be due to a delay in the spreading of the outer shear layer in the atmospheric pressure jets. This delay decreases as the pressure and hence the Reynolds number is increased. Once this shear layer spreading initializes at the injector exit no additional pressure or Reynolds number effects are found. This same trend exists in both reacting and nonreacting cases and is not related to the equivalence principle or reactants being used.

References:

- [1] R. Snyder, G. Herding, J.C. Rolon, S. Candel, *Combust. Sci. Technol.* 124 (1997) 331–370.
- [2] M. Favre-Marinet, E.B. Camano-Schettini, *Int. J. Heat Mass Transfer* 44 (2001) 1913–1924.
- [3] W.J.A. Dahm, C.E. Frieler, G. Tryggvason, *J. Fluid Mech.* 241 (1992) 371–402.
- [4] S.A. Schumaker, J.F. Driscoll, *AIAA 43rd Joint Propulsion Conference*, Cincinnati, OH, 2007, Paper AIAA-2007-5590.
- [5] K.M. Tacina, W.J.A. Dahm, *J Fluid Mech.* 415 (2000) 23–44.