EXPERIMENTAL VALIDATION OF NUMERICAL ANALYSIS OF FLOW ACROSS TUBE BANKS FOR LAMINAR FLOW

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Introduction

There are numerous heat exchanger designs involving a bank of tubes in a fluid cross-flow. Depending on application and design criteria, there are many possible tube layouts in an array. A heat exchanger designer therefore needs to have a large data base available to assist in making the optimal choice among the different design options. Recently, due to rapid advances in computers, computational speed and memory capacity have increased drastically, and therefore numerical methods will become useful in the design of engineering devices as well as in experiments.

In previous numerical studies of tube banks,[1,2,6,14] numerical solutions were compared with experimental results for overall properties such as pressure drop and heat transfer coefficients to validate the numerical methods. The numerical solutions provide not only the overall properties, but also local properties such

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as surface pressure, shear stress and heat transfer coefficient distributions which are needed for studying the mechanisms of fluid and heat flow. However, the local properties have not been validated experimentally.

This has motivated the present investigation. To validate local flow properties in numerical solutions, we experimentally observed the fluid motion and measured the surface shear stress around a tube in the fully developed flow region of tube banks. Experiments have not been carried out previously, because experimental flow studies at low Reynolds numbers (O(100)) have been very few, except for a flow visualization study of an in-line array of four tube rows by Weaver and Abd-Rabbo.[13]

1. Numerical Analysis

The numerical method used here is based on that developed for pulsatile flow in a wavy-walled channel (Nishimura *et al.*[11,12]). Computations were carried out for Reynolds numbers up to 100.

We assume that the fluid motion is two-dimensional laminar steady flow, and is identical for each row in a tube array, i.e. periodically fully developed flow. The unsteady Navier-Stokes equations expressed in terms of the vorticity and the stream function were solved by the Galerkin finite-element method, because the time-marching method was used in the numerical calculation of the steady flow. Both staggered and in-line arrays with longitudinal and transverse pitch-to-diameter ratios of 2 were studied.

2. Experimental Apparatus and Procedure

The experimental apparatus was the same type of recirculating water tunnel as used in previous studies,[8,9] with rectangular duct 160 mm × 80 mm (height × width) as the test section. The acrylic cylinders comprising the array were oriented parallel to the principal walls of the test section, i.e. the upper and lower walls. In both staggered and in-line arrays, 11 rows of cylinders 15 mm in diameter were employed.

Flow visualizations were made by means of the aluminium dust method. Perfusion with a suspension of aluminium particles, about 40 μm in diameter, enabled us to observed path lines corresponding to streamlines because of steady fiow. An exposure time of 2 s was selected for aluminium particles to trace paths sufficiently long. Illumination was provided by a 500 W projector light source.

For measurements of surface shear stress, we employed an electrochemical probe. To the knowledge of the authors the results of this study are the only direct measurements of surface shear stress for laminar flow in tube banks, although Dimopoulos and Hanratty[3] used the electrochemical method to study velocity gradients around a single cylinder over a Reynolds number range of 60 to 360.

The technique of the electrochemical method is well described by Mizushina[7] and has been widely used for several flow fields.[5,10] The cathode used here is a platinum wire 0.5 mm in diameter set in the center of an acylic tube. Nickel-plated cylinders surrounding the test cylinder corresponding to the cathode were used for the anode.

3. Results and Discussion

The fluid motion was observed in the middle part of the tube banks, i.e. the 5th to 7th rows. Flow visualizations show that the flow changes from steady to unsteady state at about $Re = 100$ due to vortex shedding for both staggered and in-line arrays. Flow-visualization results for steady flow at $Re = 60$ are presented in **Fig. 1**. Flow-visualization photographs indicate that the fluid flow is periodically fully developed, confirming the spatial periodicity of flow.

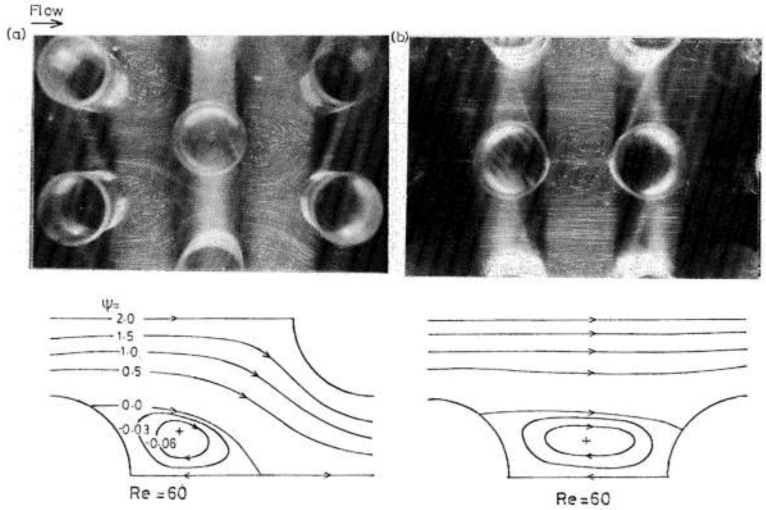

Fig. 1. Comparison of experimental and numerical streamline patterns at $Re = 60$. (a) staggered tube array (b) in-line tube array

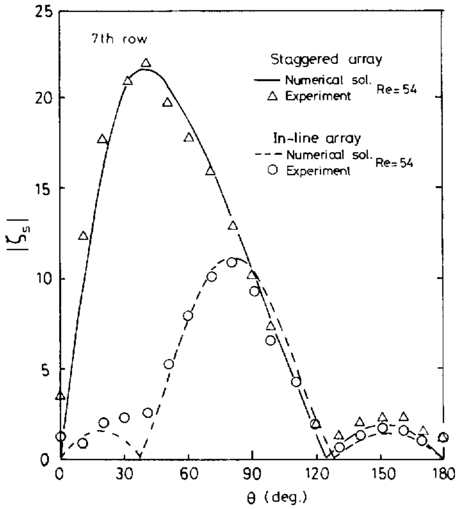

Fig. 2. Comparison of experimental and numerical surface shear stress distributions at $Re=54$ for staggered and in-line arrays

Experimental and computational results show good qualitative agreement in terms of streamlines and recirculation vortices for both staggered and in-line arrays as shown in Figs 1(a) and (b).

Figure 2 shows the experimental surface shear stresses at $Re=54$. Although the experimental data are slightly scattered, agreement with the computational results are very good for both staggered and in-line arrays. It is striking that a large difference in shear stress between the staggered and in-line arrays occurs at front part of the cylinder while the shear stresses at the rear part are almost identical. The difference at the front part appears to affect the heat transfer characteristics. That is, a staggered array has higher heat transfer coefficients than an in-line array as indicated by Zukauskas and Ulinskas.[15]

For the staggered array, the streamlines tend to move closer to the front part of the cylinder before being deflected sideways as shown in Fig. 1(a), which suggests the existence of a laminar boundary-layer flow. According to boundary layer theory, the dimensionless surface shear stress expressed by the surface vorticity ζ_s should be varied with the 0.5 power of the Reynolds number Re. **Figure 3** shows the result for numerical computations. It shows that a laminar boundary layer is formed at the front part of the cylinder at Reynolds nambers more than 30. The experimental result* shown in **Fig. 4** also indicates that the laminar boundary layer flow is maintained even for unsteady flow due to vortex shedding at high Reynolds numbers, despite the fact that the fluid motion is highly turbulent due to unsteady wakes of the preceding row of cylinders. This relationship was not recognized for the in-line array, which is not shown here due to limitations of space. The results for the in-line array can be found in the literature.[4]

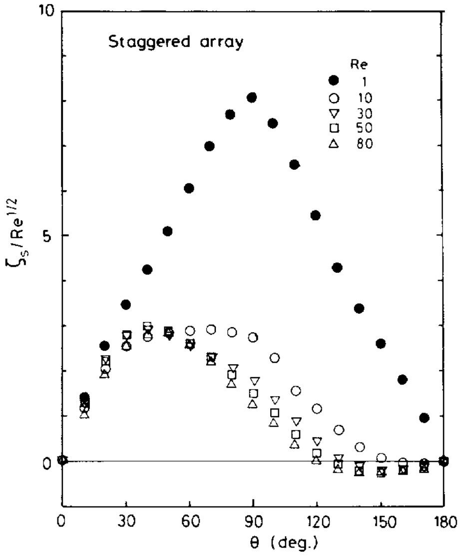

Fig. 3. Numerical surface shear stress distributions normalized by $Re^{1/2}$ for staggered tube array at low Reynolds numbers

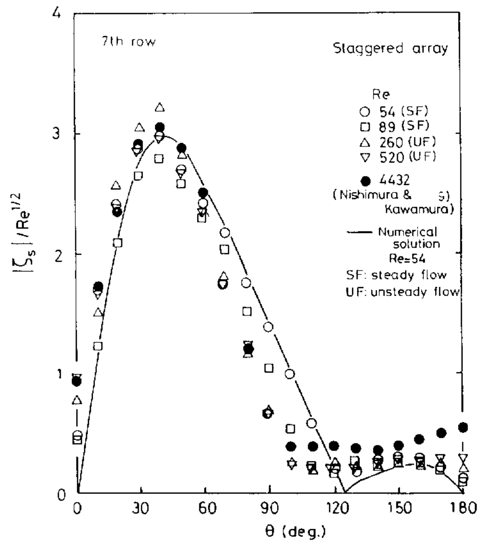

Fig. 4. Experimental surface shear stress distributions for staggered tube array at high Reynolds numbers

From the above numerical and experimental results, numerical computations are confirmed to be useful during design of heat exchangers under steady laminar-flow conditions, although they are still difficult to use in predicting the transition from steady to unsteady flow at the present time. The numerical computation of transitional and turbulent flows in passages with a complex geometry is left for future work.

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* Since the shear stress is proportional to the electrode diameter raised to the -5 power, it is necessary to accurately determine the electrode diameter. However, inevitable errors occur in measurement of the electrode diameter and thus the experimental uncertainty of the shear stress seems to be 10 to 15%.

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Nomenclature

B = surface velocity gradient [1/s]
D = cylinder diameter [m]
Re = Reynolds number $(=U_iD/\nu)$ [—]
U_i = average inlet velocity of a tube bank [m/s]

ζ_s = dimensionless surface shear stress $(=BD/(2U_i))$ [—]
θ = angle in cylindrical coordinates [deg]
ν = kinematic viscosity of fluid [m^2/s]
Ψ = dimensionless stream function [—]

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