BUOYANCY-DRIVEN TURBULENT CONVECTION IN A BUNDLE OF VERTICAL HEATED CYLINDERS

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ABSTRACT

Background

Buoyant, turbulent convective heat transfer around cylindrical rods arranged in bundles is a technically relevant heat transfer configuration which finds application in steam generators, cooling of reactor core fuel assemblies and heat exchangers in general. Most of the research performed so far considered forced convection conditions on vertical rod bundles, corresponding for example to the configuration of a nuclear reactor primary loop. Fewer works have focused on the effect of buoyancy, with or without an external source of momentum.

In their experimental investigation, Hallinan and Viskanta [4] employed a thermosyphon loop to determine the average heat transfer coefficients for water under natural circulation conditions in a tube bundle containing twenty-one tubes; their work is mainly focused on the favorable effect of grid spacers on heat transfer enhancement. El Genk *et al.* performed experiments of upflow- and downflow-forced turbulent and laminar convection, natural convection and buoyancy-assisted combined convection of water in a uniformly heated square lattice of seven [2] and nine [3] rod bundles with variable pitch-to-diameter ratio, Reynolds and Rayleigh number. They proposed heat transfer correlations and concluded that the rod arrangement only negligibly affects the overall Nusselt number in both forced and natural convection regimes.

Concerning the numerical modeling of this class of flows, only very recent works resort to the Large Eddy Simulation [5], and even less frequently, to the Direct Numerical Simulation [7]. This is largely due to the geometric complexity of the flow domain and the difficulties related to the adoption of numerical techniques allowing for sufficiently accurate results.

Problem statement

This paper reports a Direct Numerical Simulation study of the fully developed, mixed convection in a bundle of vertical, heated cylinders, where each cylinder releases an equal, uniform heat flux distribution q'' and a Boussinesq approximation is introduced to represent buoyancy effects. Periodic boundary conditions are enforced along the cross flow directions y and z as well as the streamwise direction x on all computed variables representing the velocity field, and normalized pressure and temperature fields. To allow for the computation of normalized, periodic variables instead of the pressure and the temperature fields, a specific mathematical treatment is followed [8], leading to additional source terms to be introduced in the momentum and thermal energy equations.

The flow domain considered in this study is sketched in Figure 1. The heated cylinders of diameter D are arranged in a square lattice of pitch P, where $P = \frac{5}{4}D$. The computational domain in the cross flow plane (y, z) is a square of side $2P$, thus including four cylinders, while the domain length along the streamwise, vertical direction x is $L_x = 2\pi D$, which correspond to about 8 to 25 times the cross flow dimensions ($L_x \approx 25\, h_{\min}$ and $L_x \approx 8.2\, h_{\max}$) .

Numerical method and parallel implementation

The numerical technique adopted is based on a Finite Volume implementation of a second order projection method. Spatial derivatives and interpolations are approximated with second-order symmetric schemes on staggered Cartesian grids, which can be non-uniform on the transverse $y - z$ plane. The modelling of arbitrarily irregular cylindrical boundaries on Cartesian grids is achieved from an Immersed Boundary technique [1], which involves a local modification of the 5-point computational stencil where boundary segments intersect the stencil arms. Overall, the method is second-order accurate in both space and time. Parallelism is introduced by the message-passing library MPI and through a one-dimensional domain decomposition in the streamwise direction x except for the Poisson equation, for which a Fourier decomposition method is applied and the domain decomposition implemented in MPI is two-dimensional.

$L_y = 2.5D$	$L_z = 2.5D$	$L_x = 2\pi D$
$n_y = 512$	$n_z = 512$	$n_x = 512$

Table 1. Domain dimensions and number of grid points in each direction
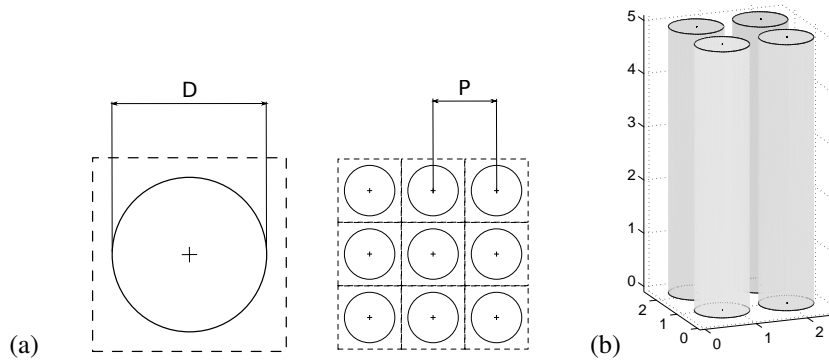
Figure 1. Unit cell of a square array of rods: cross section including nine cylinders (a) and computational domain (b)
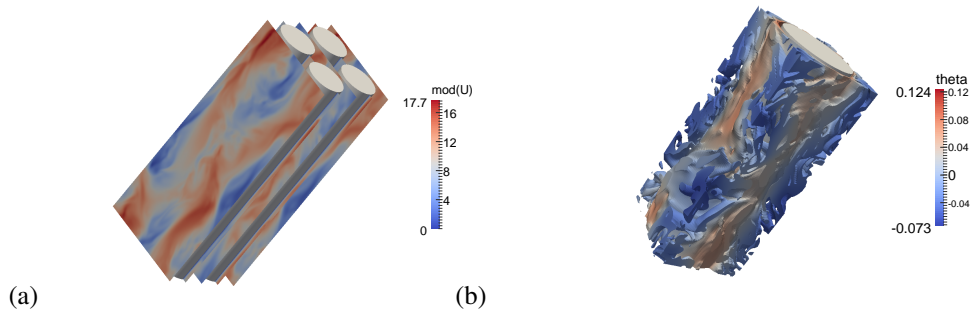

Figure 2. Instantaneous plot of the velocity field module (a) and iso-surfaces of the vorticity module colored by the temperature-like variable θ around a single cylinder, $\Delta_x = L_x/2$ (b)

Results

Turbulent simulations are performed for $\mathrm{Gr} = 10^7$, $\mathrm{Re}_\tau = 180$ and $\mathrm{Pr} = 0.1$. In the mathematical formulation followed, $\mathrm{Re}_\tau > 0$ is used to represent the mean streamwise pressure drop associated with a non zero net mass flow rate, and ensures a mean velocity field free of flow reversal regions.

As experimental velocity and temperature profiles are not available in the literature, a preliminary validation of the method employed is performed by the comparison of the global quantities like f and Nu against results in Ref. [4] and [2].

The time averaged velocity and temperature fields are reported in the paper, together with first order and higher-order statistics. In addition the main turbulent flow features are described through coherent structure eduction methods. The main heat transfer mechanism in the cross flow plane needs to be elucidated: for example, Meyer [6] comments on the mechanism leading to mixing through the gaps between rods which enhances heat transfer. Such a feature was initially ascribed to the effect of turbulent diffusion and secondary flow, but, eventually, evidence was found of the existence of macroscopic periodic flow pulsations, corresponding to transversal "vortex trains". Figure 2 displays instantaneous representations of the velocity and the temperature fields for the mixed convection regime considered.

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