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# Weakly swirling flow in a model of blood vessel with stenosis: Numerical and experimental study

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**Abstract**

Investigation of weakly swirling flow in a model of a blood vessel with asymmetrical stenosis has been performed using both experimental flow measurement techniques (ultrasound Doppler) and computational fluid dynamics methods. A special attention is paid to getting data for the length of the reverse-flow zone occurring past the stenosis. It has been established that the laminar steady-state flow model is acceptable for numerical analysis of flow past the given-geometry stenosis at Reynolds number values less than 300. At higher values of this parameter, application of the semi-empirical $k$-$\omega$ SST turbulence model is preferable. It has been shown that flow swirl can lead to an increase of the reverse-flow zone.



*Keywords:* Blood vessel; Swirling flow; Non-symmetric stenosis; $k$-$\omega$ SST turbulence model; Ultrasound Doppler; Computational fluid dynamics.

## Introduction

Numerous study results indicate a swirling (translational-rotational) blood flow existing in separate segments of the human cardiovascular system. The following mechanisms are most commonly cited as causing the blood flow to swirl: the rotational motion of the heart, the spatial curvature of some blood vessels, the helical structure of the endothelial layer of the arterial internal surface. The phenomenon of swirling blood flow was first experimentally recorded in a study of aortic blood flow [1], and subsequently in studies of femoral arterial flow [2,3] and of blood flow in the common carotid artery [4]. Since then, swirling blood flow has been attracting an increased interest from researchers [5].

Even though a large amount of evidence indicates the existence of swirling blood flow in the body, its role in the development of cardiovascular diseases, atherosclerosis being the most commonly occurring among them, is as yet unclear. Arterial stenosis (a local narrowing) is one of the most common blood vessel diseases. Stenosis occurs due to various substances depositing on vessel walls or due to connective

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tissue overgrowth. The flow passage narrowing and the blood flow accelerating in the central part of the stenosis cause elevated shear stresses, which increases the likelihood of atherosclerotic plaque rupture. On the contrary, the shear stress values in the reverse-flow zone forming past the stenosis are relatively small. Under low shear stresses, platelets and other thrombogenic proteins attach to the arterial walls much easier, causing the plaque to grow further [5].

The research into swirling flows in models of stenosed vessels is relatively recent: the first study in this field was published in 2004 [3]. Its author studied the effect of weak flow swirling on the flow past the stenosis using the methods of phase-contrast magnetic resonance and mathematical modeling using the Star-CD CFD package. A swirling flow with the maximum peripheral velocity equal to 0.17 of the axial one was supplied to the model's inlet. The author of Ref. [3] concluded that the swirling has a stabilizing effect on the turbulent flow past the stenosis. The data of the subsequent numerical studies [6,7] which examined a model of a vessel with axisymmetric 75% stenosis also prove that flow swirling (at the inlet velocities ratio of 0–0.3) suppresses turbulence in the zone past the stenosis and reduces the inverse-flow zone. The authors of Refs. [8,9] conducted an experimental study of the weakly swirling flow (the swirl parameter $S=0.25$) in a stenosis of the same configuration by using the method of particle image velocimetry (PIV). The measurements showed that swirling shortens the length of the inverse-flow zone by about 20% and reduces the length of the laminar-turbulent transition.

All the papers dedicated to studying the swirling flow in stenosed vessel models (that we know) dealt with an axially symmetrical shape of the flow-passage narrowing. However, the majority of real stenosis exhibits an asymmetrical shape. The present work is a computational and experimental study of the swirling flow in a blood vessel model with a non-axisymmetric stenosis using computational fluid dynamics software and the ultrasonic Doppler technique.

The aims and objectives of our study:

- to obtain experimental data on the velocity fields of the non-swirling and the weakly swirling steady flows in a model of an asymmetric 75% stenosis with varying Reynolds numbers;
- to numerically simulate this flow in a three-dimensional setting and find the applicability limits for the laminar flow model;
- to develop a procedure for measuring the length of the reverse-flow zone past the stenosis and to study the influence of flow swirl on the extent of this zone.

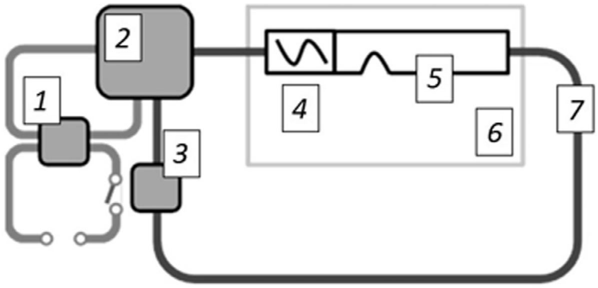


Fig. 1. Schematic of the experimental setup: pump control device (1), (5), acoustic tray containing the vessel model (6), closed hydraulic circuit (7).

## Experimental setup and measurement procedure

We have created a setup to study experimentally the flow in a stenosed vessel model. This setup is a closed circuit with the fluid (water) circulating in it. A schematic of the experimental setup is shown in Fig. 1.

The fluid flow with a fixed rate $Q$ from 90 to 270 ml/min was supplied by a centrifugal pump *2*, controlled by a multi-way flow control valve *3* and monitored by an electromagnetic flowmeter. The liquid flowed through a long tube 6 mm in diameter until reaching a fully developed velocity profile before entering the working section. The Reynolds number Re at the maximum flow rate, based on the inner tube diameter and the velocity of the mean fluid flow, was 960.

The stenosed vessel model *5* was cast from silicone by the technology developed by the authors of Ref. [10] and was a tube with the diameter $D=6$ mm and the wall width of 1.5 mm. The local narrowing modeling the stenosis of the vessel started at a distance of 25 mm from the tube's inlet section (Fig. 2a). The length of the stenosis was $L_s=12$ mm, the drift diameter in the narrowest area (the 'bottleneck' of the stenosis) $D_s=3$ mm. The vessel lumen was a circle in any cross-section of the narrowing segment. The stenosis index

$$STI = (1 - D_s^2/D^2)\cdot 100\%,$$

computed from the surface area, was 75 %. The shape of the stenosis was non-axisymmetric and was described by the formulae for the upper $y_{up}(x)$ and the lower $y_{down}(x)$ borders of the stenosis in the mean longitudinal cross-section:

$$y_{up} = D,$$