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REVIEW OF FLOW DYNAMICS OF VARIOUS FLUIDS FROM TUBE BANKS GEOMETRIES

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Abstract- **This review paper is focused on the works available for the flow of fluids over tube banks in various geometrical arrangements. A quick examination of literature reveals that most of the investigations from such an industrially important geometry has been done numerically and scant works are reported experimentally. The local and global features of fluids such as streamlines and isotherm patterns, drag forces and heat transfer phenomena, etc. has been described for both numerical and experimental studies using various ranges of engineering parameters. This paper also discloses the various gaps available in the literature to investigate and explore for the better understandings of the flow dynamics of tube banks geometries.**

Keywords – Cylinders, periodic flow, drag coefficients, streamlines, isotherms

I. INTRODUCTION

The transport phenomena of fluids over tube banks is a broad area of research today because of its numerous applications in heat and mass transfer equipment, filtration, polymer processing, porous media flow and foods and biological industries, etc. [1-2]. It is evident from the flow geometries of tube banks that the kind of flows which occurs are periodic in nature i.e. it repeats over the tube banks of certain length so called the periodic length. Such a process simplifies the problems to be solved numerically and experimentally as well so that the local and global characteristics of fluids can be investigated. Because, the above flows are found frequently in many industrial processes (e.g. flow of process stream in shell side of tubular heat exchangers, screens used to filter polymer melts and fluidized bed drying of fibrous materials, etc.), it has received great attention over the years [3-4]. In view of above, relevant available literature has been reviewed the following section.

II. AVALAIBLE WORKS FOR FLOW OVER TUBE BANKS

The available literature suggests that the most of the research is concerned with flow in porous media and tube bundles, perhaps the quantitative nature of flow in high porosity cylinder arrays is still a new area of research [5]. The triangular, square, rectangular and hexagonal array of cylinders are the main geometrical arrangements for the flow over tube banks which has been considered in the investigations [1-7]. Moreover, many dimensionless parameters such as Reynolds, Prandtl and Richardson numbers, fluid volume fractions, porosity/voidages of cylinders and permeability, etc. have been used in various ranges to display the numerous characteristics of the fluids investigated. Notwithstanding, the flow dynamics from such an industrially important geometries have attracted the great attention of researchers over the years, for instance, see Launder and Massey (1978) [8]. If the cylinders are arranged in square or hexagonal array, the method of Rayleigh (1892) [9] can be successfully applied to determine solution of linear set of algebraic equations. Exploiting the above information, numerous investigations have been made to understand the flow dynamics across the tube banks. For instance, steady and slow flow of an

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incompressible viscous fluid across a square and hexagonal array of cylinders have been studied [5] numerically for the solution of model equations. It has been shown that the drag on a cylinder as a function of the volume fraction of the cylinders. Subsequently, the laminar viscous flow through regular arrays of cylinders in various geometrical arrangements was studied [2] for square, rectangular, triangular and hexagonal array of cylinders. The results show that the drags for the transverse flow is twice of the drag for longitudinal flow. Further, McPhedran (1986) [10] investigated the transport properties of cylinder pairs and of the square array of the cylinders. They have evaluated the drag coefficients for a perfectly conducting cylinder pair separated by unit potential difference using Greens theorem. The flow through fibrous media and tube bundles has been reviewed by Zukaukas (1987) [4]. He noted that the quantitative nature of flow in high porosity cylinder arrays (treating cylinder arrays as porous media) is still question of concern. Likewise, Singh et al. (1989) [11] investigated the stability of periodic arrays of cylinders across the flow stream by direct simulation for a horizontal array of infinitely long cylinders spaced periodically under the steady flow conditions (Re≤ 100). Further, Edward et al. (1990) [12] calculated the flow field within spatially periodic arrays of cylinders arranged in square and hexagonal lattices at higher Reynolds numbers (0 to 200). They emphasized on low porosity of cylinders less than 0.8. Similarly, Chmielewski et al. (1990) [13] investigated the cross flow of elastic liquid through arrays of cylinders (triangular and rectangular array of cylinders) for the low Reynolds numbers (Re< 0.1). Georgiou et al. (1991) [14] studied the Newtonian and non-Newtonian flow in a channel obstructed by an antisymmetric array of cylinders and concluded that the tortuous geometry and rheology combine to produce significant viscoelastic effects with regard to both the flow field and resistance to flow. Subsequent study by Astrom et al. [3] presents the Newtonian flow through aligned fiber beds to develop the relationship in between the flow rate and pressure drop for the purpose of the composite processing. Further, Bruschke and Advani (1993) [15] examined the flow of generalized Newtonian fluids across a periodic array of cylinders in which the capillary model has been used to describe the permeability-porosity relationship for porous media. A scaling is suggested which allows to separate the effect of the fluid rheology and porosity on the resistance to flow. It is clear that all the above-mentioned studies are emphasized on low porosity and slow flow region.

Besides, further studies are focused on high porosities and medium to high inertial regions. For instance, the numerical simulations of forced convective incompressible flow through porous media has been presented by Amiri and Vafai (1994) [16] to investigate the various transport properties. Subsequently, Nagelhout et al. (1995) [17] have studied the permeability for flow normal to a sparse array of fibers which are visualized as circular cylinders arranged in square array. This study confirms the validity of the assumption of steady flow at very high-volume fraction (as high as 0.99) of liquid in a square array at Reynolds number up to 40. Furthermore, Donald and Anthony (1997) [18] investigated the effects of fluid inertia on the pressure drop and on the magnitude of drag coefficients for Reynolds number up to 180. Their results for low Reynolds number (Re<<1) are consistent with that Sangani and Acrivos [5]. It can clearly be seen from the literature that none of the previous studies have explored the effects of periodicity on the heat transfer characteristics on the cylinder array. Though, Martin et al. (1998) [1] aimed to fulfill this gap and investigated the frictional losses and convective heat transfer in laminar cross flow for the sparse, periodic cylinder arrays in square and triangular pitch arrangement with fluid fractions ranging from 0.80-0.99 and particle Reynolds numbers in the range of 3-160. They found that the frictional losses follow the Darcy's law when the Darcian Reynolds number is of the order of one while significant non-Darcian effects are seen at higher Reynolds numbers. Subsequently, Bartoli et al. [19] have experimentally investigated the heat transfer from three cylindrical heaters to a water jet. The presented their results in the form of closure relations to delineate the dependency of Nusselt number (Nu) on the Reynolds (Re), Prandtl (Pr) and Grashof (Gr) numbers. Moreover, Vijaysri et al. (1999) [20] have studied the steady flow of power law fluid across an array of long circular cylinder by solving continuity and momentum equations using the finite difference method. The hydrodynamics of porous media is approximated by zero vorticity cell model to present the gross fluid dynamic parameters in terms of friction and pressure drag coefficients. Spelt et al. (2001) [21] have presented the numerical simulations of power law fluids through periodic arrays of aligned cylinders for both creeping flow and flow with finite inertia. It has been shown that despite the strong non-linearity of the equations of motion, the results for the drag coefficient can be explained with simple scaling arguments. Simultaneously, Shibu et al. (2001) [22] predicted the drag on cylinder for the range of 1≤Re≤500; 1≥ n ≥0.5 and cylinder voidages of 0.4 and 0.5. It is noticed that the resistance to flow for shear thinning fluid is reduced for the flow of a Newtonian fluid under identical conditions. Next, Alococer and Singh (2002) [23] have numerically investigated the motion of viscoelastic liquid passing through two-dimensional periodic arrays of cylindrical particles using the finite element method. They have shown that the permeability and viscoelastic stress distribution is a function of dimensionless relaxation time and wave number. In parallel works, Arora et al. (2002) [24] experimentally examined the purely inelastic instabilities in periodic arrays of closely spaced cylinders (PAC). The test geometries have the same wavelength and amplitude associated with the periodic variation in the cross-sectional area. Their pressure measurement shows temporal fluctuations that appear when Weisenberg number exceeds approximately 0.7 and 1.1 for PC and PAC geometries, respectively. Woods et al. (2003) [25] explored the creeping flows of power law fluids through periodic elliptical cylinders based on the numerical simulations and lubrication theory. The apparent permeability values obtain for on-axis flows of power-law fluids are shown to obey a simple scaling, which relates the apparent permeability tensor for power-law fluids to the corresponding permeability for Newtonian fluids. They summarized their results in the form of closure relations for the apparent permeability tensor and velocity variances for off-axis flows of power-law fluids through arrays of elliptical cylinders for a range of aspect ratios using look-up graphs for only a few scalars.

Subsequent investigation of Spelt et al.(2005a) [6] explored the flow of inelastic non-Newtonian fluids through arrays of aligned cylinders for creeping flow. Similar to Woods et al. [25], the numerical results have been presented along with the lubrication theories for the flow of truncated power law fluids through square and hexagonal arrays. The strong dependence steady state drag coefficient on the power law index was shown to be caused by the choice of velocity and length scale in the definition of the drag coefficient which is useful for understanding of other inelastic non-Newtonian fluid flow. Further, Spelt et al. (2005b) [7] continued his work to investigate the flow of inelastic non-Newtonian fluids through arrays of aligned cylinders for inertial effects for square arrays. Also, the local heat transfer and fluid flow conditions based on drag coefficients (C_D) and Stanton number have been studied by Hovart et al. 2006 [26]. They concluded that the drag coefficients and Stanton number monotonically decreases with increase in Re. Gamrat et al. (2008) [27] studied the heat transfer phenomena over banks of square rods in aligned and staggered arrangement with porosity in the range of 0.44-0.88 and focused on low Re flow (0.05-40). They primarily focused on the thermal equilibrium in a porous medium. It was shown that the heat transfer in the array of rods was insensitive to the highest values of Reynolds and Prandtl numbers and lowest values of Nusselt number. Further, Tamayol and Bahrami (2009) [28] have presented the viscous permeability of fibrous porous media. Due to random nature of porous microstructures, determination of exact permeability of real fibrous media is impossible, however, it agrees well with the experimental data for the ordered unit. Additionally, Geoffrey et al. (2010) [29] have experimentally investigated the flow of worm-like micelle solutions through a periodic array of cylinders. By systematically varying the Deborah number, the flow kinematics, stability and pressure drop were measured. The pressure drop was found to decrease initially due to the shear thinning of the test fluid, and then exhibit a dramatic upturn as other elastic effects begin to dominate.

Moreover, many investigations has been done to display the various features such as permeability, effective viscosity, stability, inelastic instabilities, pressure drop, etc. [30-40]. For instance, Yazdchi et al. (2011) [30] used finite element model to predict the permeability in the viscous incompressible flow through a regular array of cylinders/ fibers array. Their results show that the immobile circle and ellipses have lowest and highest permeability respectively. Subsequently, Quesada and Ellero (2012) [31] presented the numerical study of flow of a viscoelastic liquid around a linear array of cylinders confined in a channel. The dimensionless drag force acting on the cylinder is observed to be in good agreement for a wide range of Weissenberg number up to 1.5. Likewise, James et al. (2012) [39] has studied the slow flow of Bogger fluids through fibrous porous media which employs square array of parallel cylinders for the solid volume fractions of 2.5%, 5% and 10% and Reynolds number less than 0.1. Measurements were made with glycerol /water mixture to establish an inelastic baseline for the Deborah number in the range of 0.5-4. Recently, Gillissen (2013) [40] investigated viscoelastic polymer solution flow simulations through a periodic, hexagonal array of cylinders. The simulated, non-monotonic behavior of the effective viscosity as a function of the Weissenberg number (We) is in qualitative agreement with experiments.

Similarly, Tahseen et al. (2013) [41] have studied flow of fluids over the staggered geometry of circular cylinders to analyze the thermal features in the range; 25 ≤ Re ≤ 250, pitch to diameter ratio of 1.25, 1.5, 2 and at a Prandtl number of 0.71. The velocity and temperature fields, Nusselt numbers, etc. have been assessed. Further, Fornarelli et al. (2015) [42] utilized 6 in-line circular cylinders to observe the flow and heat transfer for Reynolds and Prandtl numbers of 100 and 0.7(air), respectively and cylinder spacing of L/D = 3.6 and 4. A transitions were seen for both of the momentum and heat transfer. Afterward, Crowdy (2016) [43] examined the flow across a periodic array of cylinders. A new transform technique and solutions are presented using set of coefficients of suitable linear systems. Then, Mangrulkar et al. (2017) [44] studied the flow dynamics and thermal natures for cross-flow in the tube banks in the staggered arrangementwith splitter plate for the high Reynolds numbers upto 14500. Using splitter plate improves the heat transfer and decreases the pressure drop than the bare cylinders. Additionally, Kumar and Jayadev (2017) [45] studied the flow and heat transfer features over circular tubes in cross-flow. They observed three different flow shedding by changing the flow rate and blockage ratios. Besides, many studies of tube bundles have used the different cell models such as cell vorticity and free cell models to assess the drag coefficients and local and average Nusselt numbers etc. [46-49].

In summary, the critical review of the available literature for flow over tube banks in various arrangements reveal that the momentum and heat transfer characteristics are explored for the various ranges of flow and heat transfer governing parameters. Limited results have also been presented for the power-law fluids, bogger fluids and polymeric and viscoelastic fluid. It is also be highlighted here that the non-Newtonian flow-based study have utilized the approximated geometrical models such as cell vorticity models in addition to whole computational domain. In fact, the literature accounts for the detailed insights of the global engineering parameters such as the drag coefficient (C_D), pressure loss, permeability (K), Nusselt number (Nu), etc. but they are limited to creeping flow, laminar flow and low porosity of the cylinders.

III. CONCLUSIONS

Based on the critical review, it has been concluded that most of the available studies are concentrated on Newtonian fluids as compared to non-Newtonian fluids to reveal the various characteristics using tube banks geometries. Further, these studies have used mostly steady state and two-dimensional flow in in-line array of cylinders. Therefore, its appropriate to mention herein that this literature review suggest various gaps to study further to gain more insights of flow kinematics. Some of the areas which could be the future scope of research work may be the various types of cylinder arrangements like triangular, rectangular, hexagonal with in-line or staggered configurations for high to low fluid volume fractions or the porosity of the cylinders. The steady and unsteady flow conditions in 2-D and 3-D using varieties of fluids can also be considered. So, it depends on the investigator or the researcher that what kind of combination he chose to investigate. Overall, a rigorous research works are needed to know the flow dynamics of fluids over the tube banks.

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