ALTERNATIVE STRATEGIES FOR MODELLING FLOW OVER IN-LINE TUBE BANKS

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ABSTRACT
This paper reports alternative strategies for modelling turbulent flow and heat transfer around in-line tube banks. The suitability and accuracy of well-resolved Large Eddy Simulation (LES) and Unsteady Reynolds-Averaged Navier Stokes (URANS) approaches are examined on generic square in-line tube banks, where experimental data are limited but available. Within the latter approach, both eddy-viscosity and Reynolds stress models have been tested. The assumption of flow periodicity in all three directions is investigated by varying the domain size.

INTRODUCTION
Engineering applications of cross-flow tube banks are abundant. Such configurations achieve high heat transfer with relatively low manufacturing complexity, making them attractive heat exchangers for use in fossil-fuel and nuclear power plants. Reliable prediction of the flow and heat-transfer characteristics of such tube-bank flows is therefore essential for heat-exchanger design and life-time management. Such heat-exchangers may consist of arrays of hundreds or even thousands of tubes, through which a fluid flows while a second fluid is blown normal to them, the overall purpose being to promote heat exchange between the two fluids. Detailed testing on such systems, both experimental and computational, is largely done on much smaller systems, typically consisting of clusters from four to a few tens of tubes, the hope being that the data emerging will be representative of those in the full-scale plant. Experiments on widely-spaced in-line and staggered tube banks have been carried out inter alia by Ishigai et al. (1973) where several distinct flow patterns were observed. Costs with tightly packed bundles are lower, however, and extensive data have been reported on close-packed staggered tube banks. There are few experiments of closely-spaced in-line tube banks (Iwaki et al., 2004) and even fewer providing data of local heat transfer (Aiba et al., 1982). Large-eddy simulations (LES) of closely-spaced square in-line tube banks of various pitch-to-diameter ratios, P/D, have recently been conducted in Manchester by Benhamadouche (2005) and Afgan (2007). It was found that as the pitch:diameter ratio decreased below 1.6 the flow pattern deviated from the symmetric flow patterns observed by Ishigai et al. (1973), the mean flow preferring to travel in a diagonal path through the domain. Such a flow path has seldom been seen in experiments in such small arrays, because then the confining wind-tunnel walls restrict cross-flow motion. Jones et al. (1978), however, reported cross-flow drift in their 22x22 tube test section while Aiba et al. (1982) noted, for P/D=1.2 with only 4 tubes in the cross-flow direction, that “it is very clear that the flow through the tube bank deflects as a whole”.
Numerical simulation of tube banks can be greatly simplified by assuming flow periodicity at certain boundaries. These cyclical boundaries are placed at user-chosen locations where the flow is judged to repeat itself. The present study has aimed to determine the limitations of using periodic flow conditions and to determine the level of turbulence modelling necessary for future simulations of specific closely-spaced in-line tube banks.

COMPUTATIONAL AND PHYSICAL MODELS
Both LES and URANS approaches employed the finite-volume code, Code_Saturne (Archambeau et al., 2004) with a collocated grid. It was decided to use this freely available and versatile software although it does not offer the more advanced modelling practices developed in our in-house code, STREAM. Some computations were also made with the latter which broadly confirmed the conclusions reached with Code_Saturne. The velocity-pressure coupling is achieved by a predictor/corrector method using the SIMPLEC algorithm where the momentum equations are solved sequentially. The Poisson equation for the pressure field is solved using a conjugate-gradient method and a standard pressure gradient interpolation to avoid oscillations. As spatial and temporal discretisation are second order (central-difference and Crank-Nicolson interpolations respectively), the time step was kept sufficiently small to ensure the maximum Courant number was below unity.

Periodic boundaries are applied in all three Cartesian directions placed at distances of Lx, Ly and Lz. see Figure 1a where Lx and Ly are varied to obtain the desired P:D ratio. Figure 1a shows a portion of the computational grid employed for the standard (Case 1) grid. Block-structured grids gave greater control of the number of cells and a more effective resolution of the near-wall regions. As flow periodicity is used, a constant mass flow rate is imposed to obtain the desired bulk velocity by specifying an explicit self-correcting mean pressure gradient at every time step. Previous periodic calculations of in-line tube banks (Afgan, 2007; Beale, 1999; Benhamadouche, 2005) have found a 2x2 tube domain to be sufficient to capture the unsteady flow characteristics and mean quantities of interest. While Benhamadouche, (2005) also tested a larger 4x4 tube domain for an in-line bank of P/D=1.44, the same flow pattern was predicted in each case and no differences in mean quantities were reported.
A uniform heat flux is prescribed on the tube surfaces. To maintain a fixed bulk temperature, the periodic inlet temperature distribution is rescaled using a bulk correction corresponding to the total amount of energy added to the domain. Thermo-physical fluid properties are assumed to be constant.

For the URANS computations, grid sensitivity studies were first performed for both high-Re (i.e. used with wall functions) and low-Re (integration to the wall) grids (details of these studies are given in West, 2012). The finest low-Re grid was used as a starting point for the LES grid sensitivity studies. The optimum number of grid cells for the LES and other grid parameters are given in Table 1. The grid parameters for the LES resolution and domain size study are summarised in Table 2. A factor of 1.1 is used for the radial cell-expansion from the tube walls. Around the tube surface 160 cells were used except 256 cells for Case 4. Figure 2 shows the wall-adjacent cell size around the central cylinder in wall units for Case 1. The centre of the wall-adjacent cell is located at \( y^+=\Delta y^+/2=0.25 \) over most of the cylinder wall. The spanwise resolution was initially chosen (Case 1) in order that in the central region cell dimensions were comparable with those in the streamwise and cross-wise direction (i.e. they were as close as possible to a regular hexahedron or a cube). Piomelli and Chasnov (1996) recommend \( y^+<2 \), \( \Delta x^+=50-150 \), \( \Delta z^+=15-40 \) for a wall-resolving LES. Their findings imply that Case 1 needs better resolution in the \( z \)-direction to resolve fully the near-wall structures. Case 4, with over three times as many cells as Case 1, meets these recommendations with a mean \( \Delta z^+ \) of around 30. Case 3, with 130 spanwise cells also meets the requirements.

### Turbulence Modelling

The turbulence models used for the URANS calculations are listed in Table 3 (these amount to those available within Code_Saturne). Details of each model can be found in the respective references. The high-Reynolds number models (\( k-\varepsilon \) LP and RSM SSG) have been used with the rudimentary scalable wall function (Grotjans and Menter, 1998) embedded in the code.

The wall-resolved LES uses the dynamic Smagorinsky model (Germano et al., 1991) and least squares minimisation of (Lilly, 1992) to model the subgrid-scale tensor. The current LES procedure is the same as that used by Kahil (2011) in his study of flow over single and tandem cylinders. The Smagorinsky coefficient was limited between 0 and 0.065 and 1% local blending with upwind was used to avoid artificial numerical oscillations with 2nd-order central differencing. As heat-transfer predictions were a major practical output, the immediate near wall region was resolved via a fine mesh rather than wall functions.

### COMPUTATIONAL RESULTS

All simulations were conducted at the same Reynolds number used for the experiments of Aiba et al. (1982); \( Re=41,000 \) based on the tube diameter, \( D \) the kinematic viscosity of the fluid, \( v \) and the bulk gap velocity, \( U_\infty \).

The periodic computational domain is chosen. A 2x2 tube as the standard section to simulate the flow pattern deep within a tube bank. Averaging of the output began once the instabilities at the start of the calculation had disappeared and a periodic flow-field was obtained. For the LES at small \( P/Ds \), periodic pressure forces on the cylinders were not observed so averaging began once the lift signal had fluctuated several times around a clear mean value. Averaging over twenty complete cycles (or phases) then began.

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<th>Case</th>
<th>( L/D )</th>
<th>( L_y/D )</th>
<th>( N_y )</th>
<th>( N_z )</th>
<th>( N_{tot} )</th>
<th>( \Delta y^+ )</th>
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<td>EVM</td>
<td>( k, \varepsilon )</td>
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<tr>
<td>( k-\omega ) SST</td>
<td>Menter (1994)</td>
<td>EVM</td>
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<tr>
<td>( \phi-f )</td>
<td>Laurence et al. (2004)</td>
<td>EVM</td>
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<td>Speziale et al. (1991)</td>
<td>RSM</td>
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<td>✓</td>
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<tr>
<td>EB-RSM</td>
<td>Manceau &amp; Hanjalic (2002)</td>
<td>RSM</td>
<td>( r_p, \tau, \Phi )</td>
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Figure 2. LES of $P/D = 1.6$: Wall-adjacent cell size around central cylinder in wall units for Case 1.

Figure 3. LES of $P/D = 1.6$: Ratio of SGS to molecular viscosity, $\nu_{SGS}/\nu$ for Case 1 (left) and Case 4 (right).

Domain Size and Grid Sensitivity for LES

The study of the domain size and grid resolution for LES was limited to $P/D=1.6$. Five cases were simulated, see Table 2. The turbulent Reynolds number, $Re_t (= k/\epsilon \nu)$ was found from the precursor RANS to be around 1,200 over most of the domain. Figure 3 shows the ratio of sub-grid-scale to molecular viscosities for the standard and most refined cases. The volume-averaged values are about 10 for Case 1 and 6 for Case 4.

First, the spanwise domain width, $L_z$ was investigated using a domain size of $2 \times 2$ tubes. Benhamadouche (2005) had tested different spanwise domain widths up to 5 diameters for a square bank for $P/D=1.75$ at $Re=20,000$. He had concluded that 2 diameters were sufficient to obtain correct vortex shedding characteristics such as fluctuating lift and drag forces and Strouhal number. Here the domain width in the spanwise direction was limited to 2 (Case 1) and 3 diameters (Case 2) to confirm that the same still holds true for $P/D=1.6$. The predicted time- and space-averaged streamlines using spanwise domain lengths of 2 and 3 diameters, shown in Figure 4(a,b), are consistent with the findings of Benhamadouche. A larger domain size of $4 \times 4$ tubes in both the streamwise and cross-flow directions is then investigated (Case 5) using identical grid densities as for Case 1. Figure 4(c) shows only very small differences in the re-circulating vortices behind the cylinders, which justifies adoption of the smaller domain. Finally, the grid resolution along the tube is examined. Both Cases 3 & 4, using the finer grid ($N_z=130$) to cover the domain width of 2-diameters are presented in Figure 4(c, d). The two patterns are essentially the same. They both show a slightly larger vortex on the lower side of each cylinder than for Case 1 but the differences do not appear so great as to invalidate the use of the coarser mesh.

Effects of Pitch: Diameter Ratio

All the LES computations presented above displayed the same striking behaviour that, while the starting flow field was purely from left to right, the converged behaviour indicates that a slanting flow path through the tube bank is followed. In some runs the flow would slope upwards, in others downwards; but always the same angle for the mean flow path is indicated. The effects of changing $P/D$ was therefore examined, the results for the three cases considered being shown in Figures 5-7. It is seen that for $P/D$ of 2.0 the mean flow does pass smoothly through from left to right. The vortex shedding behind the tubes is more vigorous and there is also strong flow.
impingement at the front of each tube, which gives rise to higher levels of time-averaged turbulent kinetic energy. The interesting time variation of lift coefficient in Figure 6 reveals not only the nearly sinusoidal behaviour for this P/D but also suggests a low frequency amplitude modulation of the lift. Figure 7 shows that the computed variation of the pressure coefficient around the central tube is in excellent agreement with the experimental data of Batham (1973).

For the case of P/D=1.6 there is no regular vortex shedding; that is, a plot of turbulence energy spectra versus wave number shows no spike (West, 2012), a result consistent with the experimental study of Tsunoda et al (1996) who proposed that vortex shedding was suppressed for P/D smaller than 1.7. It is noted that the earlier Manchester LES study of Afgan (2007) found no asymmetric path for P/D=1.6. However, this is a value close to the transition from straight-through to diagonal flow and, with periodic boundary conditions, any slight error is recycled and possibly amplified. Afgan’s LES used a non-conforming, block-structured grid. Non-conforming meshes are known to be prone to numerical noise resulting in higher sub-grid-scale viscosity. Moreover, the present standard results employed roughly twice the number of cells as the earlier study. Indeed, the same flow pattern was seen when the very fine mesh of 10 million cells (Case 4) was used.

For P/D=1.4 the angle of the deflection of the mean streamline increases to approximately 40° above the horizontal (Figures 5 and 7). Vortex shedding, as such, is absent and the mean flow exhibits only small recirculating zones behind each cylinder. This diagonal flow path evidently offers the route of minimum pressure loss through the bank. The purely horizontal driving force balances drag only in that direction, yet there is obviously friction drag associated to the vertical component of the flow. This is compensated by the asymmetry of the circulation and pressure on the cylinder leading to non-zero lift.

![Figure 5. LES: Streamlines of the spanwise-averaged velocity field (top) and contour plots of the spanwise-averaged turbulent kinetic energy field (bottom) at different pitch-to-diameter ratios.](image)

![Figure 6. LES: Time-dependent lift coefficient.](image)

![Figure 7. LES: Spanwise-averaged static pressure coefficient around the central cylinder.](image)
URANS Predictions

The Unsteady, Reynolds-Averaged Navier-Stokes (URANS) approach has already been shown to produce reliable results for staggered tube banks (Benhamadouche & Laurence, 2003) which do not exhibit any cross-flow deviation. Here the pitch-to-diameter ratio of 1.6 was chosen to assess the performance of various RANS models, a choice which, it was felt, would pose a challenge for these schemes because, as noted above, LES performed by different authors have predicted different flow patterns. Both 2D and 3D computations have been made (West, 2012) but, while there were significant differences between the two, only the latter are reported here.

All RANS models run in 3D predict a periodic, vortex shedding behaviour. As seen from Figure 9 which compares the time-averaged mean streamlines for different models, all the schemes exhibit a straight-through behaviour except the k-ε EVM which shows a flow pattern very similar to that of the LES results. However, this apparently satisfactory behaviour is a consequence of two serious weaknesses with this approach: the use of a wall function with seriously limited validity and a turbulence model that adopts a linear stress-strain relationship. By chance, in this particular case, the resulting errors have proved to be self-cancelling. The SSG stress-transport closure which also employs wall functions, shows some evidence of asymmetry in the recirculating eddies and a slight migration of fluid upwards, but overall a straight-through flow is found. It is noted, however, that when this model is also constrained to 2D a diagonal flow pattern similar to the LES pattern is returned.

Pressure coefficient and Nusselt number comparisons for P/D=1.6: The resultant local pressure coefficient and Nusselt number generated by the URANS simulations are compared in Figure 10 with the LES and the experimental data of Aiba et al. (1982) obtained deep within their 7x4 tube bank. All the results except the LES and k-ε are very nearly symmetric about the 180° position as are, presumably, the experimental data (since although recorded over only half the circumference the pressure is nearly uniform near the rear stagnation point). None of the URANS computations track the measured or the LES variation over the cylinder accurately.

The Nusselt number shown in Figure 10b displays even greater variation from model to model. While the circumferentially averaged Nusselt number would in some cases be satisfactorily in accord with the data, the local distribution shown here reveals serious disagreements. The experimental data in general show less variation around the tube than the computations (including the LES results). However in the experiment the flow and consequently the thermal development, is influenced by the presence of side walls (only 1.5 tubes away from the measured tube), which are absent in the current periodic computations. This has been confirmed by subsequent

![Figure 9. URANS of P/D = 1.6: Mean streamlines through the tube-bank compared with LES behaviour.](image)

![Figure 10. URANS of P/D = 1.6: Pressure coefficient (top) and Nusselt number (bottom) variation around the central cylinder.](image)
LES calculations using the same confining horizontal walls as the experiment, showing much closer Nusselt number agreement (West, 2012).

Nevertheless it is impossible to conclude other than that the quality level of the URANS predictions is poor. Although the level is overall too low the best shape is achieved with the SSG stress-transport model.

CONCLUSIONS

The effect of the tube spacing on the flow around a periodic in-line tube-bank section has been investigated using wall-resolved LES. As the pitch-to-diameter ratio decreases the flow departs from a straight-through behavior, with the level of flow deviation increasing with decreasing \( P/D \).

These results clearly show that in closely-pitched tube banks with the assumption of flow periodicity (effectively without confining walls) the flow will seek the path of least resistance and prefer to travel in a diagonal manner. However, capturing the deviation from a straight-through behaviour requires high precision in the numerics and is equally difficult to imitate in experiments in arrays with just a small number of rows due to the confining effects of the walls. Much further LES data on the effects of confining walls have been generated (West, 2012) and will be externally published in the near future.

The attempts to mimic the LES flow pattern for \( P/D=1.6 \) with URANS computations have on the whole been disappointing. It is felt that where the rather simple wall functions employed in the solver have been used, that has contributed to the problem, especially regarding the attempts to predict local heat transfer rates. However, low-Re models where the integration extends up to the cylinder surface also experience problems. It is suggested that a renewed attempt to tackle this case and the somewhat simpler configuration with \( P/D=2.0 \) with modeling at a higher level than a linear eddy viscosity model and with more powerful wall functions (for example, Craft et al. 1994) will provide great insight into the overall capabilities of URANS schemes for tackling this important class of engineering flows.

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Authors’ names are sequenced alphabetically.

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