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Heat transfer from a flat plate in inhomogeneous regions of grid-generated turbulence

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ABSTRACT

Experiments on the convective heat transfer from a flat plate, vertically mounted and parallel to the flow in a wind tunnel, were carried out via Infra-Red thermography and hot-wire anemometry. The Reynolds number based on the inflow velocity and on the length of the plate was about 5×10^5. A step near the leading edge of the plate was used to promote transition to turbulence, with tripping effects on the heat transfer coefficients shown to be negligible for more than 90% of the plate's length. Different types of grids, all with same blockage ratio $\sigma_g = 28\%$, were placed upstream of the plate to investigate their potential to enhance the turbulent heat transfer. These grids were of three classes: regular square-mesh grids (RGs), single-square grids (SSGs) and multi-scale inhomogeneous grids (MIGs). The heat transfer coefficients at the mid-length of the plate were correlated with the mean velocity and the turbulence intensity of the flow at a distance from the plate at which the ratio of the standard deviations of the streamwise and wall-normal velocity fluctuations began to increase. However, the heat transfer was shown to be insensitive to the turbulence intensity of the incoming flow in close proximity of the tripping step. Furthermore, the integral length scale of the streamwise turbulent fluctuations was found not to affect the heat transfer results, both near the tripping step and in the well-developed region on the plate. For the smallest plate-to-grid distance, the strongest heat transfer enhancement (by roughly 30%) with respect to the no-grid case was achieved with one of the SSGs. For the largest plate-to-grid distance, the only grid producing an appreciable increase (by approximately 10%) of the heat transfer was one of the MIGs. The present results demonstrate that MIG design can be optimised to maximise the overall heat transfer from the plate. A MIG that produces a uniform transverse mean shear, which is approximately preserved over significant downstream distances from the grid and with a velocity decreasing with distance from the plate, allows a sustained heat transfer enhancement, in contrast to all other grid designs tested here. The most efficient configuration for a MIG is one for which the section of the grid that has lower blockage and thicker bars is adjacent to the plate.

1. Introduction

Convective heat transfer from a flat plate is a topic of interest in classical fluid mechanics and in many engineering applications, as different industrial devices make use of flat surfaces to exchange heat with a fluid in motion. A relevant example in the renewable energy industry is the case of high-temperature pressurised-air solar receivers, which are key components in solar power tower plants [33,6]. Considerable effort has been made towards achieving the highest possible heat transfer rate in such devices. Among the suggested solutions, there are two main categories: modifications to the heat transfer surface (e.g., by the addition of roughness or riblets) and modifications to the flow upstream of the flat surface [5]. In many cases, the latter approach could be the only practical one, as it does not require alterations of the entire heated surface, which may be undesirable or too cumbersome to make. The present study is focused upon devising strategies to enhance heat transfer from a flat surface that is contained within a duct (in this case the test section of a wind tunnel). Two strategies appear to be potentially effective in this respect. An obvious one would be to increase the near-wall mean velocity, which can be achieved by diverting fluid from distant regions of the cross-section towards the wall. An important condition for this approach would be to sustain the near-wall velocity increase over sufficient distance along the heated surface to make a significant enhancement of the

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Nomenclature

β	coefficient of thermal expansion of air
ϵ	turbulent kinetic energy dissipation rate per unit mass
ε_p	emissivity of black paint
δ_{99}	99% boundary layer thickness
η	Kolmogorov length scale
Θ_u	integral time scale of u
λ	Taylor length scale
ν	kinematic viscosity
ν_t	turbulent viscosity
ρ	density
σ_g	blockage ratio of the grid
σ_{SB}	Stefan-Boltzmann constant, $\sigma_{SB} = 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$
τ	dimensionless strain

Roman symbols

A_p	area of the heated section of the flat plate
c_p	specific heat capacity
C_ϵ	dissipation coefficient
d_{hw}	diameter of the hot-wire
d_p	distance between the heated side of the flat plate and the nearest wind tunnel's lateral wall
$\mathcal{D}_i$	measured values of St/St_∞^{NG}
E_{1e}	mean value of $\overline{St_\infty}/\overline{St_\infty^{NG}}$ in $0.3 \le X/L_p \le 0.4$
E_2	mean value of $\overline{St_\infty}/\overline{St_\infty^{NG}}$ in $0.45 \le X/L_p \le 0.85$
$E_{1e,2}$	mean value between E_{1e} and E_2
E_u (E_v)	power spectral density of u (v)
f	frequency
f_{sh}	vortex shedding frequency of the largest bars of the grid
$\mathcal{F}_i$	values of St/St_∞^{NG} predicted by the fit
g	gravitational acceleration
Gr_{H_p}	Grashof number based on H_p
h	convective heat transfer coefficient
H_p	height of the flat plate
h_s	height of the step (trip) on the flat plate
H_t	height of the wind tunnel's test section (or total length of the cylinder)
I	electric current
k	streamwise wavenumber, $k = 2\pi f/U$
K_p	pressure gradient parameter
k_s	mean shear rate parameter in the z-direction
L_0	distance between the largest bars of the grid
l_{hw}	sensing length of the hot-wire
L_j	distance between the bars in the j-th iteration of the multi-scale grids
L_m	average value of the distance between the bars of the central iterations of the multi-scale grids
L_p	length of the heated section of the flat plate
L_u	integral length scale of u in the streamwise direction, $L_u = U\Theta_u$
L_ϵ	dissipation length scale
n_j	number of bars in the j-th iteration of the MIGs
q_{cond}	heat flux lost by thermal conduction
q_{conv}	convective heat flux
q_{input}	input heat flux
q_{rad}	radiative heat flux
R^2	coefficient of determination of the fit
Re_θ	boundary layer momentum thickness Reynolds number
Re_{L_0}	inlet Reynolds number based on U_∞ and L_0
Re_{t_0}	inlet Reynolds number based on U_∞ and t_0
Re_X	Reynolds number based on U_∞ and X
Re_{H_p}	Reynolds number based on U_∞ and H_p
res	sum of squared residuals
St	local Stanton number
$\overline{St}$	vertically averaged value of St
T	temperature
t_0	thickness of the largest bars of the grid in the $y - z$ plane
T_{aw}	adiabatic wall temperature
T_{film}	film temperature
t_m	average value of the thickness of the bars for the central iterations of the multi-scale grids
t_p	thickness (in the $x - z$ plane) of the flat plate
t_w	thickness of the Inconel foil covering the flat plate
u, v, w	streamwise (along x), vertical (along y), transverse (along z) velocity fluctuations
u', v', w'	standard deviations of u, v, w
$\widetilde{U}$, $\widetilde{V}$, $\widetilde{W}$	streamwise (along x), vertical (along y) and transverse (along z) instantaneous velocity components
U, V, W	time-averaged values of $\widetilde{U}$, $\widetilde{V}$, $\widetilde{W}$
U_∞	inlet velocity (upstream of the grids)
V_D	voltage drop
w_s	width of the step (trip) on the flat plate
w_{LE}	width of the flat plate's leading edge
W_t	width of the wind tunnel's test section
x^*	wake interaction length scale for the largest bars of the grids
x_m^*	wake interaction length scale for the central iterations of the MIGs
x_{LE}	distance between the leading edge of the flat plate and the grid
x_{peak}	centreline streamwise location of the maximum turbulence intensity
x_{TE}	distance between the trailing edge of the flat plate and the grid
xyz	reference frame with its origin fixed at the centre of the grid
XYZ	reference frame with its origin fixed at the heated side of the flat plate
z_p	z-coordinate of the heated side of the flat plate
z_r	z-coordinate where res is minimum

Subscripts

c	centreline values ($y = z = 0$)
$film$	evaluated at T_{film}
r	values at $y = 0$ and $z = z_r$
w	wall values
∞	inlet values or based on inlet conditions

Acronyms

FOV	Field Of View
FSG	fractal square grid
HW	hot-wire
IR	Infra-Red
MIG	multi-scale inhomogeneous grid
NG	No Grid
RG	regular grid
SSG	single square grid

overall heat removal. A second strategy would be to produce near-wall turbulence with an intensity, length scale and structure that would be most effective in enhancing convective heat transfer. Once more, it is essential that such turbulence would be sustained sufficiently to affect appreciably the overall heat removal. Because local mean velocity and turbulence characteristics are intimately