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Heat transfer enhancement in a ribbed channel: Development of turbulence closures

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ABSTRACT

The ability to accurately predict turbulent heat transfer in massively separated flows is of immense practical importance especially in the field of heat transfer enhancement in compact heat exchangers. This paper describes new developments in the modeling of the flow and the turbulent heat fluxes in a representative benchmark flow namely that in a heated channel with periodic surface ribs. This flow, which is well-documented by experiments, poses severe challenges to conventional closures due to the significant non-equilibrium effects that are present. Several closure strategies were therefore considered ranging from the eddy-viscosity closures that are routinely used in practice, to the more sophisticated full differential transport closures that can better capture rapidly-evolving flow and thermal fields. As the heat transfer rates are largely determined by the flow conditions in the near-wall region, low Reynolds number versions of these closures were also considered. As for the turbulent heat fluxes, two alternative models were considered: the conventional Fourier's law, and a more complete, algebraic model which is explicit in these fluxes and which correctly allows for their dependence on the turbulent stresses and on the gradients of mean velocity. The models were implemented in the open source software OpenFOAM and the computations were performed with cyclic boundary conditions that are appropriate for this periodic flow. Details of models implementation are reported. Comparisons with experimental measurement indicate significant improvements over existing approaches.

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1. Introduction

There are many applications in engineering where enhancement of the heat-transfer rates by active means provides benefits that far outweigh the associated penalty of increased pressure loss. Amongst the more practical techniques used is the placement of surface ribs with axes perpendicular to the direction of flow. This is the geometry of interest here, shown schematically in Fig. 1 where the coordinates system is also defined. Typically, several identical ribs are used such that after an initial period of development, periodic flow conditions are established. Flow reversal invariably occurs in the gaps between successive ribs. Depending on the ratio of pitch to rib height, the flow within the gap may either form a single vortex that extends across the entire region in between successive ribs, or it may separate from the corner of an upstream rib, re-attach within the gap and then separates again upstream of the following rib. Our interest here is in the latter case where the conditions render the mean flow and the turbulence structures far removed from equilibrium. The departure from equilibrium conditions poses a severe test for turbulence closures that are used in practice since non-local effects become quite large, and the assumption that the turbulent stresses and heat fluxes are determined by local conditions becomes invalid. In this paper, we report on research that was performed to improve our ability to accurately predict the extent of heat-transfer enhancement in these flows.

The geometry depicted in Fig. 1 was studied experimentally by Drain and Martin [2] who used Laser Doppler Velocimetry to obtain mean-flow and turbulence data for water flow in a ribbed channel with a relative rib height of $e/h = 0.4$, a pitch to height ratio of 7.2, and a Reynolds number of 37,000. The corresponding heat transfer measurements were conducted by Liou et al. [3] who performed real-time holographic interferometry at a Reynolds number of 12,600. A uniform heat flux boundary condition was applied at the lower wall by means of a controllable thermal foil. The upper wall was manufactured from Bakelite and was further insulated to obtain adiabatic conditions. The sidewalls of the duct were made of Plexiglas to provide optical access for the interferometry measuring devices. The measurements were performed at

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Nomenclature

A	stress-flatness parameter $(= 1 - \frac{9}{8}(A_2 - A_3))$
A_{ij}	anisotropy tensor $= \left(\frac{\overline{u_i u_j}}{k} - \frac{2}{3}\delta_{ij}\right)$
A_2	second invariant of anisotropy $(= A_{ij}A_{ij})$
A_3	Third invariant of anisotropy $(= A_{ij}A_{jk}A_{ik})$
$C_1, C_2, \ldots$	turbulence model coefficients
$C_{t1}, C_{t2}, \ldots$	heat-flux model coefficients
e	rib height
$F,\ f_s$	Functions in low-Re turbulence model
H_d	hydraulic diameter
h	channel half-width
k	turbulence kinetic energy
Nu	Nusselt number
$P_{ij},\ P_k$	production rates of $\overline{u_i u_j}$ and k
Pe	Peclet number $(= Re_t Pr)$
Pr	Prandtl number
q_w	wall heat flux
Re	Reynolds number $\left(= \frac{U_b H_d}{\nu}\right)$
Re_t	turbulence Reynolds number $\left(= \frac{k^2}{\nu\varepsilon}\right)$
U_i	velocity vector
u_τ	friction velocity $\left(= \sqrt{\frac{\tau_w}{\rho}}\right)$
$\overline{u_i u_j}$	Reynolds-stress tensor
$\overline{u_i t}$	turbulent heat flux
X_r	reattachment length

Greek symbols

ε	dissipation rate
ν	kinematic viscosity
Φ_{ij}	pressure–strain correlations
σ	Prandtl number
ζ	distance along surface

Subscripts

b	bulk
s	smooth
t	turbulent
w	wall

a streamwise location which was twelve hydraulic diameters downstream of the inlet to obtain fully developed flow and thermal conditions. In order to achieve a reasonable two-dimensionality of the flow, Liou et al. used a channel aspect ratio of 10:1. Their measurements show a spanwise scatter of the average temperature of around 6%, and an overall error in the temperature field of around ±9%. Lockett and Collins [4] performed similar experiments at various Reynolds number using real-time holographic interferometry. Their measurements of Nusselt number in the gap between successive ribs showed that this parameter increases with distance to reach a peak near the downstream corner. In contrast, the measurements of Liou et al. [3] showed this parameter to be fairly flat.

Previous computational studies of the geometry of present interest include those of Ciofalo and Collins [5] and of Meng and Pletcher [6] who used Large-Eddy Simulations (LES) to predict both flow and heat transfer. Other computational studies have been reported by Cui et al. [7] who also used LES, and by Miyake et al. [8] who used Direct Numerical Simulations (DNS) to examine the mechanisms responsible for the heat-transfer enhancement. The influence of geometric parameters on the thermal field was investigated computationally by Nagano et al. [9].

In this paper, we address a specific issue concerning the prediction of heated flows in a ribbed channel namely that of how best to represent the effects of turbulence on the heat transfer rate. Interest is focused on prediction methods that solve time-averaged equations governing conservation of thermal energy and momentum. These methods (referred to in the literature as Reynolds-Averaged Navier–Stokes, or RANS) remain the primary tool for engineering analysis despite the spectacular advances in computer technology that was expected to make them obsolete. In the RANS framework, the unknown heat fluxes that appear in the time-averaged energy equation are modeled using Fourier's law in which they are assumed to be linearly proportional to the gradients of mean temperature. The proportionality coefficient, the eddy diffusivity, is defined by the eddy viscosity and a (usually constant) turbulent Prandtl number. However, experiments and recent Direct Numerical Simulations (e.g. [10]) strongly suggest that the eddy diffusivity is not a scalar quantity but is in fact a second-order tensor whose components depend on the direction of mixing. Another assumption in Fourier's law which is not supported by experiments is that it does not allow for the heat fluxes to depend on the gradients of mean velocity. Such dependence is required if the model is to be consistent with the exact equations that govern the evolution of the turbulent heat fluxes – its absence from Fourier's law renders the model insensitive to the effects of rapid changes in the mean flow field. Such changes occur in the massively-separated flows under consideration here.

With these limitations of Fourier's law, it seemed worthwhile to investigate whether the adoption of a more physically-based alternative model would yield distinct improvements in the predictions. In this work, we assess the performance of a new model for the turbulent scalar fluxes that has hitherto yielded significant improvements in the prediction of attached shear flows. The model is that of [11]. It is one of several that have been proposed as alternatives to Fourier's law but it is the only one which has been extensively tested in multi-dimensional inhomogeneous shear flows [12–15]. The present study extends this model's assessment to the more difficult case of non-equilibrium separated flows.

Details of the turbulence closures are given in the next section. In Section 3, computational details are provided, followed in Section 4 with presentation and discussion of the results. The conclusions are presented in Section 5.

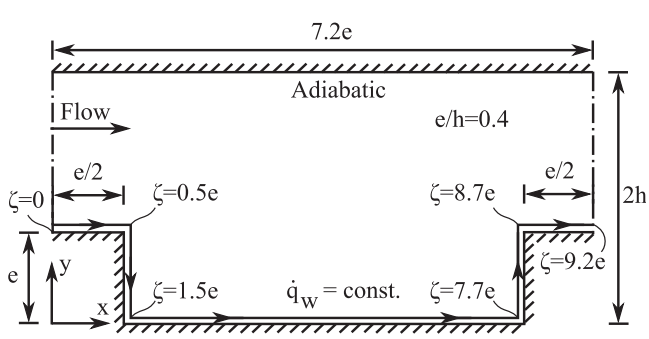

Fig. 1. Geometry and coordinates system [1].

2. Mathematical formulation

2.1. Governing equations

The results presented here were obtained using OpenFOAM [16] – an open source toolbox for the development of numerical

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