INVESTIGATON OF FLOW STRUCTURE IN A PLATE FIN AND TUBE HEAT EXCHANGER MODEL COMPOSED OF SINGLE SLOTTED-CYLINDER

*Slotlu Silindir Modeli Isı Eşanjöründe Akış Yapısının İncelenmesi **

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ABSTRACT

The aim of this experimental study is to determine the flow characteristics of a single slotted-staggered cylinder placed in a rectangular water channel with a narrow gap using the Particle Image Velocimetry technique. Qualitative flow visualization was initially employed in order to observe the overall nature of the vortical flow patterns of single slotted-cylinder. Quantitative flow visualization was secondly employed for the same slotted-cylinder in order to understand the physics of complex flow behaviour that gives rise to unsteady loading with the eventual intent of implementing control schemes to enchance the rate of heat transfer hydrodynamically.

Key Words: Confined flow, vorticity, slotted-cylinders,

ÖZET

Bu çalışmanın amacı, dikdörtgen kesitli sığ kanal içerisine yerleştirilmiş slotlu bir silindir etrafındaki akış karakteristiklerini Parçacık Görüntülemeli Hız Tekniği ile deneysel olarak hesaplamaktır. Başlangıçta slotlu bir silindir etrafındaki doğal akış girdap parametrelerini baştanbaşa nitel olarak gözlemlemek amacıyla boya deneyi yapılmıştır. İkinci olarakta hidrodinamik açıdan ısı transferi miktarını artırma amaçlı daimi olmayan akış kontrol uygulamalarındaki kompleks akış davranışının fiziğini anlamak için PIV ile akış yapısı nicel olarak incelenmiştir.

Anahtar Kelimeler: Sınırlandırılmış akış, girdap, oyuklu silindir

Introduction

A large amount of work has been devoted to the study of the flow around bluff bodies which have different geometries but especially circular cylinders. Bluff body is a widely studied subject since Strouhal (1878) observed vortex shedding from a circular cylinder. So far most of works were carried out on the cylinders having circular, square and rectangular cross-section, but the flow around circular cylinders remains the principal subject of researchers because, despite the geometric simplicity, the mechanisms involved are complex and the flow patterns are not easy to understand, especially for large Reynolds numbers and when control processes are implemented. Flow around circular cylinders has practical significance in many branches of engineering such as design and analysis of flows past tall towers, chimneys, bridge piers, heat exchangers and offshore structures.

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Therefore, investigation of flow characteristic is so important. Nowadays, flow configuration still presents one of the challenging subject to study in fluid mechanics, such aspects as aerodynamic forces, vortex shedding phenomena, instantaneous pressure field, governing the wake formation and its downstream evolution etc**.** Besides energy is an important subject in the world because energy shortage will rise in all areas in the near future. For that reason, all countries around the world try to investigate alternative energy sources and also work on the energy saving technologies. As it is known heat exchanger is one of the devices that can be developed further in the energy saving aspects and is used in a wide variety of industrial, thermal, commercial and household applications. So heat transfer problem and the efficiency in the heat exchanger are strongly depended on the flow structure. Plate fin and tube heat exchangers are most commonly used in space heating and cooling devices and in heat recovery systems. Due to the complex flow geometry, in recent years, most of the research work performed on the fin-tube heat exchanger is numerical. In the present work, flow structure in the flow passage of the fin-tube type heat exchanger has been studied experimentally both by dye visualization and using particle image velocimetry technique in order to examine the influence of flow structure on the performance of the heat exchangers.

Typical geometrical parameters of a plate fin and tube heat exchanger are illustrated in Figure 1 where d is tube diameter, s is distance between lower and upper fin plates, l_c is distance measured from the leading edge of the fin plate to the center of the tube, l_f is fin length, w is fin width, l_{x1} is distance between the leading edge of the plate and the inlet of the heat exchanger flow passage, l_{x2} is distance between the trailing edge of the plate and the outlet of the heat exchanger flow passage.

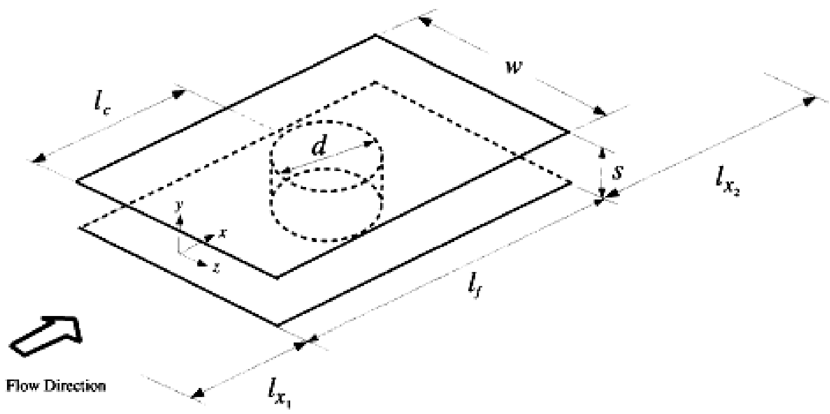

Figure 1. Geometrical parameters of a typical plate fin and tube heat exchanger (Mendez et al., 2000)

Due to importance of flow structure, many researchers performed either numerical and/or experimental studies to determine flow characteristics around circular cylinder. Anagnostopoulos (1997) studied the laminar vortex shedding behind a circular cylinder using the finite element method. Persillion and Braza (1998) studied physical analysis of the transition to turbulent flow in the wake region of a circular cylinder using three-dimensional numerical simulation of the Navier-Stokes equations. Akıllı et al. (2008) investigated experimentally passive control of vortex shedding behind a circular cylinder by splitter plates of various lengths attached on the cylinder base in shallow water flow. Sumer et al. (1997) conducted experiments to determine the flow around the base of a vertical wall-mounted cylinder. Sahin et al. (2009) investigated the flow behaviour at the junction of cylinder and base plate in deep water by using the PIV method experimentally for different Reynolds numbers. Ozturk et al (2009) performed PIV measurements in order to find out the flow characteristics downstream of a circular cylinder mounted on a flat surface for Re_d =4000 and 7000. Muzzammil and Gangadariah (2003) investigated the characteristics of the primary horseshoe vortex on the plane of the symmetry in front of a circular cylinder. Pattenden et al. (2005) performed PIV experiments to visualize flow details on different planes and examined the location and motion of the horseshoe vortex system in front of the cylinder mounted on a ground plane. Fu and Rockwell (2005) studied horseshoe vortex system in shallow water in case of laminar flow. Mendez et al. (2000) examined effect of fin spacing on a single cylinder heat exchanger with plain fin configuration. Sahin et al (2006) investigated the flow structure in a plate fin and tube heat exchanger model composed of single cylinder by using PIV method. Sahin et al (2008) investigated the horseshoe vortex in a rectangular duct with a narrow gap which is designed to simulate a fin-tube heat exchanger containing a single circular cylinder for Re_d=1500 and 6150 experimentally by using the PIV method. Akilli and Rockwell (2002) investigated the vortex formation in the base of a vertical cylinder in shallow water flow using a combination of flow visualization and PIV techniques.

Material and Method

In this study, flow characteristics around a circular slotted-cylinder has been investigated experimentally. Both dye visualization and the PIV experiments were employed at Mechanical Engineering Department of Cukurova University, in the Fluid Dynamics Research Laboratory. Firstly, qualitative flow visualization was employed during the initial scope of experiments in order to determine the overall flow patterns for a circular cylinder of 50 mm diameter and a circular slotted-cylinder of 50 mm diameter with 5 mm slot's width mounted over a flat plate and also located between two parallel plates. Secondly in order to determine the instantaneous velocity fields around the surface mounted cylinder in the heat exchanger flow passages, high-image-density Particle Image Velocimetry (PIV) technique was employed. The Laser Doppler Velocity and hot wire velocity measuring devices can only measure once at a single point. It is not possible to perform measurements at multiple points. The use of PIV technique is very famous in modern fluid mechanics, because it helps to understand unsteady flow phenomena by scanning technique over a certain area of flow field. In this study two different geometries were taken and experiments carried out. These arrangements are single completed cylinder and single slotted-cylinder in a narrow gaped rectangular duct respectively as seen figure 2. and figure 3. The cylinder height (Gap) is h=20mm and the experiments were only carried out for the ratio of B/D=0.1 where D is diameter of the cylinder and B is the width of the slot along in the centerline of the cylinder. During the experiments, Reynolds numbers were changed between 1500 and 4000 at the same elevation of h_l/h_w=0.1.In both of test geometries the cylinders and the plates are made from Plexiglas material so that the laser light propagates easily. The dimensions of the base plate are 1000mm x 400mm x 10mm. Before the image processing, all the spurious vectors are detected and removed using Cleanvec software and then the digital images were improved and smoothed by neighborhood averaging technique.

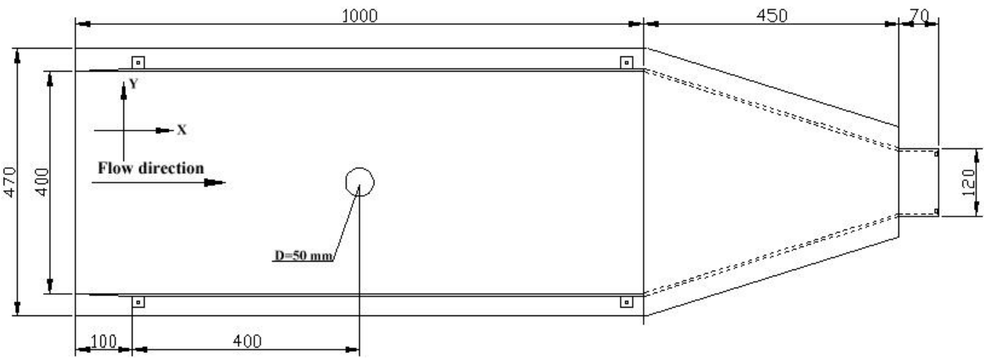

Figure 2.Test geometry of single cylinder, location of measuring planes in plan view plane (Dimensions in mm).

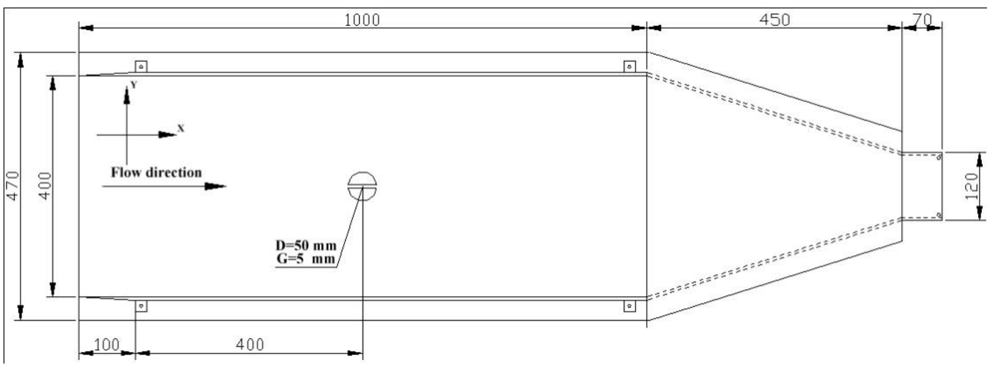

Figure 3. Test geometry of single slotted-cylinder, location of measuring planes in plan view plane (Dimensions in mm).

Particle Image Velocimetry (PIV) is a non-intrusive measurement technique used to simultaneously determine the velocities at many points in a fluid flow. The technique involves seeding the flow field, illuminating the region under investigation and capturing two images of that region in rapid succession. From the displacement of the tracer particles, provided that the time interval between image captures is known, a velocity vector map can be calculated in the flow field. Basic PIV analysis process is shown in figure 4.

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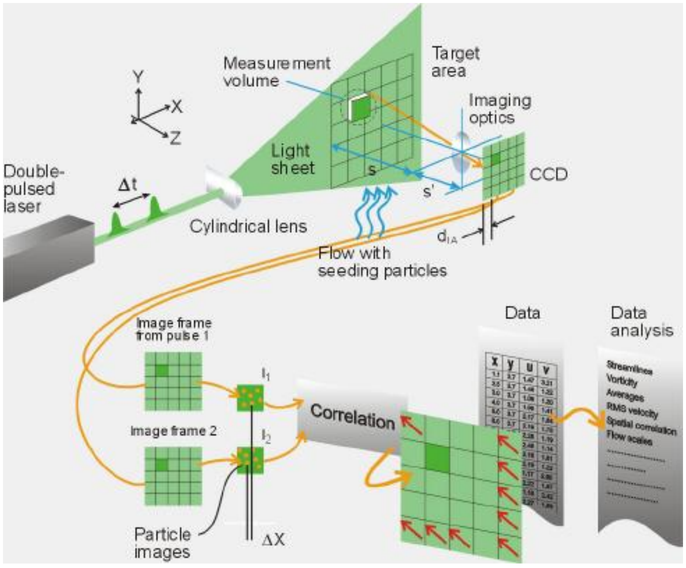

Figure 4. Basic PIV analysis process

Results and Discussion

The objective of the present work is to perform qualitative and quantitative flow studies in plan-view laser planes for a circular cylinder and a circular slotted-cylinder which are mounted on a bottom plate in the rectangular narrow gaped duct. for the purpose of revealing the structure of the flow details using instantaneous and time-averaged flow data. In figure 5. a well-seen saddle point occurs upstream of the cylinder surface. The region between the circumferential flow emanating from the saddle point and the surface of the cylinder involves upstream flow, which is associated with the horseshoe vortex in that region. Spiraling horseshoe vortex on both side of the cylinder moves further downstream along the wake region. Almost a distance of one D starting from rear surface of the cylinder, between horseshoe vortices and shedding vortices interactions take place. These interactions increase the turbulence intensity of the flow to a higher level. The wake region downstream of the cylinder enlarges in the free-stream flow direction randomly. In other words, merging points of shedding vortices move forward and backward in the main flow direction. On the other hand horseshoe vortices on both sides of the cylinder wonder in the lateral direction giving rise the entrainment between wake flow and core flow regions. Along the shear layers Kelvin-Helmholtz vortices are developed predominantly. After merging of shear layers downstream of wake flow region Von Karman vortices occur.

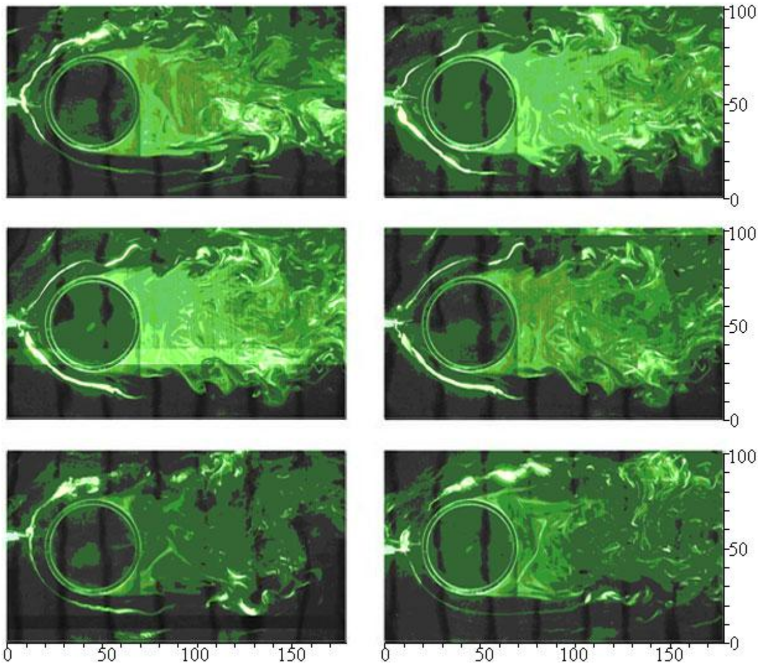

Figure 5. Instantaneous dye visualization of single cylinder for Re_d =1500, h_l/h_w=0.1

Dye visualization of the present work reveals that having slot at the center of the cylinder activates the wake flow region to the higher value. For example, the jet flow which is caused by slots goes through the center of the wake flow regions as seen in figure 6. This jet flow moves side to side in quasi periodic regime. This movement of jet flow increases the entrainment of the main flow across the shear layer and this entrainment is expected to increase the rate of heat transfer in the cases of heat exchanger. Primary horseshoe vortex system moves further close to the slotted-cylinder due to the suction of the flow by this slot and hence the level of interactions between horseshoe and shedding vortices increase. Because of this high level of interactions put the entrainment between main and wake flows to upper level.

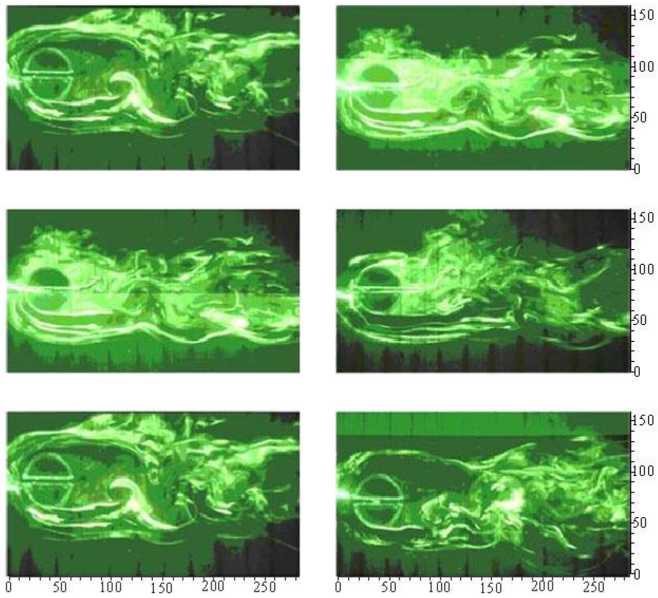

Figure 6. Instantaneous dye visualization of a single slotted-cylinder for Re_d =1500, h_l/h_w=0.1

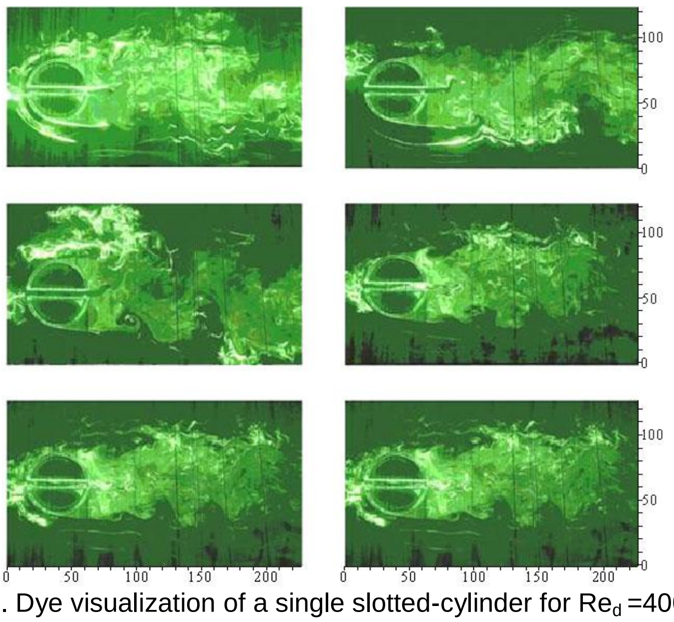

Figure 7. Dye visualization of a single slotted-cylinder for Re_d =4000, h_l/h_w=0.1

Examine of figure 6 and 7 reveals that having 5 mm slot at central line of the circular cylinder vortical flow behavior around the slotted-cylinder is completely changed. For example, the saddle point in the upstream region of the slotted-cylinder move close to the forward face of the cylinder for both cases of Reynolds numbers. Furthermore, horseshoe vortices travels in the free stream flow direction close to the outer surface of the shedding vortices. Having flow jet through the slot a wake flow region of the cylinder is further activated.

Figure 8, shows the time-averaged velocity vector map, $<V>$ time-averaged vorticity contours, $<\omega>$ and time-averaged contours of Reynolds stress correlations, $<u'v'/U^2>$ at elevation of $h_l/h_w=0.1$, for $Re_d=1500$ and $Re_d=4000$. Regarding the exit region of the slot at the first row of this figure, patterns of velocity vectors show the transformation from the slot flow to the free jet. The influence of the jet from the slot on the flow in the base region becomes apparent, as it induces two recirculation cells. The size of the wake region is obtained wider and two symmetric vortices rotating in opposite direction are clearly seen in both cases of Re_d =1500 and 4000. It seems that velocity vectors in the exit region of the slot is higher comparing to the case of a single cylinder without slot. This flow behavior can increase the heat transfer rate hydrodynamically.

The second row of this figure demonstrates the time-averaged vorticity contours, $<\omega>$ at elevation of $h_l/h_w=0.1$ above the base of the cylinder. Regarding the exit region of the slot, patterns of time-averaged vorticity show the transformation from the slot flow to the free jet. It is clearly seen that the vorticity layers beginning from the slot entrance are convecting in the flow direction in the shear layer. It is observed that the vorticity layers are symmetric with each other according to the plane of symmetry of the cylinder. Vorticity contours are seen nearly parallel with only mild deflections towards the wake centerline. A pair of vortices is developed at the wake region due to the jet flow emanating from the slot. Well defined shedding vortices along the shear layer moves further downstream in the free-stream flow direction a companying with horseshoe vortices. A well defined positive and negative cluster of vortices occur at exit of the slot. It prevails that the jet flow emanating from the slot activates the wake flow region.

The third row of this figure shows contours of constant Reynolds stress $<u'v'/U^2>$ in the near-wake region at an elevation of $h_l/h_w=0.1$ as seen that the peak values of Reynolds stress correlations, $<u'v'/U^2>$ are evident, regarding magnitudes of the Reynolds stresses at the bed. It is obvious that the unsteadiness associated with the developing jet emanating from the slot does not locally enhance the Reynolds stresses for Re=1500. On the other hand, it is evident that for Re=4000, momentum of the jet flow has a significantly large magnitude and therefore locally higher values of $<u'v'/U^2>$ are attainable in the region of jet formation. On the shoulder of the cylinder a small size cluster of the Reynolds stress correlations occur for the case of Reynolds numbers Red=4000 due to the existence of horseshoe vortices around the slotted-cylinder. However, the peak values of Reynolds stress correlation, $<u'v'/U^2>$ occur along the shear layer. In addition, jet flows emanating from the slot of the cylinder cause positive and negative clusters of Reynolds stress correlations **<**u'v'/U^2**>** at a location a distance of a half diameter far from the rear surface of the cylinder in the downstream region.

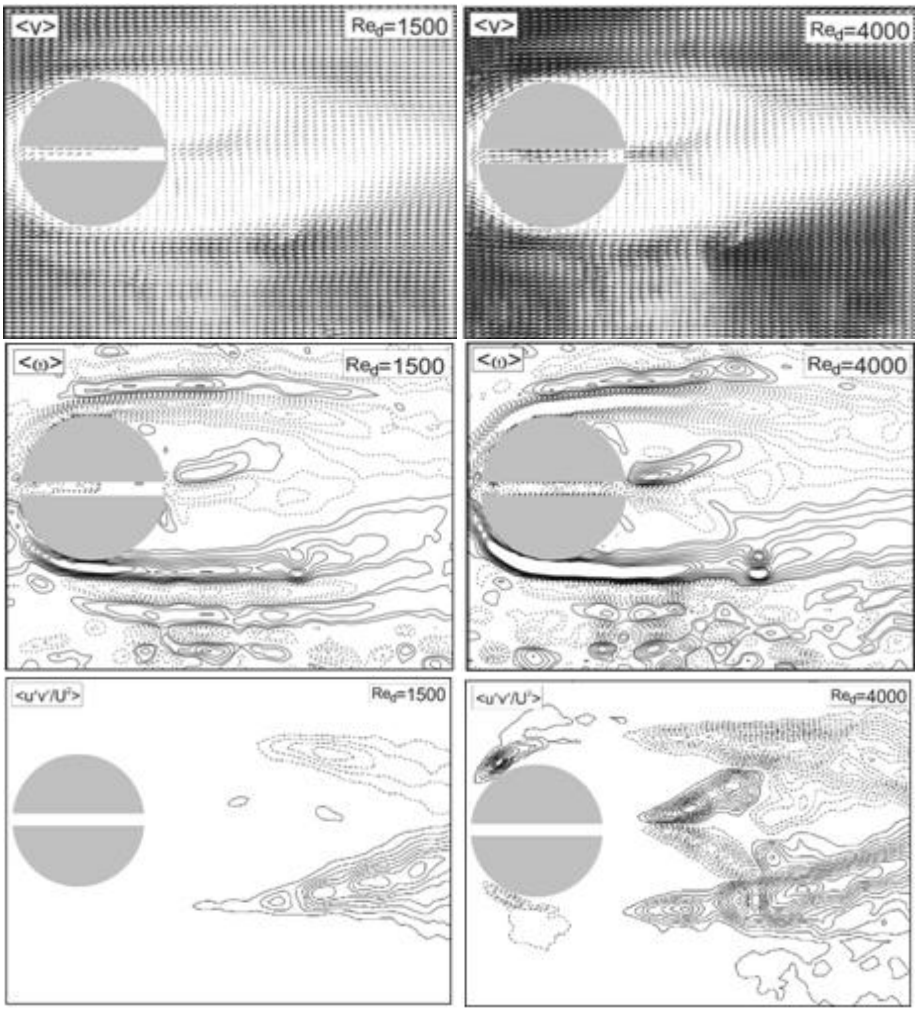

Figure 8. Time-averaged velocity vector map, <V>, time-averaged vorticity contours, <ω>, ω_{min}=±0.5 s^{-1} and $\Delta\omega$=1 s^{-1},time-averaged contours of Reynolds stress correlations, **<**u'v'/U^2**>,** minimum and incremental values of Reynolds stress correlation are **<**u'v'/U^2**>**$_{min}$ =±0.005 and Δ **<**u'v'/U^2**>** = 0.005 in wake flow of single slotted-cylinder for h_l/h_w=0.1, Re_d =1500 and 4000,

Conclusions

It is concluded that, heat transfer efficiency around the cylinders in the heat exchanger flow passages is strongly related to the flow structure and hydrodynamics. A deeper physical understanding of local flow structure in the heat exchanger flow passage is very important for design and optimization purposes. Therefore in the present study the physics of the flow and the horseshoe vortex mechanism were investigated in detail using time-averaged, instantaneous, and phase averaged flow statistics obtained by the Particle Image Velocimetry (PIV) technique.

The slotted-cylinder significantly change the flow characteristics in downstream directions. The slot width has an effect on the flow characteristics. The peak value of Reynolds shear stress concentration decreases due to slot width. Following conclusions can be derived from the overall experimental studies. A test model geometry comprised of slotted-cylinders surrounded by a fin plate configuration can be considered in the context of optimization and design of plate fin and tube heat exchangers. Tube arrangement with slot, fin configuration and Reynolds number are important governing design parameters for the plate fin and tube heat exchangers.The heat transfer rate increases with an increase of the Reynolds number.Slotted-cylinder arrangements enhance the heat transfer rate hydrodynamically, even in wake-flow region compared to the arrangement of cylinders without slot.The magnitude of the pressure drop along the tube surface in the slotted- cylinder arrangement is found to be lower comparing cylinder arrangement without slot.The size of the wake region differs slightly depending on the Reynolds number for single slotted-cylinder as the Reynolds number is increased, the size of the wake region becomes smaller. The positive and the negative vorticity layers are approximately equal and symmetric with each in both case of Re_d =1500 and Re_d =4000

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