

## Kinematic and Dynamic Characteristics of Pulsating Flow in 180° Tube

Tin-Kan Hung<sup>1,\*</sup>, Ruei-Hung Kuo<sup>2</sup> and Cheng-Hsien Chiang<sup>3</sup>

<sup>1</sup>Department of Bioengineering, University of Pittsburgh, 4200 Fifth Ave, Pittsburgh, PA 15260, USA.

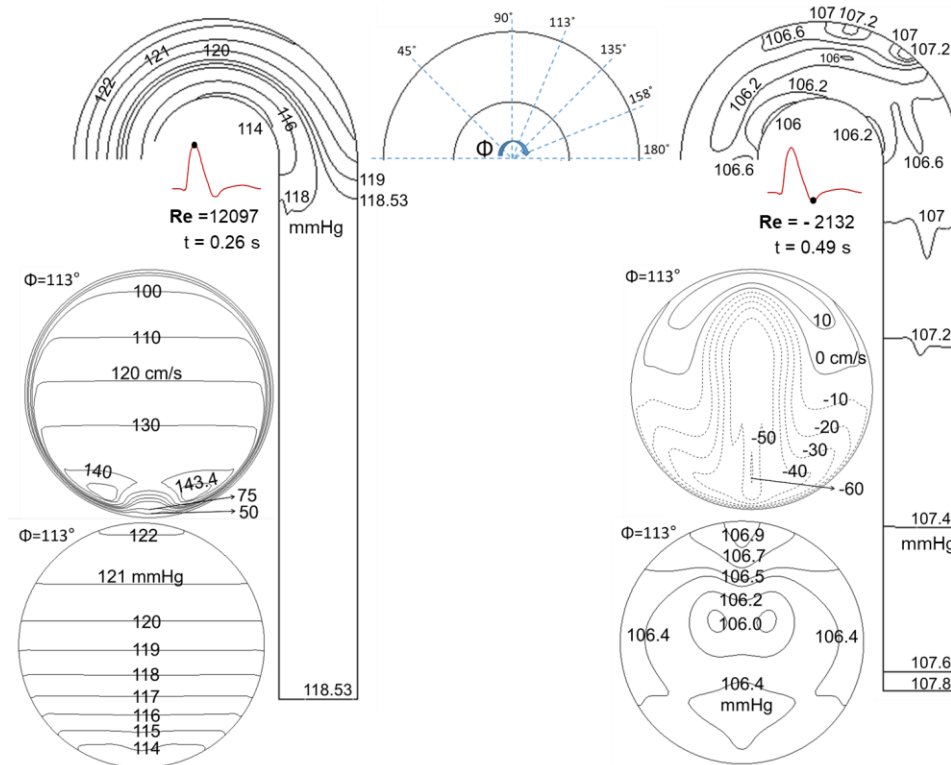
<sup>2</sup>Department of Aeronautics and Astronautics, National Cheng Kung University, Taiwan.

<sup>3</sup>Department of Biomedical Engineering, National Cheng Kung University, Tainan, Taiwan.

\*Corresponding Author: Tin-Kan Hung. Email: tkhung@pitt.edu.

Pulsating flow in a human aortic arch is studied from its kinematic and dynamic characteristics of transient tubular boundary layer. The results can only be obtained by a 3D fluid dynamic (CFD) analysis for the rapidly accelerated and decelerated systolic flow. The flow is based on a prescribed inlet velocity,  $V_o(t)$ , which can be expressed as the instantaneous Reynolds number,  $Re(t) = \rho DV_o/\mu$  in which  $D$  is the tube diameter,  $\rho$  the blood density and  $\mu$  the dynamic viscosity. Computation of pressure field requires a reference pressure at the downstream end section. The pressure is based on the pulse in Professor Y. C. Fung's book on Biomechanics: Circulation. The finite volume method of an arbitrary Lagrangian–Eulerian (ALE) formulation of the Navier-Stokes equations developed by Hirt et al. is used [2].

The results in the figure include pressure contours on the symmetric plane for  $Re = 12097$ , the longitudinal velocity and pressure distributions on a cross section  $\phi = 113^\circ$ . The peak systole is developed from  $t = 0.15$  to  $0.26$  sec. At  $t = 0.18$  sec. the instantaneous  $Re$  reaches 5104; the velocity and pressure are dominated by the rapid boundary layer development from the onset systole. The curvature effect is coupled with flow acceleration for spatial and temporal growth of boundary layer. The longitudinal velocity distribution developed from the inlet to section  $\phi = 113^\circ$  shows higher velocity occurred along the inner bend. The growth of tubular boundary layer is associated with a transient irrotational core. Similar phenomena appear in the upstream and downstream sections for spatial growth of boundary layer in early systole. The pressure distribution at the section shows higher pressure near the outer bend due to centrifugal forces. The effect is visible in pressure distribution on the longitudinal mid plane. The results indicate a rapid rising of pressure at  $t = 0.18$  second with the predominant pressure drops toward the downstream. They are associated with acceleration during early systole. The pressure distribution on the symmetric plane for the peak flow at  $t = 0.26$  second with  $Re$  reaching 12097 indicates insignificant longitudinal pressure gradients because of  $dV_o/dt$  vanished momentarily. At this instant, the presence of radial pressure variations along the curved segment is due to strong centrifugal forces. The  $w$ -contour becomes complicated along the inner bend characterized by a hump (refer to  $w = 75$  cm/sec) with a pair of peak velocities (see  $w = 140$  and  $143.4$  cm/sec) by its sides. The growth of three-dimensional boundary layers is associated with the secondary flow and pressure variations on the section. The pulsating flow continues with a rapid deceleration. Further development of laminar layer is demonstrated for flow when  $Re$  reduces to 5482. For the 3D pulsating flow, using the contour of  $w = 0$  to demarcate backflow from forward stream is good for analyzing the 3D vortex. Also shown in Fig. 1 is the  $w$ -contour and pressure distribution for back flow when  $Re = -2132$ . The negative velocity (see  $w = -60$  cm/sec) on the inner bend is in the laminar layer while the forward momentums remain on the outer bend.



**Figure 1.** Longitudinal velocity ( $w$ ) and pressure contours at section  $\phi = 113^\circ$  on the symmetric plane.

TKH first met Professor Fung at the 1970 Urodynamics Symposium where he presented a generalized Bernoulli's equation with energy pumped from the ureter to urine bolus transport [3]. One professor from aerospace engineering made a comment: "I hate to attack a junior colleague. On God's green world, there is no such Bernoulli equation". At the conclusion of the conference, Professor Fung was asked by Dr. Saul Boyarsky for a comment. He said:

"We are from the conventional engineering fields to work on unconventional biological system. Dr. Hung's Bernoulli equation was correct".

This junior colleague, TKH, would later have the honor and opportunity to participate in many activities with Professor Fung, including ASME, ASCE, USNBC, ICMMB, JMMB, and NCKU. His admiration of Dr. Fung's kindness and friendship is evident in celebrating Professor Fung's 65th, 90th and 100th birthday conferences at UCSD. This paper is dedicated to Professor Yuan-Cheng Fung for his creativity and leadership in modern biomechanics and biomedical engineering.

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