Business from technology

Differential boundary layer model for wind turbine blade icing code TURBICE™

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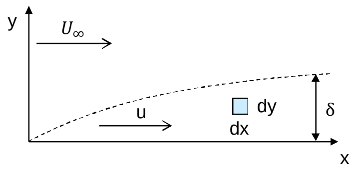
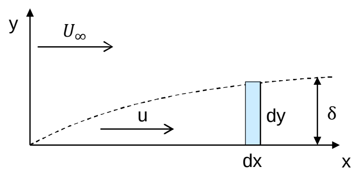
Motivation for differential boundary layer model

- Velocity distribution within the boundary layer can be calculated instead of approximate distribution used by integral methods.
  - More accurate heat flux analysis via Reynolds analogy
  - More advanced heat and mass transfer analysis
  - More accurate ice accretion simulation



differential method



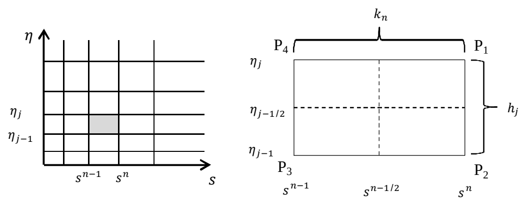
integral method

Main features of the model (1/2)

- Differential boundary layer equations solved by Keller's box method

$$\bar{u}\frac{\partial \bar{u}}{\partial s} + \bar{v}\frac{\partial \bar{u}}{\partial y} = -\frac{1}{\rho}\frac{dp}{ds} + \nu\frac{\partial^2 \bar{u}}{\partial y^2} - \frac{\partial}{\partial y}(\overline{u'v'})$$

- Grid scaling in normal direction $(\eta = \sqrt{\frac{u_e}{2\nu s}}y)$ to account for large gradients



grid and cell description – Keller's box method

Main features of the model (2/2)

- Zero-equation algebraic turbulence model with two layer structure: inner viscous region, outer inviscid region

$$(\nu_t)_i = l^2\left|\frac{\partial u}{\partial y}\right|\gamma_{tr}$$

$$(\nu_t)_o = 0.0168 Re_s^{0.5}[\eta_e - f(\eta_e)]\gamma_{tr}\gamma\nu$$

- Michel and laminar separation transition criteria

- Local heat transfer coefficient from local Stanton number for forced convective heat transfer

$$St_l = \frac{1}{2}c_f Pr^{1/3}$$

$$St_t = \frac{c_f/2}{1 + 12.8(Pr^{0.68} - 1)\sqrt{c_f/2}}$$

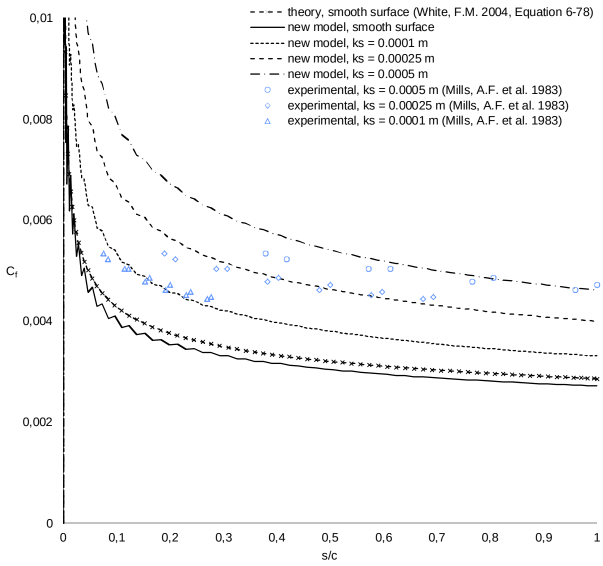
Flat plate results

- Fully turbulent flow over smooth and rough flat plates
- $Re = 5 \times 10^6$, $\alpha = 0°$
- Mixing length (l) modified for roughness effects following Cebeci *(2004)*

$$l = \kappa(y + \Delta y)\left[1 - e^{-(y+\Delta y)/A}\right]$$

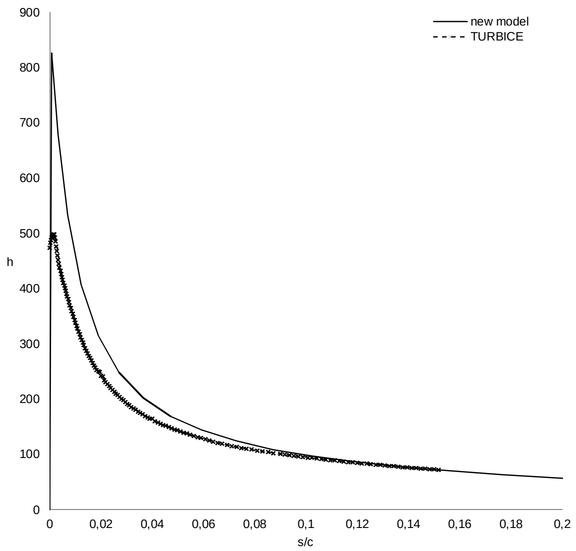
$$\Delta y = 0.9\left(\frac{\nu}{u_\tau}\right)\left[\sqrt{k_s^+} - k_s^+ e^{(-k_s^+/6)}\right]$$

- Typical equivalent sand grain roughness height (k_s) for rime ice is 0.4 … 1.0 mm



NACA 0012 results

- Smooth NACA 0012 airfoil
- $Re = 1 \times 10^6$, $\alpha = 0°$
- Heat transfer coefficient (h)on the leading edge is higher than with the current integral boundary layer method on TURBICE
- Experimental references required for comparison
- Initial conditions will be examined in detail



Future work

- Checking inconsistencies and fine tuning the model
- Implementation of an inverse method to include separation bubble simulation
- Roughness model – Evaluating scope of experimental methods, testing different roughness models
- Testing different transition criteria
- Implementation of the boundary layer model into TURBICE

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