Available online at www.sciencedirect.com
SCIENCE DIRECT
International Journal of Heat and Mass Transfer 49 (2006) 905–918
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

The thermal characteristics of a hot wire in a near-wall flow

Li Wenzhong [a], B.C. Khoo [a,b,*], Xu Diao [c]

[a] Department of Mechanical Engineering, National University of Singapore, Kent Ridge, Singapore 119260, Singapore
[b] Singapore-MIT Alliance, 4 Engineering Drive 3, Singapore 117576, Singapore
[c] Institute of High Performance Computing, 1 Science Park Road, #01-01 The Capricorn, Singapore Science Park II, Singapore 117528, Singapore

Received 16 April 2004; received in revised form 15 May 2005
Available online 21 November 2005

Abstract

A two-dimensional numerical study is carried out to obtain the correction curve for the near-wall measurements by an infinitely long hot wire having been calibrated under free stream condition for the two extreme cases of isothermal and adiabatic wall conditions. Unlike previous studies particularly in experiments where the correction curve is primarily based on only the distance (h) between the wall and the wire expressed in wall units ($Y^+ \equiv \frac{hU_\tau}{\nu}$), it is found that a second dimensionless parameter h_0 ($\equiv h/D$) accounting for the effect of the hot wire diameter (D) is necessary to describe fully the overall near-wall correction curve. Our calculations also reveal a possible reason for the apparent discrepancy between the near-wall hot wire correction curves of Chew and Shi [Y.T. Chew, S.X. Shi, Wall proximity influence on hot-wire measurements, In: R.M.C. So, C.G. Speziale, B.E. Launder (Eds.), Near-Wall Turbulent Flows, Elsevier, Amsterdam, 1993, pp. 609–619] and Lange et al. [C.F. Lange, F. Durst, M. Breuer, Wall effects on heat losses from hot-wires. Int. J. Heat Fluid Flow 20 (1999) 34] next to a thermally non-conducting wall.

Keywords: Hot wire correction factor; Near-wall measurement; Critical Y_c^+; Overheat ratio

1. Introduction

In Perry and Morrison [3], it was found that their hot wire system with the DANTEC-made CTA operating under free stream condition has a frequency of well over 5 kHz when subject to direct velocity perturbations via the Karman vortex shed from one side of the cylinder. The said frequency response agreed well with the conventional square-wave voltage perturbation tests, which indicates a roll-off frequency of 5 kHz. Subsequent model/theory put forth by Freymuth [4] has shown the near-equivalence between the velocity and voltage perturbation tests in determining the dynamic response of the hot wire system. The square-wave voltage perturbation test, thus, has been used extensively and almost exclusively by experimentalists to justify the very rapid thermal response of the hot wire in faithful measurement of the fluctuating velocity in a turbulent flow with its typical range of frequency expected [5,6]. That is, a hot wire having been calibrated under imposed mean free stream condition can be employed for fluctuating velocity measurement. This practice is incumbent on the heat transfer characteristics of hot wire as exposed in the measured flow to be the same as that during the calibration. Such assumption, however, is no longer valid when the same hot wire is used in near-wall measurements. The wall may change the heat transfer characteristics of the hot wire with its calibration curve obtained under free stream condition, since more or even less heat is released from the hot wire due to the influence of wall effects. Therefore, some corrections on the measured velocity are needed for the near-wall measurement for the hot wire having been calibrated under free stream (wall-remote) flow condition. The problem was studied experimentally by numerous researchers over the years like Wills [7], Oka and Kostic [8], Singh and Shaw [9], Hebber

* Corresponding author. Address: Department of Mechanical Engineering, National University of Singapore, Kent Ridge, Singapore 119260, Singapore. Tel.: +65 68742889; fax: +65 67791459.
E-mail address: mpekbc@nus.edu.sg (B.C. Khoo).

0017-9310/$ - see front matter
doi:10.1016/j.ijheatmasstransfer.2005.06.044

Nomenclature

C_d	drag coefficient
C_u	correction factor $= \frac{U_0}{U_{meas}}$
C_{ua}	correction factor for adiabatic wall case
C_{ui}	correction factor for isothermal wall case
D	diameter of hot wire
du^+	correction factor $= \frac{U_{meas}-U_0}{U_\tau}$
d^+	Reynolds number $= \frac{U_\tau D}{\nu}$
Ec	Eckert number $= \frac{U_0^2}{C_P(T_w-T_\infty)}$
Gr	Grashof number $= \frac{g\beta(T_w-T_\infty)D^3}{\nu_\infty^2}$
H	the distance from the center of the hot wire to the wall
H'	heat flux through the closed circulation which surrounds the cylindrical hot wire
H_0	the non-dimensional distance from the center of the hot wire to the wall $= \frac{h}{D}$
L	hot wire length
N_u	Nusselt number
N_{u0}	Nusselt number obtained under free stream operating condition
N_{um}	measured Nusselt number
N_{uf}	Nusselt number (N_{u0}) based on fluid properties evaluated at the film temperature
Pe	Peclet number $= Re\,Pr$
Pr	Prandtl number $= \frac{\mu_\infty Cp_\infty}{k_\infty}$
Re	Reynolds number $= \frac{U_0 D}{\nu_\infty}$
Re_f	Reynolds number based on fluid properties evaluated at the film temperature
T	temperature
U_0	the (true) upstream incoming flow velocity at the location of hot wire center
U_{meas}	measured velocity value
U_τ	friction velocity
Y^+	non-dimensional wall distance $= \frac{hU_\tau}{\nu} \equiv h_0 \frac{U_\tau D}{\nu}$
Y_c^+	critical Y^+, beyond which wall influence can be neglected

Greek symbols

ε_f	maximum difference between the respective values of stream function on successive iterations
ε_v	maximum difference between the respective values of vorticity on successive iterations
ε_t	maximum difference of the temperature on successive iterations
ν	kinematic viscosity
τ	overheat ratio ($\equiv T_w/T_\infty$)

Subscripts

∞	at the inlet of computational domain
w	conditions at the hot wire

[10], Krishamoorthy et al. [11] and Chew et al. [12], to name a few. Numerically, Bhatia et al. [13], Chew and Shi [1] and Lange et al. [2,14], have tried to find a suitable universal correction for the near-wall hot wire measurements velocity, but met with limited success and in some instances presented conflicting trends.

In early hot wire applications, Van der Hegge Zijnen [15] measured the heat loss of the hot wire in still air near the wall as the required correction quantity to the measured signal for the flowing air in the near-wall region. Wills [7] introduced the term $k_w(2y/D)$ to account for the wall effect in his experimentally obtained wall corrections relationship for laminar flow:

$$N_u\left(\frac{T_w}{T_a}\right)^{-0.17} = A + k_w\left(\frac{2y}{D}\right) + B * Re_D^{0.45}. \quad (1)$$

Here k_w is the ratio of the thermal conductivity of wall material to the thermal conductivity of air; y is the distance of hot wire from the wall; D is the wire diameter; N_u is the Nusselt number; Re_D is Reynolds number based on wire diameter, and A and B are arbitrary constants. One may also note that Collis and Williams [16] fitted their experimental data in the range of Reynolds number from 0.02 to 44 on the curve:

$$N_u\left(\frac{T_f}{T_a}\right)^{-0.17} = 0.24 + 0.56\,Re_D^{0.45} \quad (2)$$

where the fluid properties were evaluated at the film temperature, T_f ($\equiv(T_{wire} + T_a)/2$), the mean of hot wire and ambient air temperature. On comparing the two equations, it is clear that Eq. (1) implies the additional heat loss due to the presence of the wall is (or can be) determined by the dimensionless parameter h_0 ($\equiv y/D \equiv h/D$). For turbulent flow measurement, Wills [7] suggested that only half of the correction for laminar flow should be employed. However, no explanation, whether physical or otherwise, is given.

Still, Oka and Kostic [8] and Hebbar [10] obtained the corrections from measurements in turbulent channel and boundary layer flows, respectively, and suggested that the correction can universally collapsed to a single curve $\Delta U^+ = f(Y^+)$. Here ΔU^+ and $Y^+$are defined as

$$\Delta U^+ = \frac{U_{meas} - U_0}{U_\tau} \quad (3)$$

$$Y^+ = \frac{yU_\tau}{\nu} \quad (4)$$

where U_{meas} is the measured apparent velocity, U_0 is the actual velocity, and U_τ is the wall shear velocity. Such a cor-