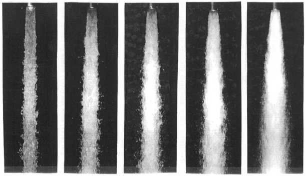
Turbulence intensity's effect on liquid jet breakup from long circular pipes

Ben Trettel
University of Texas at Austin

2017-11-19



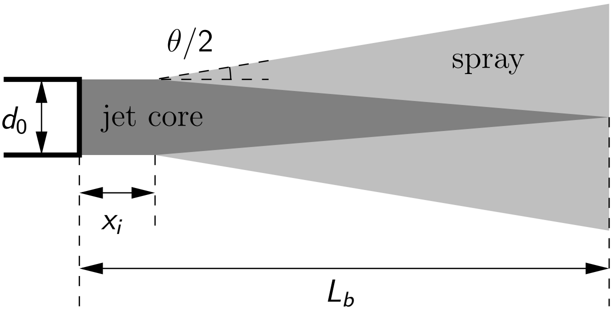
From P.-K. Wu (1992)

Why pipe jets?

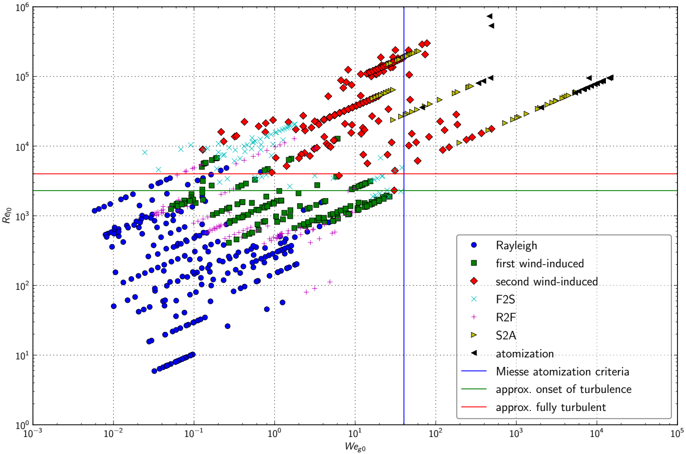
- Easy to set up
- Common in previous literature
- Universal flow state
- Problems with previous experiments:
    - confounding between variables: *Re* and *We*, and *Re* and *Tu*
    - neglected an important quantity: *Tu*
    - apples to oranges comparisons: need nozzle standardization to ensure that other variables (e.g., the integral scales, velocity profile, anisotropy) remain consistent
- Can estimate turbulence intensity from friction factor measurement:

$$Tu_0 = \frac{\sqrt{\frac{2}{3}\overline{k}}}{\overline{U}_0} = \frac{\sqrt{\overline{u'^2}}}{\overline{U}_0} = 0.36552 f^{0.45867}$$

Jet nomenclature



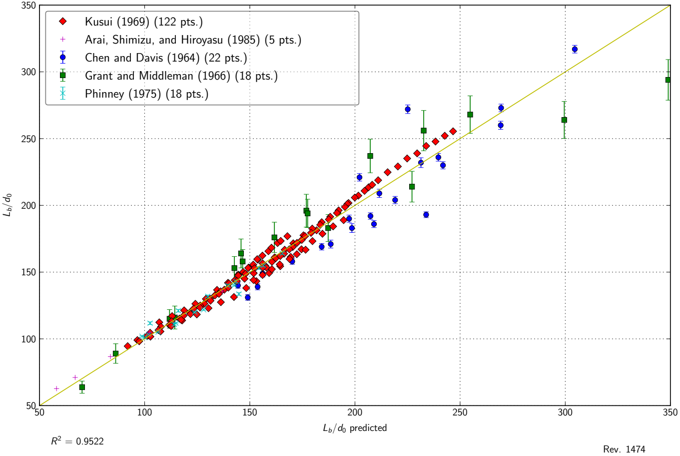
Regime map



Rev. 1474

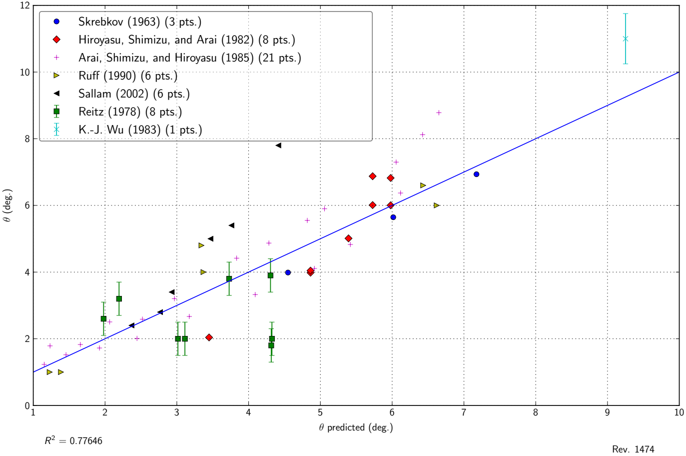
Breakup length

$$\frac{L_b}{d_0} = 3.1869\, We_{\ell 0}^{0.3101}\, Re_{\ell 0}^{0.0207}\, Tu_0^{-0.2603} \left(\frac{\rho_\ell}{\rho_g}\right)^{0.02197}$$



Spray angle

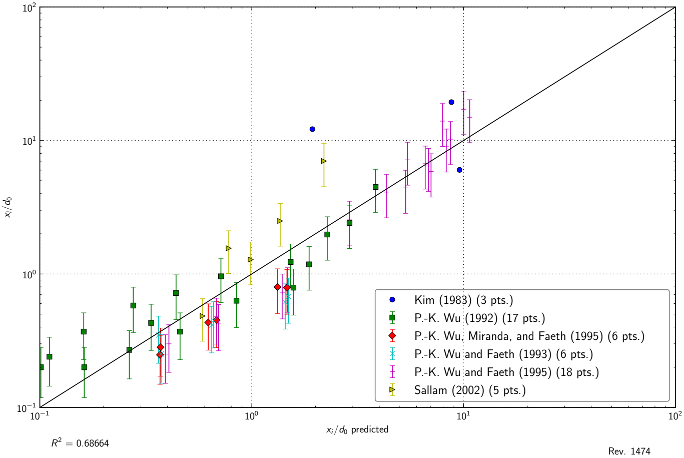
$$\tan\left(\frac{\theta}{2}\right) = 0.007870\,We_{\ell 0}^{0.4300}\,Re_{\ell 0}^{-0.0177}\,Tu_{0}^{0.7841}\left(\frac{\rho_\ell}{\rho_g}\right)^{-0.1488}$$



Rev. 1474

Breakup onset location

$$\frac{x_i}{d_0} = 16.0298(We_{\ell 0}\,Tu_0^3)^{-0.9567}$$



Droplet size (D_{32})

- Inverse scaling: $D_{32}/d_0 \propto (We_{\ell 0} Tu_0^2)^{-1}$
  - Natanzon (1938), Bogdanovich (1948), Sitkei (1963), and Lebedev (1977)
  - Similar: Kerstein, Movaghar, and Oevermann (2017)
- Faeth group: $D_{32}/d_0 \propto (We_{\ell 0} Tu_0^2)^{-3/5}$
- Me (nearly inverse):

$$\frac{D_{32}}{d_0} \propto (We_{\ell 0} {Tu_{v0}}^2 F_v)^{-1}$$

F_v is a function of the integral scale-rms velocity Weber number and the ratio of minimum velocity to form a droplet to the rms velocity. (Minimum velocity: either Hinze or Kolmogorov velocity scale, whichever larger.)

Ben Trettel
ben.trettel@gmail.com
http://trettel.org

Non-dimensionalization

$$Re = Re_{\ell,0} = \frac{\overline{U}_0 d_0}{\nu_\ell}$$

nozzle liquid Reynolds number

$$Fr = Fr_0 = \frac{\overline{U}_0^2}{g d_0}$$

nozzle Froude number

(kinetic energy to gravitational energy ratio)

$$We = We_{\ell,0} = \frac{\rho_\ell \overline{U}_0^2 d_0}{\sigma}$$

nozzle liquid Weber number

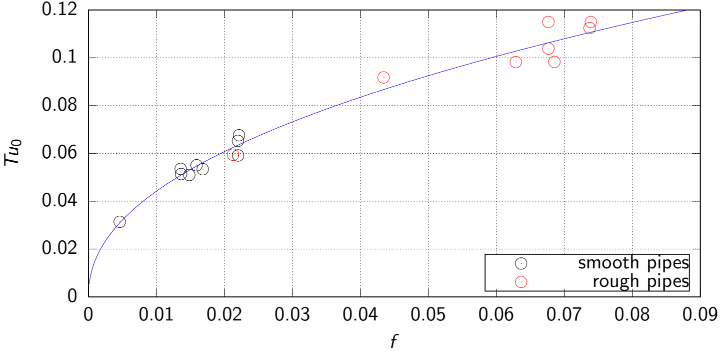
(kinetic energy to surface energy ratio)

$$Tu = Tu_{\ell,0} = \frac{u'}{\overline{U}_0}$$

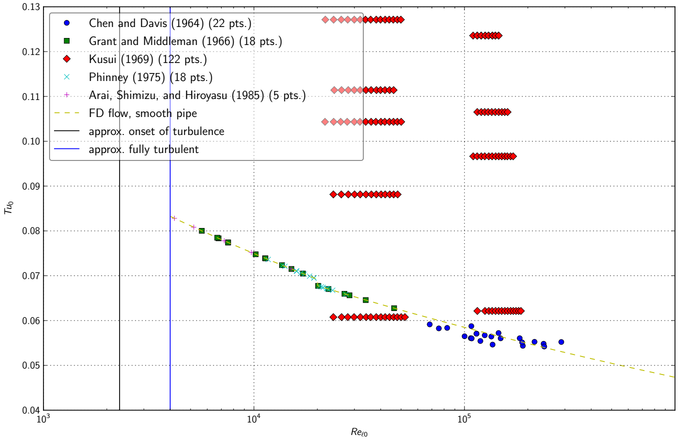
turbulence intensity

Fully developed pipe *Tu* correlation

$$Tu_0 = \frac{\sqrt{\frac{2}{3}\overline{k}}}{\overline{U}_0} = \frac{\sqrt{\overline{u'^2}}}{\overline{U}_0} = 0.36552 f^{0.45867}$$



Confounding example



Rev. 1474

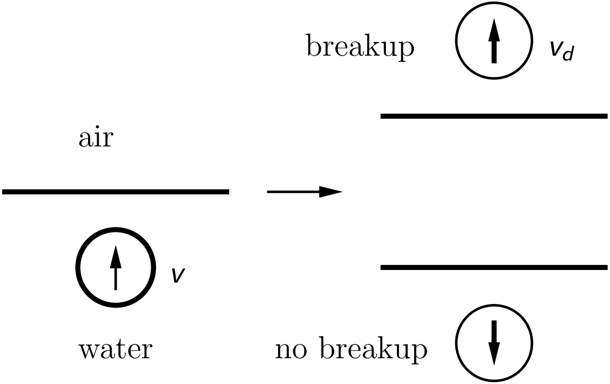
Problems with pipe jets

- *Tu* can be much higher than in practice (e.g., fire hose jets should have low *Tu*)
    - Some $Tu > 0$ has been found to *stabilize* jets Sauerwein, 1992
- Harder to study transition in the jet rather than nozzle/pipe
- *Tu* estimate may not be very precise (better than nothing!)
- Kusui (1969) not rough for entire length of tube

Data compilation

- 21 studies (so far)
- 1027 data points:
  - 25.7% measured friction factors
  - 68.1% measured hydrodynamic regimes
  - 13.7% rough pipes
  - $We_{\ell 0} = 5.0 \cdot 10^0 - 1.9 \cdot 10^7$
  - $Re_{\ell 0} = 5.9 \cdot 10^0 - 1.0 \cdot 10^7$
  - $Tu_0 = 0.0 - 0.127$
  - $Fr_0 = 4.0 \cdot 10^0 - 2.3 \cdot 10^8$
  - $\rho_\ell / \rho_g = 19.0 \cdot 10^0 - 1.3 \cdot 10^5$
  - $Ma_g = 0.001 - 0.741$
  - $L_0/d_0 = 16.8 - \approx 2200$
- Detail about experiment included as well: flow conditioning, nozzle outlet geometry, error estimates, photographic details, orientation of jet, vibration isolation, chamber diameter

Model idea: conditioning on droplet formation



"Ligament" model and energy balance for mean droplet size

Ligament model leads to:

$$v_d = v\left(1 - \frac{6C_F}{\pi}\frac{\sigma}{\rho_\ell \ell v^2}\right)$$

Energy balance leads to:

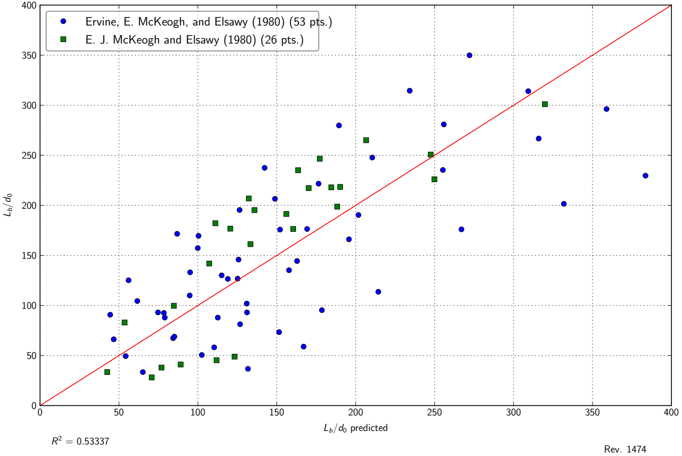
$$\frac{6\sigma}{D_{32}} = \frac{1}{2}\rho_\ell {v'}^2 F_v$$

where F_v is a messy function determined by applying a conditional average to the ligament model, i.e.., $\langle v_d^2 \mid v > v_{\min}\rangle$, where $v_{\min}$ is the minimum turbulent fluctuation velocity which can form a droplet (scales with Hinze scale or Kolmogorov scale).

Early work on turbulent energy balance for droplet formation: Natanzon (1938)

Breakup length correlation compared against non-pipe jets

$$\frac{L_b}{d_0} = 3.1869\, We_{\ell 0}^{0.3101}\, Re_{\ell 0}^{0.0207}\, Tu_0^{-0.2603} \left(\frac{\rho_\ell}{\rho_g}\right)^{0.02197}$$



Breakup length model

Earlier theoretical work returned:

$$\frac{L_b}{d_0} \propto We^{1/3} Tu^{-1/3}$$

Compare with correlation from my data compilation (185 points):

$$\frac{L_b}{d_0} = 3.1869 We^{0.3101} Re^{0.0207} Tu^{-0.2603} \left(\frac{\rho_\ell}{\rho_g}\right)^{0.02197}$$

One-third scaling is a consequence of inertial range and should only apply in the "second wind-induced regime" (hypothesis at the moment).

Justification of this model earlier was sketchy, now I can see how it can be justified via my conditional process. Needs to be fleshed out, however.

Takeaways

- Use tubes of varying roughness to easily control *Tu* independent of *Re* in jet breakup experiments
- Use tubes of multiple diameters to avoid confounding of *Re* and *We*
- Read more foreign language papers!

References I

Arai, M., M. Shimizu, and H. Hiroyasu (1985). “Break-up Length and Spray Angle of High Speed Jet”. In: *Proceedings of the 3rd International Conference on Liquid Atomisation and Spray Systems at Imperial College, London, 8-9-10 July 1985*, IB/4/1–IB/4/10.

Bogdanovich, I. I. (1948). “Vliyaniye podgotovki topliva v forsunke na tonkost’ raspyla [Influence of fuel preparation in the nozzle on the fineness of the spray]”. Candidate of Technical Sciences dissertation. Moscow, USSR: Zhukovsky Air Force Engineering Academy. 136 pp. URL: `http://search.rsl.ru/en/record/01000176055`.

Chen, T.-F. and J. R. Davis (1964). “Disintegration of a Turbulent Water Jet”. In: *Journal of the Hydraulics Division* 90.1, pp. 175–206.

Ervine, D. A., E. McKeogh, and E. M. Elsawy (1980). “Effect of Turbulence Intensity on the Rate of Air Entrainment by Plunging Water Jets”. In: *ICE Proceedings* 69.2, pp. 425–445. URL: `http://www.icevirtuallibrary.com/content/article/10.1680/iicep.1980.2545,%0020http://www.icevirtuallibrary.com/content/article/10.1680/iicep.1980.2545`.

Grant, R. P. and S. Middleman (1966). “Newtonian Jet Stability”. In: *AIChE Journal* 12.4, pp. 669–678. URL: `http://onlinelibrary.wiley.com/doi/10.1002/aic.690120411/abstract`.

References II

Hiroyasu, H., M. Shimizu, and M. Arai (1982). “The Breakup of High Speed Liquid Jet in a High Pressure Gaseous Atmosphere”. In: *Reports and Proceedings of the Second International Conference on Liquid Atomization and Spray Systems, June 20-24, 1982, Madison, Wisconsin, USA.* Madison, WI, pp. 69–74.

Kerstein, A. R., A. Movaghar, and M. Oevermann (2017). “Parameter Dependences of the Onset of Turbulent Liquid-Jet Breakup”. In: *Journal of Fluid Mechanics* 811. URL: `https://www.cambridge.org/core/journals/journal-of-fluid-mechanics/article/div-classtitleparameter-dependences-of-the-onset-of-turbulent-liquid-jet-breakupdiv/C32A2323337BFCF8CAA7B732062C2FC6`.

Kim, S. (1983). “An Investigation of Heat and Mass Transport in Turbulent Liquid Jets”. PhD Dissertation. Los Angeles, CA: University of California, Los Angeles.

Kusui, T. (1969). “Liquid Jet Flow into Still Gas : 4th Report, Water Jet from Rough Circular Pipe”. In: *Transactions of the Japan Society of Mechanical Engineers* 35.270, pp. 339–349.

Lebedev, O. N. (1977). “K voprosu o raspylivanii topliva dizel’nymi forsunkami [On the issue of diesel fuel atomization nozzles]”. In: *Izvestiia Sibirskogo otdeleniia Akademii nauk SSSR, Seriia tekhnicheskikh nauk* 3.1, pp. 40–43.

McKeogh, E. J. and E. M. Elsawy (1980). “Air Retained in Pool by Plunging Water Jet”. In: *Journal of the Hydraulics Division* 106.10, pp. 1577–1593.

Natanzon, V. Ya. (1938). “O raspylivanii topliva v dvigatelyakh dizelya [On the atomization of fuel in diesel engines]”. In: *Dizelestroenie* 3, pp. 3–10.

References III

Phinney, R. E. (1975). “Breakup of a Turbulent Liquid Jet in a Low-Pressure Atmosphere”. In: *AIChE Journal* 21.5, pp. 996–999. URL: `http://onlinelibrary.wiley.com/doi/10.1002/aic.690210523/abstract`.

Reitz, R. D. (1978). “Atomization and Other Breakup Regimes of a Liquid Jet”. Ph.D. Princeton, NJ: Princeton University. 336 pp.

Ruff, G. A. (1990). “Structure and Mixing Properties of the Near-Injector Region of Nonevaporating Pressure-Atomized Sprays.”

Sallam, K. A.-E. (2002). “Properties of Spray Formation by Turbulent Primary Breakup”. Ph.D. United States – Michigan: University of Michigan. 156 pp. URL: `http://search.proquest.com/pqdtglobal/docview/276490767/abstract/D108AFC69D1243B1PQ/2`.

Sauerwein, U. K. (1992). “Theoretische und experimentelle Untersuchung der Instabilität turbulenter Kapillarstrahlen [Theoretical and experimental investigation of the instability of turbulent capillary jets]”. PhD. Darmstadt, Germany: Technische Universität Darmstadt. 170 pp.

Sitkei, G. (1963). *Contribution to the Theory of Jet Atomization*. NASA Technical Translation F-129. Washington, D.C.: National Aeronautics and Space Administration, p. 32. URL: `https://hdl.handle.net/2027/uiug.30112106740126`. Trans. of “Beitrag zur Theorie der Strahlzerstäubung [To the theory of jet atomization]”. In: *Acta technica* 25 (1-2), pp. 87–117.

References IV

Skrebkov, G. P. (1963). “Turbulentnyye pul’satsii v zhidkoy struye i yeye raspylivaniye [Turbulent pulsations in a liquid jet and its atomization]”. In: *Prikladnaya mekhanika i tekhnicheskaya fizika* 3, pp. 79–83. URL: `http://www.sibran.ru/journals/issue.php?ID=160175&ARTICLE_ID=160248`.

— (1966). “Turbulent Pulsations in a Liquid Jet, and Its Atomization”. In: *Journal of Applied Mechanics and Technical Physics (Foreign Technology Division)* 3, pp. 142–151. URL: `http://www.dtic.mil/docs/citations/AD0635269`. Trans. of “Turbulentnyye pul’satsii v zhidkoy struye i yeye raspylivaniye [Turbulent pulsations in a liquid jet and its atomization]”. In: *Prikladnaya mekhanika i tekhnicheskaya fizika* 3, pp. 79–83. URL: `http://www.sibran.ru/journals/issue.php?ID=160175&ARTICLE_ID=160248`.

Wu, K.-J. (1983). “Atomizing Round Jets”. PhD. Princeton, NJ: Princeton University. 301 pp.

Wu, P.-K. (1992). “Liquid Surface Breakup of Nonturbulent and Turbulent Liquids”. Ph.D. United States – Michigan: University of Michigan. 157 pp. URL: `http://search.proquest.com/pqdtglobal/docview/304013956/abstract/95717A4D73B84521PQ/2`.

Wu, P.-K. and G. M. Faeth (1993). “Aerodynamic Effects on Primary Breakup of Turbulent Liquids”. In: *Atomization and Sprays* 3.3. URL: `http://www.dl.begellhouse.com/journals/6a7c7e10642258cc,654c27a12922e543,17fbe8b455cd350d.html`.

References V

Wu, P.-K. and G. M. Faeth (1995). “Onset and End of Drop Formation along the Surface of Turbulent Liquid Jets in Still Gases”. In: *Physics of Fluids (1994-present)* 7.11, pp. 2915–2917. URL: `http://scitation.aip.org/content/aip/journal/pof2/7/11/10.1063/1.868667`.

Wu, P.-K., R. F. Miranda, and G. M. Faeth (1995). “Effects of Initial Flow Conditions on Primary Breakup of Nonturbulent and Turbulent Round Liquid Jets”. In: *Atomization and Sprays* 5.2, pp. 175–196. URL: `http://www.dl.begellhouse.com/journals/6a7c7e10642258cc,36727fdb5a701733,2d23159251d72d82.html`.