Fig. 5. Comparison of the entrainment rates for vertical and tilted jets. The slopes of the upper and lower lines are $-1/2$ and $-3/2$, respectively. The symbols for the vertical jet are as in Fig. 4.
$\times$ Precessing, tilted jet; $+$ non-precessing, tilted jet
Vortex near an interface

Intrinsic velocity ratio $\frac{U_1}{U_2}$

Starting jet $U_2$

Gharib et al.
Vortex stationarity parameter

\[ T \equiv \frac{1}{\pi} \frac{U_1}{U_2} \]

- critical value \( T^* \) of order one
- \( T \gg T^* \) "persistent"
- \( T \ll T^* \) "nonpersistent"
Diffusive fluxes across an interface

Effective entrainment velocity \( v_e \)

e.g. heat flux = \( \rho c_p \Delta T \) \( v_e \)

\[ v_e = \text{const.} \left( \frac{D}{\tau_\lambda} \right)^{1/2} \]

What is \( \tau_\lambda \)?
Effect of increasing $R_i$
ENTRAINMENT DIAGRAM

\[ N_e = \text{const.} \frac{\lambda}{\kappa} \]

\[ \text{Re} = \text{Sc}^{1/2} \text{Ri}^{-1/4} \]

\[ \text{Re} = \text{Sc}^{-2/3} \text{Re}^{-1/4} \]

\[ \text{Re} = \text{Sc}^{-1/2} \text{Ri}^{-1} \]
\[ \text{Sc}^{-2/3} \text{Re}^{-1/2} \quad \text{Re} = \text{Ri}^{1/4} \]
Figure 3: Streamlines of the Karman vortex street, dividing streamline in bold.
vortex generators

corrugated plate

vortex core
145. **Kelvin-Helmholtz instability of stratified shear flow.** A long rectangular tube, initially horizontal, is filled with water above colored brine. The fluids are allowed to diffuse for about an hour, and the tube then quickly tilted six degrees, setting the fluids into motion. The brine accelerates uniformly down the slope, while the water above similarly accelerates up the slope. Sinusoidal instability of the interface occurs after a few seconds, and has here grown nonlinearly into regular spiral rolls. *Thorpe 1971*

146. **Kelvin-Helmholtz instability of superposed streams.** The lower stream of water, moving to the left faster than the upper one, contains dye that fluoresces under illumination by a vertical sheet of laser light. The faster stream is perturbed sinusoidally at the most unstable frequency in the upper photograph, and at half that frequency in the lower one so that the motion locks into the subharmonic. *Photographs by F. A. Roberts, P. E. Dimotakis & A. Roshko*
Conclusions

- Unified theory of stratified entrainment
- Fundamental parameter - eddy velocity ratio
- Stationary vortices (partially) laminarize a turbulent boundary layer