

Accurate and Independent Measurements of Wall-Shear Stress in Turbulent Flows

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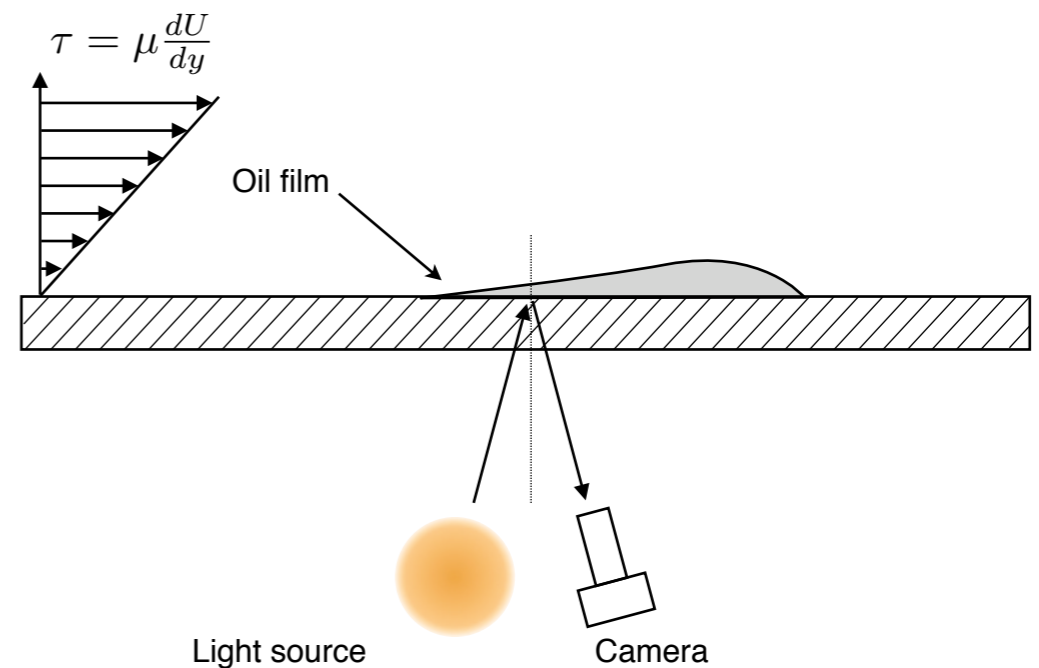
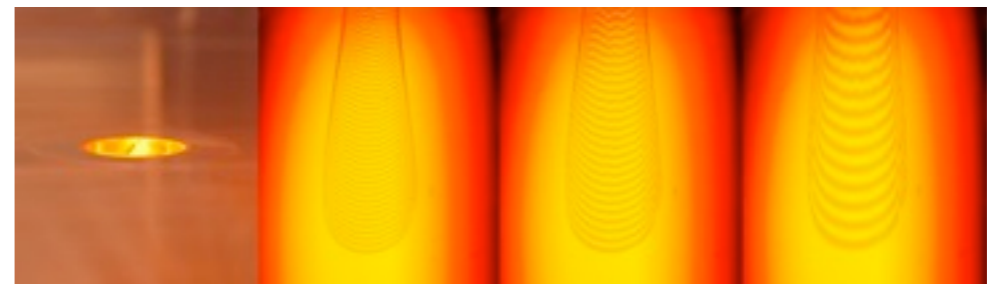
ICET wall shear stress measurements

- Independent measure of the friction velocity for the scaling of the results
- Measurements in 3 facilities
- Oil film interferometry (Direct method)
- Oil with viscosities from 20 to 1000 cs

Oil film interferometry

- Measurement of the thinning rate of an oil film
- Setup
 - Monochromatic light source
 - Digital camera
 - Glass or plexiglass surface
 - Silicone oil

$$\overline{\tau_w} = \frac{d\lambda}{dt} \mu \frac{2\sqrt{n^2 - \sin^2 \alpha}}{\lambda}$$



Measurement Procedure

- Independent calibration of the oil viscosity vs. temperature
- Spatial calibration with a target
- Acquisition of the images
- Analysis of the fringe spacing vs time

Independent calibration of the oil viscosity versus temperature

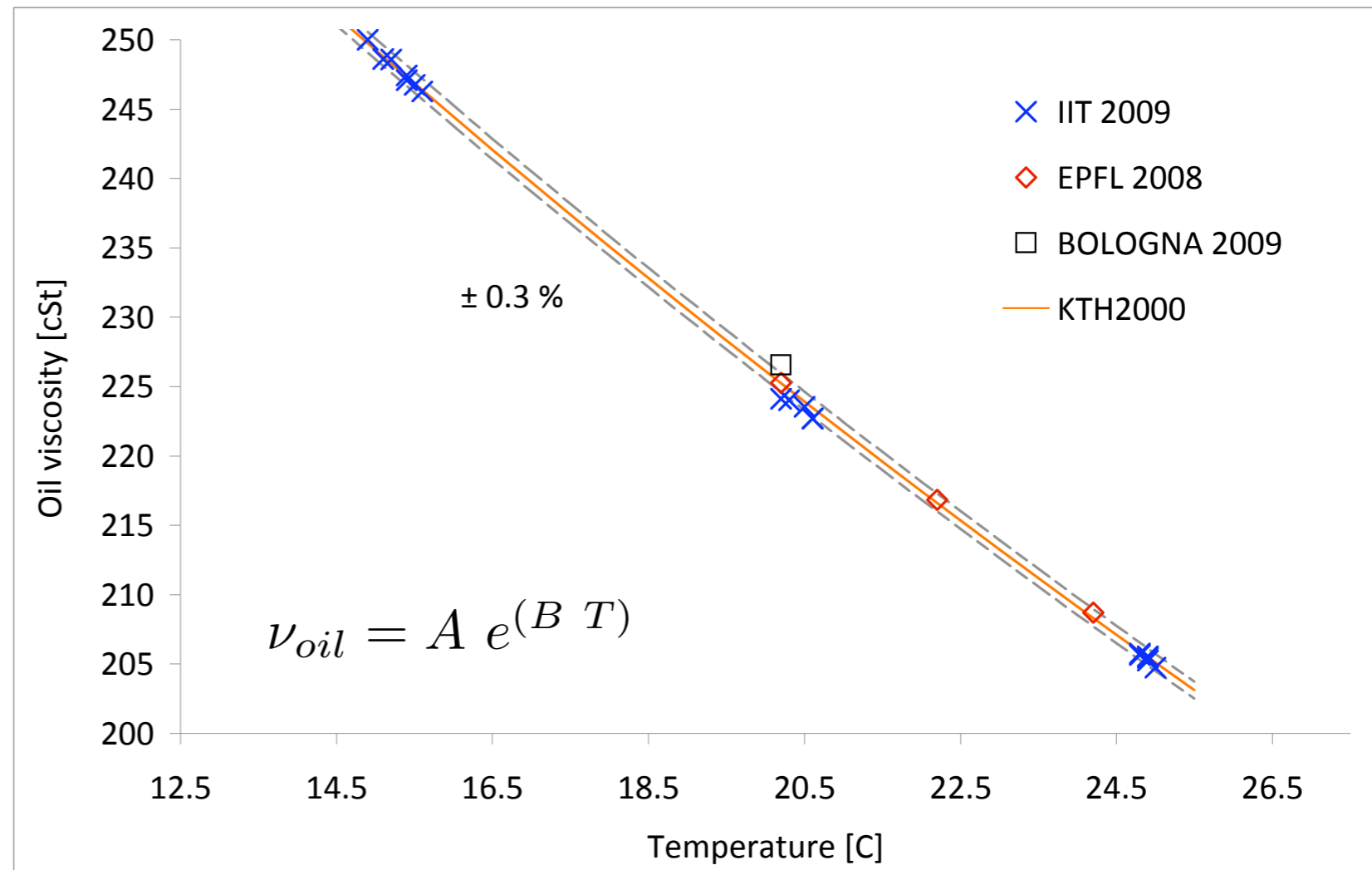
- Thermo-regulated bath
- Capillary viscometer
- Electronic light barrier or stop watch
- Reference temperature sensor



Oil viscosity calibration

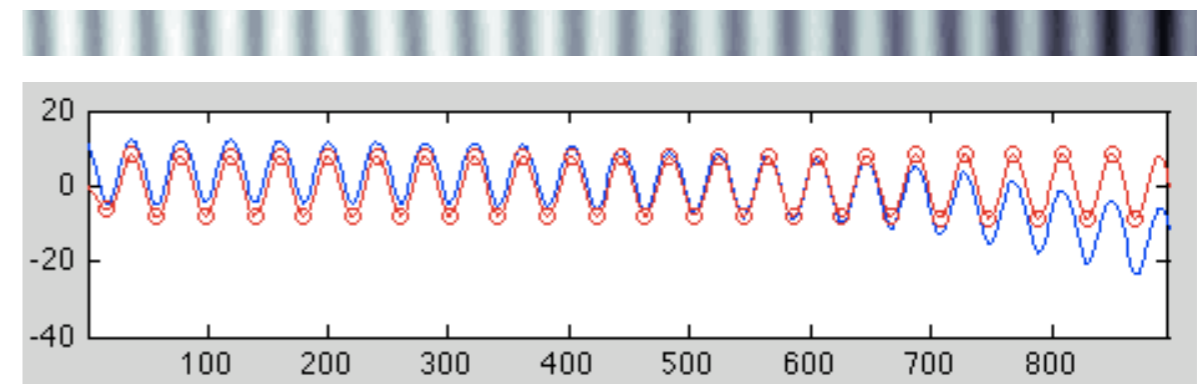
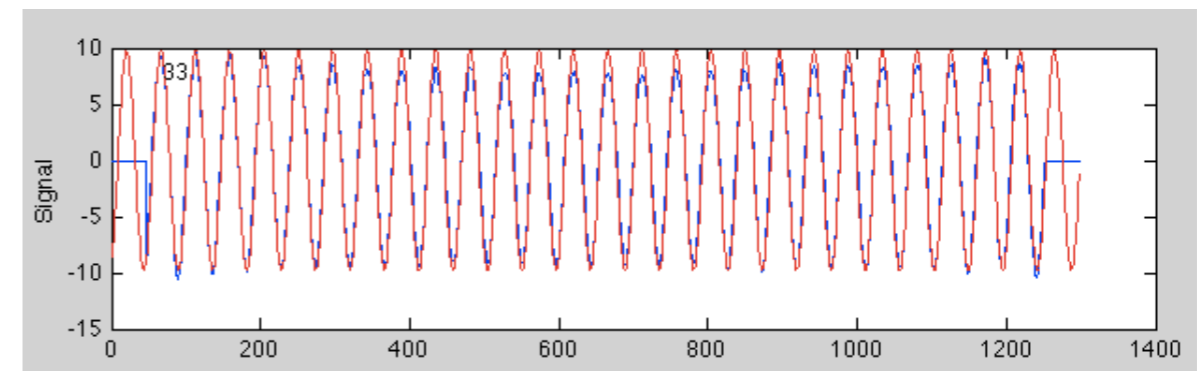
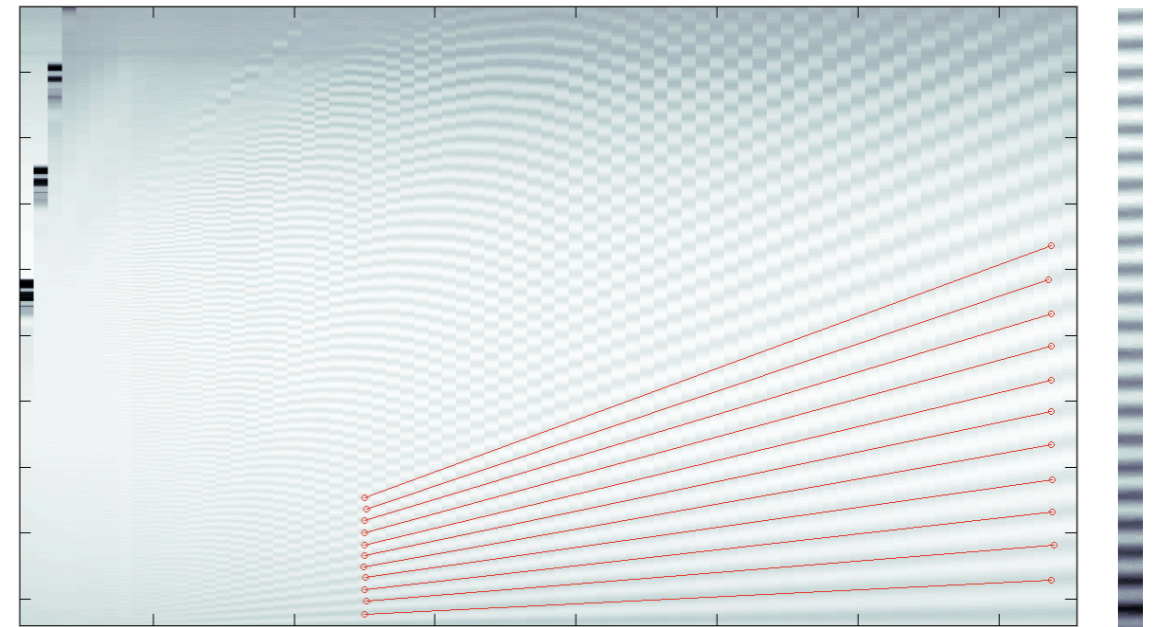
- Capillary viscometers
 - EPFL, IIT, Bologna, KTH
- Fluctuation of the results within $\pm 0.3\%$ (grey lines)
- Temperature sensitivity

$$\frac{1}{\nu} \frac{\partial \nu}{\partial T} \approx 2\%/^{\circ}C$$



Analysis method

- XT, Wavelength, Peak distance
- The manual selection of the fringes (XTmethod) is very user-dependent and can lead to a large scatter of the results
- Initial transient due to the formation of the oil film
- Non linear effects near the leading edge of the film

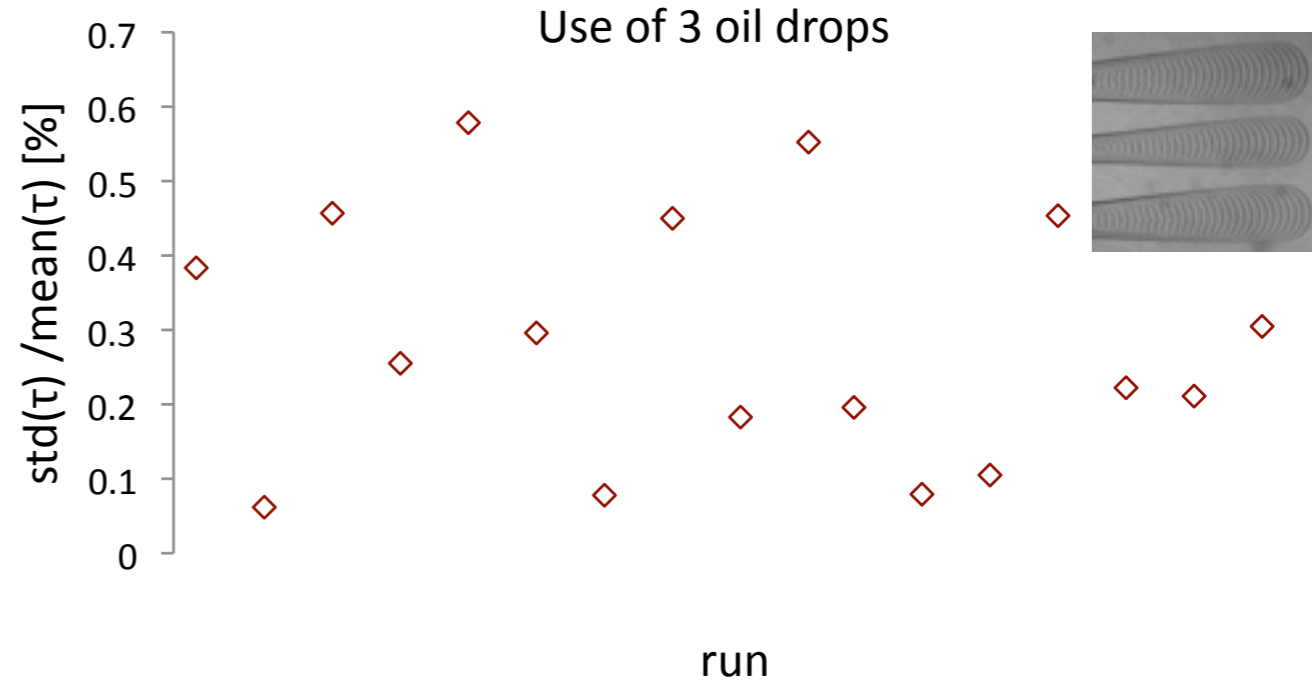


Uncertainties of the method for the measurements of the wall shear stress (τ)

Variable	Variation	Uncertainty
surface temperature	$\pm 0.2^\circ\text{K}$	0.4 %
Viscosity calibration		0.3 %
Oil density		0.1 %
Oil refraction index	± 0.001	0.07 %
Light wavelength	$\pm 0.3 \text{ nm}$	0.05 %
Angle of view	$\pm 0.5^\circ$	0.11 %
Spatial calibration		<0.1 %
Sampling time accuracy	$< \pm 0.01 \text{ s}$	0.0 %
Fringe distance determination		0.2 %
Total		1.33 %

Variance of the measurements

Variance of the measurements per run @IIT

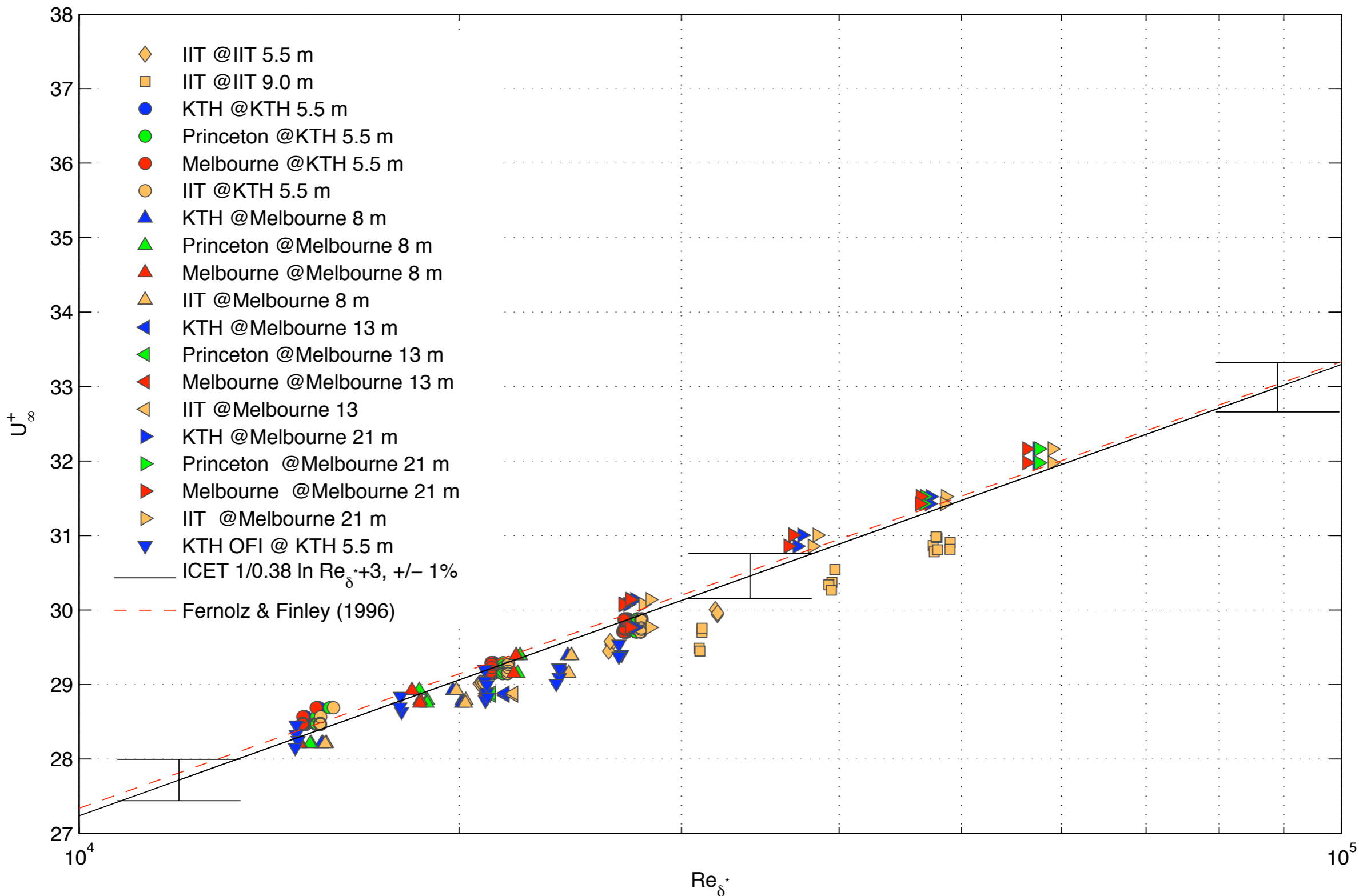


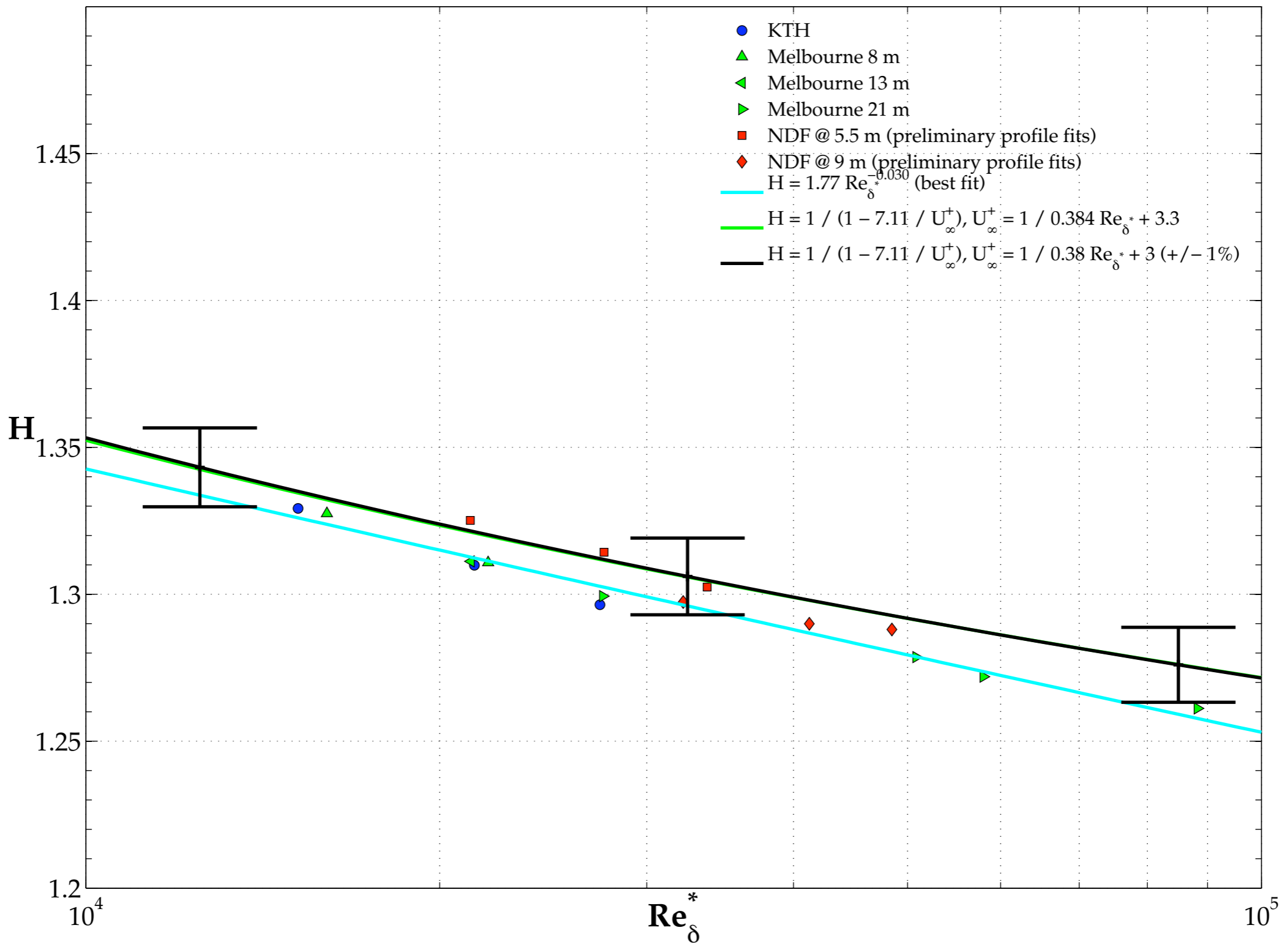
- **Uncertainty**
 - u_{τ} & U_{∞}^+ : 1.2%

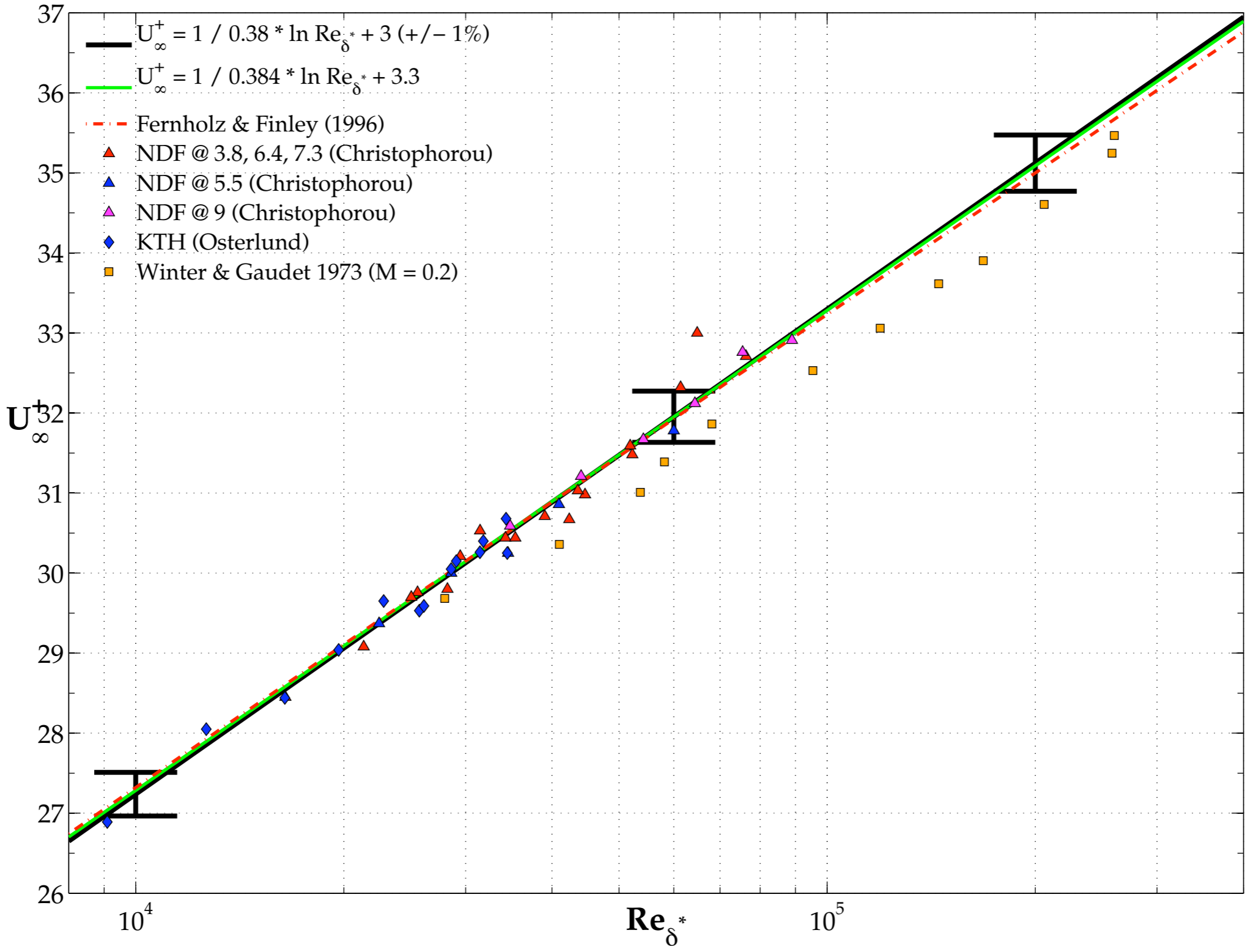
Variable	Uncertainty
Accuracy of the method for wall shear stress	1.33 %
Variance of the results per run	0.6 % (mean: 0.3%)
Air density	0.3 %
Dynamic pressure	0.4 %

Skin friction law

- All group provided an independent estimate of Re_{δ^*} and Re_{θ} based on their velocity profiles for all conditions at which oil film interferometry measurements have been performed.
- KTH
 - KTH: 2nd order fit $Re_{\theta} = A(U_{\infty} / \nu)^B$ and $Re_{\delta^*} = A(U_{\infty} / \nu)^B$
 - Melbourne: $Re_{\theta} = A Re(x+x_0)^{0.88}$ and $Re_{\delta^*} = A Re(x+x_0)^{0.85}$
- Princeton
 - 2nd order fit of $\ln(Re_{\theta})$ vs. $\ln(Re_x)$ and $\ln(H)$ vs. $\ln(Re_x)$
- Melbourne
 - $Re_{\delta^*} = A Re^2 + B Re + C$
- IIT
 - $Re_{\delta^*} = A [Re_m \cdot (x + x_0)]^{0.85}$, $Re_{\theta} = A [Re_m \cdot (x + x_0)]^{0.88}$







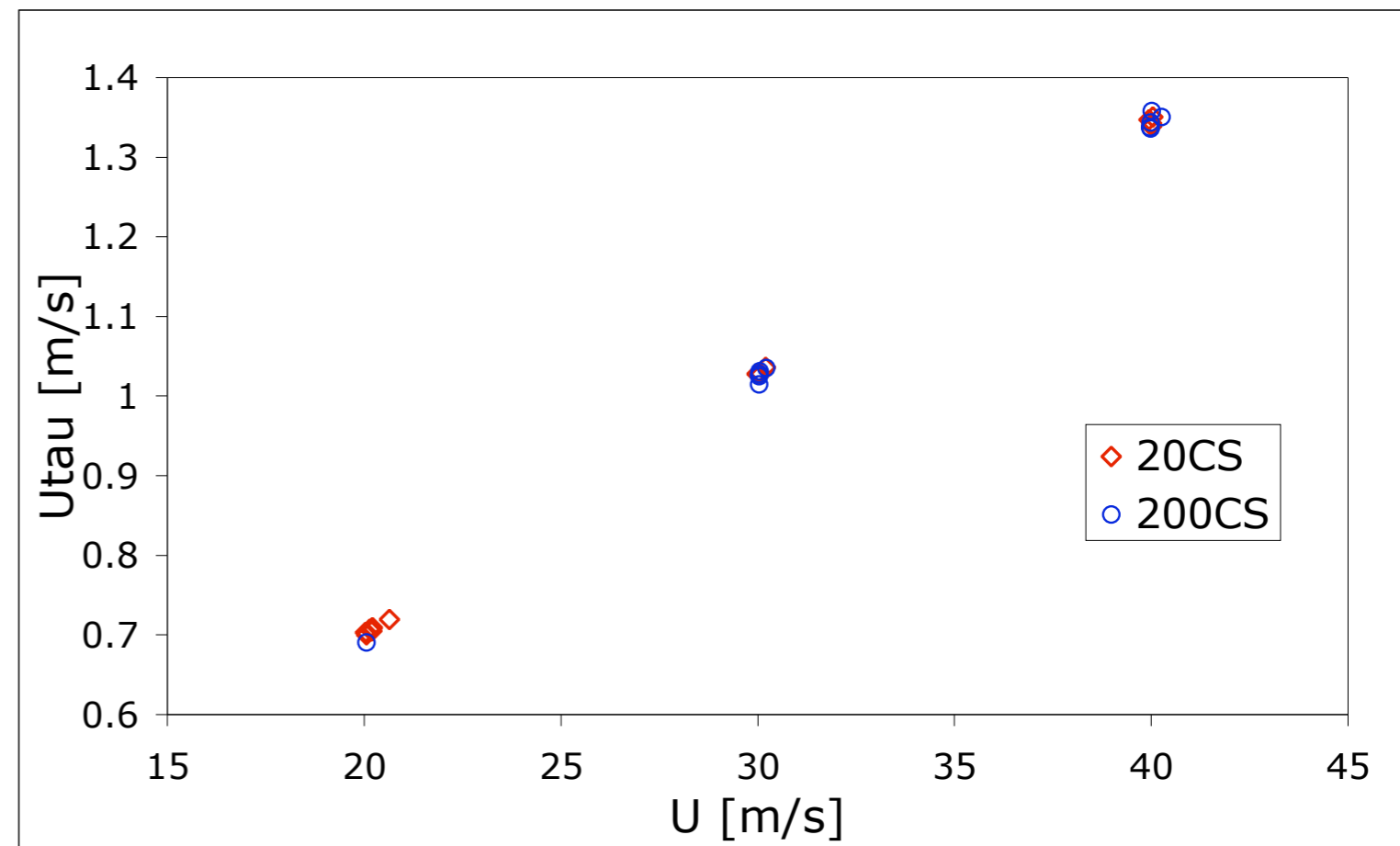
Conclusions

- Wall shear stress and shape factor from the three facilities are in very good agreement ($\pm 1\%$)
- Accurate wall shear stress measurements require:
 - Accurate calibration of the oil viscosity
 - Reference temperature sensor
 - Accurate measurement of the surface temperature

Questions ?

Influence of oil viscosity and shear dependent viscosity

- Wall shear stress measurements using different oil viscosities are within the accuracy of the method
- Rheological measurements performed did not permit to assess shear dependent viscosity effects



Oil settling time

It has been noticed that silicone oil requires significant time to settle down after transport before to reach a constant viscosity

- Probable cause
 - Inclusion of air bubbles in the oil
- Consequences
 - Temporal decrease of the viscosity
 - Effect increasing with viscosity

- Luckily, all measurement performed during ICET allowed enough settling time

