Compressible turbulent boundary layers with non-adiabatic walls

- Mean gradients effects : $T(y)$-$\rho(y)$-$\mu(y)$-$\lambda(y)$
- Morkovin hypothesis : $p_{rms} \ll \langle P \rangle$ - $T_{t_{rms}} \leq 20\% \langle T_t \rangle$

'The influence of compressibility that Morkovin's hypothesis does not treat are the effect of viscosity, in regions where mean viscous stresses are important.'

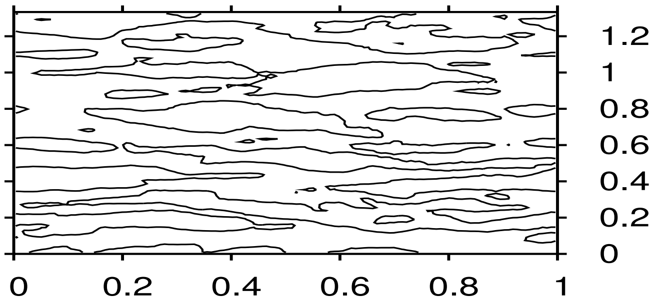
(Bradshaw *Ann. Rev. Fluid Mech.* 1977**)**

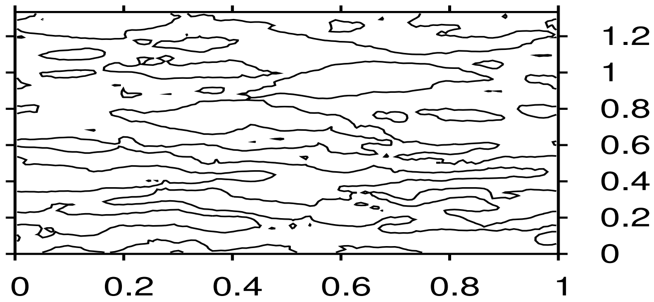
- Strong Reynolds Analogy
- Inner layer scaling

'The large scale motion should be statistically coupled to the thermal field almost exclusively through mean values of ρ, μ, λ, and the generalized law of the wall so that with a variable lateral stretching factor, it may resemble the incompressible motion.'

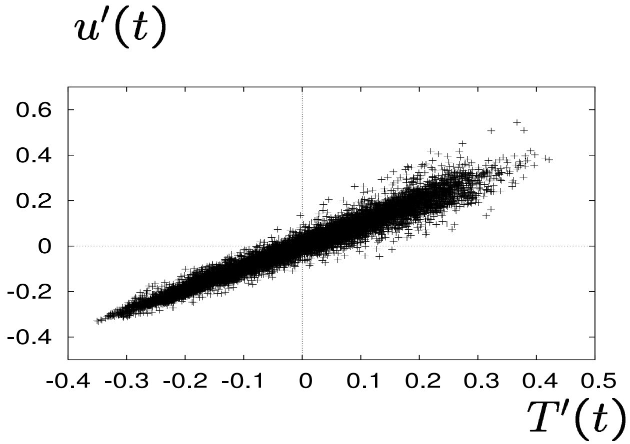
(M.V. Morkovin *Colloques Internationaux CNRS* 1962**)**

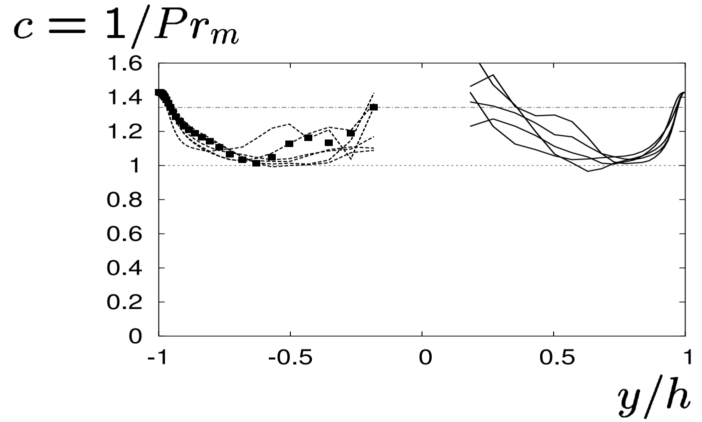
Strong Reynolds Analogy





wall friction : $\tau_w = \tilde{\mu} \frac{\partial \tilde{u}}{\partial y}|_w = \rho_w \, {u_\tau}^2$ Wall heat flux : $q_w = -\tilde{\lambda} \frac{\partial \tilde{T}}{\partial y}|_w = -\rho_w \, c_p \, u_\tau \, T_\tau$





boundary layer : MSRA (Gaviglio 1987, Rubesin 1990, Huang et *al.* 1995):

$$\frac{T'(t)}{\langle \tilde{T} \rangle} = \frac{1}{c(\partial \langle \tilde{T}_i \rangle / \partial \langle \tilde{T} \rangle - 1)} (\gamma - 1) M_l^2 \, \frac{u'(t)}{\langle \tilde{u} \rangle}$$

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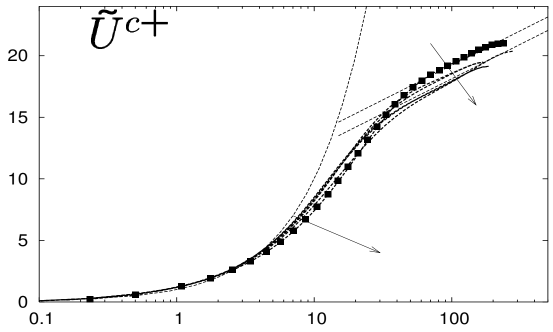
Inner Layer Scaling

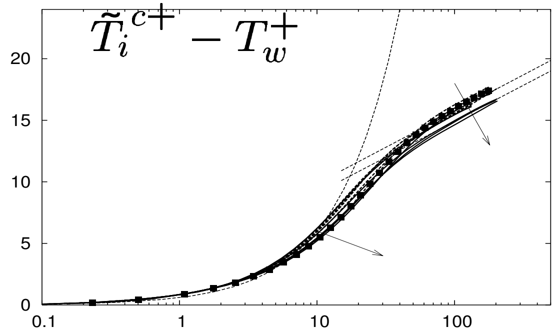
Integral wall scaling: $y^{c+} = \int_0^{y^+} \frac{\mu_w}{\tilde{\mu}}\, dy^+$ $\qquad Re_\tau^c = h^{c+} = \int_0^{h^+} \frac{\mu_w}{\tilde{\mu}}\, dy^+$

'Semi-local scaling $Re_{sl} = \frac{\rho_e u_\tau^e\ h}{\mu_e}$, $\qquad$ (Huang & Coleman *J. Fluid Mech.* 1995)

van Driest Transformation : density & viscosity correction



y^{c+}

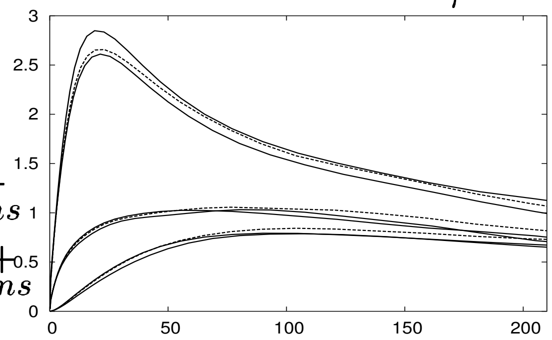


y^{c+}

$$\langle \tilde{u} \rangle^{c+} = \int_0^{\langle \tilde{u} \rangle^+} \frac{y^+}{y^{c+}} \frac{\mu_w}{\langle \tilde{\mu} \rangle} \sqrt{\frac{\langle \bar{\rho} \rangle}{\rho_w}}\, d\langle \tilde{u} \rangle^+ = \frac{1}{\kappa}\ ln\ y^{c+} + C_u^c$$

$$\langle \tilde{T}_i \rangle^{c+} - T_w^+ = \frac{Pr_t}{\kappa}\ ln\ y^{c+} + C_t^c$$

u_{rms}^{c+} $\qquad Re_\tau^c \approx 280$

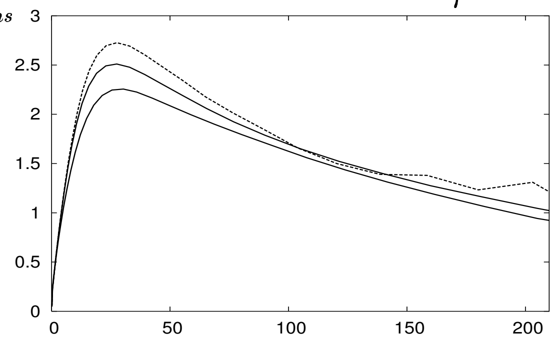


v_{rms}^{c+}

w_{rms}^{c+}

y^{c+}

$T_{i_{rms}}^{c+}$ $\qquad Re_\tau^c \approx 280$



y^{c+}

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