



Flow visualization study at the interface of alternating pitch tube bundles in a model helical coil steam generator using particle image velocimetry

M. Delgado^{a,*}, S. Lee^a, Y.A. Hassan^{a,b}, N.K. Anand^b

^a Department of Nuclear Engineering, Texas A&M University, College Station, TX 77843, USA

^b Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843, USA

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ABSTRACT

A simplified Helical Coil Steam Generator (HCSG) model was constructed to study the flow on the shell side of rod bundles that coil against one another, using a 12-degree single rod bundle interface. The test section maintained a transverse pitch-to-diameter ratio of 2.98 while lateral pitch-to-diameter ratio constantly changed. To resolve optical distortions, experiments used para-cymene to match the refractive index of the test section. Three equally spaced regions of interest along the length of the model each have unique lateral rod pitch ratios. Experiments focused to capture the flow fields at each section between the adjacent coils at Reynolds number of 9,000. Particle image velocimetry is used for velocity measurements. The flow velocity in both the stream-wise (y-axis) and transverse (x-axis) directions for each plane, vorticity and streamline plots, used Reynolds Stresses for $u'u'$, $v'v'$ and $u'v'$ for different geometric coordinates are presented. The wake and center streamline regions between the rod bundles demonstrate the complex flow structures and interactions between local adjacent rods that the changing geometry of the helical coil steam generator produces throughout its configuration. Previous studies on straight tube heat exchanger models identify the formation of vortices behind rods that form dependent on an in-line or staggered tube bundle reliant on the pitch ratios. Averaged flow visualization data for the tested model HCSG suggest that flow characteristics follow their relative location to bundle formations instead of pitch-ratio.

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1. Introduction

Tube-and-shell heat exchangers have a wide variety of applications that make their study and efficiency important across a variety of fields. Recently, tube-and-shell heat exchangers have been a focus for nuclear power researchers. One type of steam generator designs for current and future nuclear power plants is the helical coil steam generator, a type of once-through tube-and-shell heat exchanger. Proposed in various small modular reactors, SMRs [1], including the next generation nuclear plant, NGNP [2], the helical coil steam generator is a type of tube-and-shell heat exchanger with a shell side flow that interacts with a secondary flow through tubes that are bundled together. Typically, a tube and shell heat exchanger transfers heat from the shell to the tube side, creating steam within the tubes to rise. Tube configurations are defined

as in-line or staggered based on the center-to-center distances across tube bundles. The design of the tube bundles and the directionality of the flow can be altered for specific applications. Nevertheless, the helical coil steam generator provides many advantages over straight tube and shell models. Primarily, it provides a higher heat transfer area per unit volume. The helix design has demonstrated an increase of 16–43% higher heat transfer than a straight tube bundle [3]. Due to its design, it is also able to better withstand thermal expansion during transient behavior, the limitations of which are now a topic for research based on different accident scenarios [4]. The interest in the helical coil steam generator has lead a multitude of researchers to study the helical coil steam generator although the majority of these studies focus on different designs of the heat exchanger.

One of the earliest studies of flow visualization within in-line and staggered tube bundles demonstrated alternate shedding eddies [5] that lead to an increase of interest in the effects of cross-flow structures over tube bundles. Bradshaw [6] preformed smoke visualization within a single row of tubes and noted that

* Corresponding author.

E-mail addresses: mdelgad17@tamu.edu (M. Delgado), sayalee@tamu.edu (S. Lee), y-hassan@tamu.edu (Y.A. Hassan), nkanand@tamu.edu (N.K. Anand).

Nomenclature

a	transverse pitch ratio	V	velocity in the lateral (y- axis) direction
b	lateral pitch ratio	$V_{\max}$	maximum velocity in the lateral direction
d	diameter length	V_{∞}	inlet velocity, 0.525 m/s
d_H	helix diameter	W	vorticity
d_R	rod diameter	ΔX	image displacement
d_P	particle diameter	α	magnification Factor
N	number of velocity fields	δu	experimental particle displacement
P_H	helical pitch	$\sigma_{C,PIV}$	combined uncertainty of velocity components
Re	Reynolds Number	$\sigma_{R_{H_i}}$	uncertainty of Reynold's stresses
St	Stokes Number	ρ_P	particle density
S_T	transverse pitch	μ	dynamic viscosity of p-cymene
S_L	lateral pitch	θ	angle around rod (see Fig. 6)
t	time		
Δt	image interval		
U	velocity in the transverse (x- axis) direction		

the flow behind tubes of a single row were non-uniform although they had constant pitch. Zdravkovich [7] observed flow patterns and pressure distribution across tube arrays and suggested that flow induced vibration was responsible for the variation. Studies such as by Weaver and Avd-Rabbo [8] observed symmetric vortex shedding that was related to the tube vibration but lacked quantitative evaluation. Experimental velocity data from the interstitial flow became a necessary component for the design of heat exchangers. Aiba et al. [9] made velocity measurements using hot-wire anemometry and found that heat transfer coefficients were dependent on tube configuration, determining the changes were a result of velocity and turbulence characteristics. Velocity measurements done with Laser Doppler Anemometry (LDA) by Simonin and Barcouda [10] then compared the results to k- ϵ model simulations. Balabani and Yianneskis [11] also made LDA measurements to compare in-line and staggered tube bundles but the measurement points were limited. With increased computing capabilities, large eddy simulations and numerical simulations across tube bundles have become accessible which delineate the flow-induced vibration phenomena. A more comprehensive overview of simulation progress in fluid flow analysis is covered by Hoffer [2], Hassan [12], and Sweeny [13]. Nevertheless, they are limited by either the simplifications needed in order to make the computation resolution reasonable or lack detailed experimental data to compare. Attempts to resolve experimental data and two-phase pressure drop correlations have also demonstrated the need for a more comprehensive analysis of the flow field behavior contributing to heat transfer between shell and tube side flows [14]. Effective predictions of flow across tube bundles are important to their design, but with the variety of designs currently in practice, it has been difficult to analyze flow patterns based on individual geometric parameters. A comprehensive historical summary and discussion on the characteristics of flow and heat transfer for tube bundles can be found by authors Zukauskas and Ulinskas [15].

Flow visualization techniques have advanced. One technique which provides full field measurements of the velocity components with emphasis on particle tracking is known as Particle Image Velocimetry (PIV). This technique offers a great advantage by looking at an area rather than a single point measurement, such as those done with LDA and hot-wire anemometry. In recent years, researchers such as Paul [16], Iwaki [17], and Konstantinidis [18] among others have used PIV to study in-line and staggered tube bundles. Literature review of multiple proposed helical coil steam generator designs lead the authors to a helical coil steam generator, HCSG, design with multiple concentric helix bundles of alternating helical pitches [2,19,20]. Unlike the in-line and staggered

tube bundles, a design with alternating helical pitches will have areas repeating radially where the tubes are inline and staggered but changing periodically. Currently, there are several studies that utilize computational methods to predict these types of complex flow fields of alternating helical pitches [21,22].

The present study offers flow visualization data for the shell side flow within a single curved interface between tube bundles with opposing helical pitches. The term tubes and rods will be used interchangeably due to the custom for these heat exchangers to be referred to as tube-and-shell models although the experimental test section is composed of solid half-circular rods protruding from the walls. The experimental test section is a small section of a one-to-one design for a helical coil steam generator with average rod pitch-to-diameter ratio of 1.5 and helix-to-rod diameter of 120. PIV analysis for average velocity flow field, streamline profiles, vorticity, and Reynolds stresses across multiple interfaces at three different cross-sectional areas each with different rod arrangements are presented and discussed.

2. Experimental facility and method

2.1. HCSG test section design

The majority of the HCSG proposed designs rely on a single flow pass multi-tube bundle that revolves within a shell at a single helical pitch. Looking at a radial cross-section of the bundle, the relative location of the tubes in relation to one another is constant. Tube-and-shell heat exchangers are defined as either in-line or

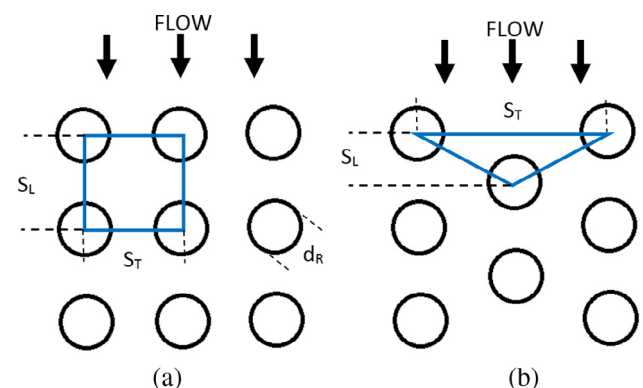


Fig. 1. Two common tube bundle patterns: (a) in-line and (b) staggered and their characteristic parameters.

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