COMPUTATIONAL STUDY OF TEMPERATURE GRADIENT EFFECTS ON HOT-WIRE MEASUREMENTS

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Abstract The present investigation is — to the author's knowledge — the first attempt to document, understand, and ultimately correct the effect of temperature gradients on the higher-order moments of turbulent boundary-layer fluctuations obtained through hot-wire anemometry. Results, based on velocity and temperature data generated by means of direct numerical simulations from a turbulent channel flow emphasise that the ignored effect of temperature gradients might be able to explain some of the puzzling observations in the literature.

Introduction and Motivation

The (insufficient) finite length of a hot-wire sensor has been known for long to attenuate the measured fluctuations. With respect to wall-bounded turbulent flows efforts date back to the early 80s. Nonetheless, it was not until Hutchins et al. [5] that the quantitative effect of spatial resolution on the spectral content of the measured signal and in turn the root-mean-square (r.m.s.) was documented, thereby enabling to distinguish between Reynolds number (Re) as well as spatial and frequency resolution effects. In particular, the debate regarding the amplitude of the inner-scaled near-wall peak of the streamwise velocity (u) r.m.s. in canonical wall-bounded turbulent flows [7] has avalanched efforts to document, understand and ultimately correct spatial resolution effects [9]. Since the amplitude grows logarithmically with Re for flat-plate boundary layers [5] and channel flows [1], the actual scaling behaviour can easily be masked by other effects. Due to the inconclusiveness of recent studies with respect to turbulent pipe flows at high Re [4] a possible explanation was thought to lie in the temperature gradient that can arise across the measurement plane in internal flows [8]. The present study is a first attempt to document and understand this effect and propose and assess possible (practical) solutions.

Data generation

Since the instantaneous velocity and temperature (θ) field are required simultaneously for this purpose, direct numerical simulation (DNS) data from a turbulent channel was deemed as the appropriate data source. For this purpose the pseudo-spectral code *SIMSON* [3] was used, initially at $Re_\tau = 180$, but is currently extended to $Re_\tau = 590$. The temperature is considered as a passive scalar and the Prandtl number is fixed to 0.71. A uniform volumetric forcing is used as heat source similar to the one in Ref. [6], and the heat introduced is balanced by the heat flux at the wall thereby yielding analogous mean velocity and temperature profiles (Fig. 1). The effect of temperature fluctuations on velocity readings was simulated through the use of King's law and conventional temperature compensation methods (*cf.* Chapter 7 in Ref. [2]).

Results

Hot-wire measurements that are not calibrated at the same temperature (T) as under measurement conditions are conventionally corrected for a mean temperature difference/drift. However, little is known from the literature whether the wall temperature (T_w) in various experiments is *exactly* equal to that of the centreline (T_{CL}), and if not how the mean temperature changes across the measurement plane. If the exact mean temperature profile is known, the mean velocity can be compensated for accurately [2]. As evident from Fig. 1 the probability density function (p.d.f.) of θ exhibits (expectedly) a large width similar to the p.d.f. of u. To the authors' knowledge, there are barely well-resolved measurements that provide simultaneous near-wall measurements of u and θ that would enable an instantaneous (incl. the high-frequency part) correction. As demonstrated in Fig. 2, such a deficiency would lead (with the boundary conditions used here) the u-fluctuations to be attenuated (or amplified in case of the inverse temperature gradient) depending on whether θ is above or below its mean (Θ). The concrete effect of the practical inability to compensate instantaneously for θ-fluctuations is depicted in Fig. 2: here the r.m.s. profiles of u — that a hot-wire would have measured, despite temperature compensation with the local mean temperature (Θ) — for $\Delta T = T_{CL} - T_w = 2$, 4, and 6 K is shown and compared to the correct profile. As apparent, the percentage error for realistic ΔT that can be encountered in high Re internal flows is quite considerable, and of the same order as the scatter — that is so far unattributable to specific "suspects" — in the literature.

Ongoing work

Efforts are currently ongoing to assess practical corrections to this problem. Among those are the two probe method [2], employing two closely spaced hot-wire probes operated at different overheat ratios. In this respect, the qualitative importance of the spacing between the probes and the length of the sensing elements will be assessed to guide future experiments, since the sensing elements cannot measure at *exactly* the same location simultaneously. Less cumbersome correction schemes will also be tested and assessed thereby enabling to put error bars on already available data sets.

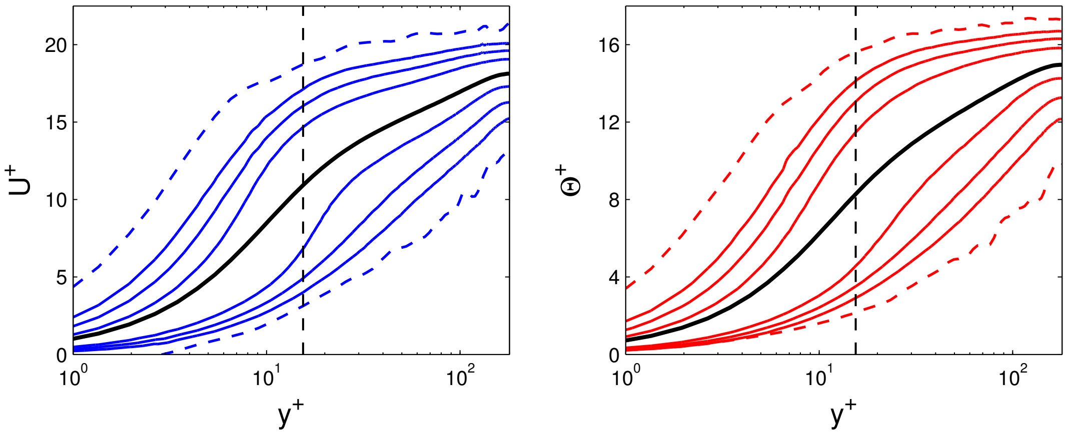

Figure 1. (*Left*) Inner-scaled mean velocity profile (——) and p.d.f. of instantaneous streamwise velocity for $Re_\tau = 180$ and $Pr = 0.71$: contour levels represent confidence interval for 50, 10, and 1 % (——) as well as the extreme values of the p.d.f. (- - -). (*Right*) Same as (*Left*) figure, however, for the passive scalar (temperature). Location of widest p.d.f., i.e. $y^+ \approx 15$, is indicated through vertical dashed line.

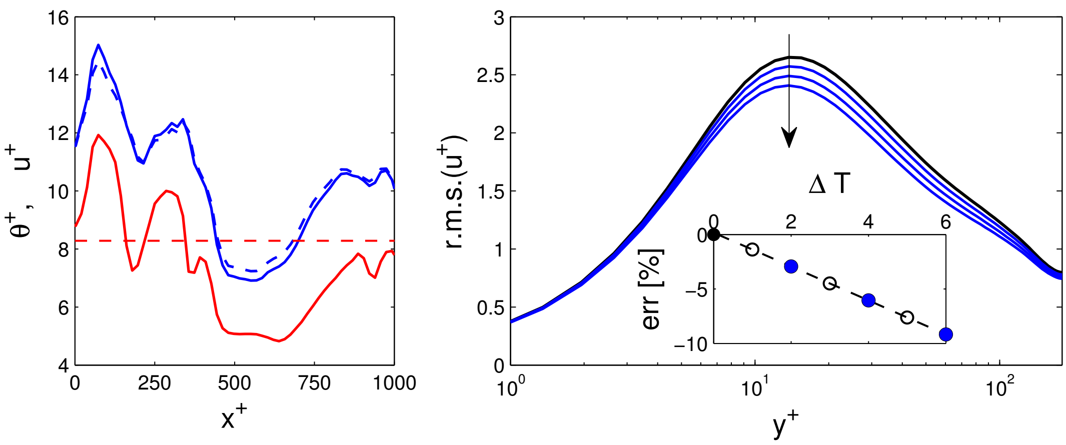

Figure 2. (*Left*) Instantaneous inner-scaled velocity (——) and temperature (——) traces at $y^+ \approx 15$. Additionally shown are the local mean temperature (- - -) and the velocity that a hot-wire would have measured despite temperature compensation with the local temperature for $\Delta T = 6$ K (- - -). (*Right*) Inner-scaled profile of the streamwise velocity r.m.s. (——) together with profiles that a hot-wire would have measured despite temperature compensation with the local temperature for $\Delta T = 2$, 4, and 6 K. Insert depicts percentage error at $y^+ \approx 15$ as function of imposed ΔT, while filled symbols correspond to the peak value of the r.m.s.(u^+) profile.

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