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Numerical and Experimental Study of the Airflow in a Square Section Bifurcation

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Abstract **Bifurcating geometries are ubiquitous in many natural and engineered systems, ranging from air conditioning units to biological respiratory pathways. The study of such geometries is of paramount importance to ensure the optimal performance and functionality of the system under investigation. This study centers on the medical aspect, specifically, the bifurcating geometry of the human trachea. A 3D-printed model of a bifurcation with comparable dimensions to the trachea was utilized to perform a range of measurements and visualizations. The paper is dedicated to the experimental studies and numerical simulations of the airflow in a 3D bifurcation with a square section.**

Keywords: **airflow, bifurcation, CFD, respiratory system.**

I. INTRODUCTION

A bifurcating pipe is a type of geometry that splits into two or more branches at one point, forming a branching structure.

The study of airflow through a bifurcation is important because bifurcating geometries are prevalent in various natural and engineering systems, including human airways and respiratory devices, [1-8].

The understanding of the fluid mechanics in bifurcating geometries can provide insights into the underlying physiological mechanisms and help optimize the design of respiratory devices. Furthermore, the study of airflow through bifurcations has implications in fields such as aerodynamics, heat transfer, and chemical engineering, where the bifurcating geometries play a crucial role in determining the performance of the systems.

In medicine, the study of airflow through bifurcations is important for understanding and treating respiratory diseases. The human respiratory system is composed of a series of bifurcating airways that distribute air to the lungs, and any obstruction or abnormality in these airways can lead to breathing difficulties and other respiratory problems. By studying the airflow characteristics in these bifurcating airways, researchers can gain insights into the mechanisms of respiratory diseases and develop more effective treatments. Additionally, the study of airflow through bifurcations can aid in the design and optimization of respiratory devices, such as ventilators and inhalers, to improve their performance and minimize potential side effects.[1]–[3]

The majority of research conducted on fluid flow through bifurcations typically centers around liquids, with a significant emphasis on the flow of blood through arteries and veins. In the field of cardiology, studies have focused on the flow of blood through bifurcating arteries, particularly in relation to the development and progression of atherosclerosis, a condition in which the artery walls thicken and narrow due to the buildup of plaque. The study of flow through bifurcations has also been important in developing and testing medical devices such as stents, which are used to prop open blocked or narrowed arteries. Understanding the flow patterns and forces within bifurcating arteries can help to optimize the design and placement of these devices. Some researchers even tackled the idea of directly 3D printing arteries with real-time occlusion monitoring [4].

On the numerical side, moving the focus on airflow, past studies have shown the influence of the flow characteristics and different geometrical features, such as the bifurcation angle. Rodkiewicz et al. [5] studied the influence of the flow characteristics in relation to the Reynolds number. In a study by Balásházy, Heistracher and Hofmann [6], the focus was on analyzing the deposition patterns of particles in the airway bifurcations through the use of computational fluid dynamics (CFD). The researchers utilized various CFD techniques to investigate the effects of particle size, flow rate, and bifurcation geometry on the deposition patterns. Their findings shed light on the mechanisms of particle deposition in the human airways, which can have significant implications in areas such as inhalation toxicology and the development of targeted drug delivery systems.

Although there are many numerical studies on the matter, most of them don’t have an experimental basis and validation of the results. Experimental validation is important in the study of flow through bifurcations because it provides a way to verify the accuracy of the numerical simulations used to model these flows. Numerical simulations are powerful tools that can provide detailed information about the flow characteristics of a system, but they are only as accurate as the assumptions and simplifications made in the models. By comparing the results of numerical simulations with experimental data, researchers can validate their models and identify areas where further refinement may be necessary. Additionally, experimental validation can provide insight into the physical mechanisms that govern flow through bifurcations, which may not be captured in the numerical models alone. Therefore, experimental validation is an essential part of the process of studying flow through bifurcations and improving our understanding of this important phenomenon.

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In the present investigation the flow properties were evaluated by analyzing a 3D printed model of a square section bifurcation. Furthermore, smoke was introduced into the printed geometry to analyze the flow patterns.

II. THE EXPERIMENTAL SETUP

In order to investigate the characteristics of airflow, an experimental arrangement was devised. A mechanical ventilator was used to convey the air through a 3D printed bifurcation. A pair of flow transducers and a pressure transducer were utilized to monitor the flow and pressure parameters. To replicate the elasticity of the lungs, a two-lung simulator consisting of balloons was employed, fig. 3.

Data on the flow characteristics was collected through the use of an acquisition board, which translated the values of the transducers into the corresponding flow characteristics and was then recorded onto a computer.

The input parameters were setup using the mechanical ventilator, serving as both the inlet and outlet in the setup.

Visualizations were conducted by utilizing a smoke machine to generate smoke within the printed geometry. Smoke visualizations are useful in the study of fluid flow because they provide a visible representation of the flow pattern, fig. 1. Smoke visualizations can also be used to validate computational fluid dynamics simulations by comparing the visualized flow patterns to the predicted patterns.

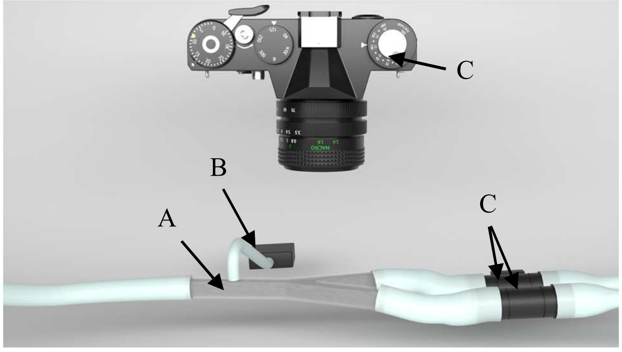

Fig. 1. Image acquisition using smoke; A. 3D printed geometry, B. pressure sensor, C. Flow meters, D. High-speed camera.

On the electronics side, an Arduino board was used to read the raw incoming data from the transducers and translate it into computer readable data, fig. 2. A real time plotting software was used to plot the incoming data in real time. The software was also capable of exporting the data in a table form, as a .csv file.

In addition to the transducers, the setup needed a way to read the flow data from both flow sensors. Given the fact that both sensors used the same I2C (Inter-Integrated Circuit) address, a multiplexer board was used to quickly switch between the flow inputs.

The acquired data was postprocessed and plotted with the aid of a software capable of plotting data. To synchronize the flow patterns visualized through the smoke visualization method and the data recorded by the high-speed camera, the plots were mapped onto the corresponding video frames. This allowed for a more accurate and precise analysis of the flow characteristics in the bifurcation model.

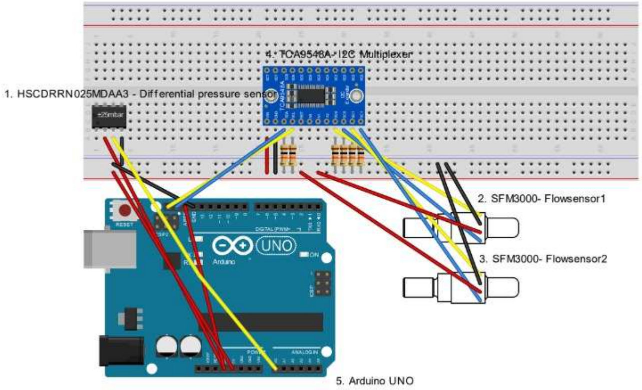

Fig. 2. The electronics diagram, 1- pressure transducer, 2,3 - flow transducers, 4-i2c multiplex module, 5-Arduino

The geometry under analysis in this study was a bifurcation with a square cross-section, where the two branches of the bifurcation formed an angle of 45 degrees (fig. 3). The angle between the branches is an important parameter affecting the airflow characteristics in the bifurcation. The 45-degree angle was chosen based on its similarity to the angle of the trachea bifurcation in humans or other animals.

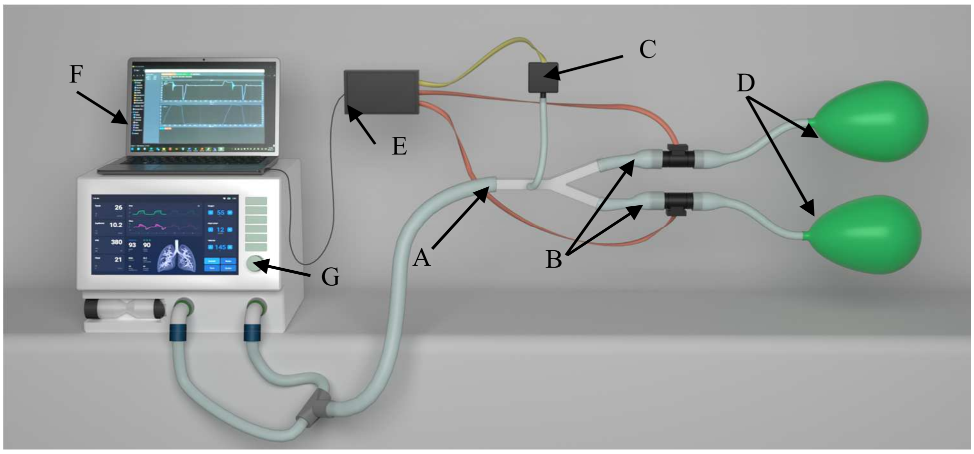

Fig. 3. The experimental setup: A. 3D printed bifurcation, B. Flow meters, C. Pressure transducer, D. Lung simulator balloons, E. Acquisition board, F. Computer, G. Mechanical ventilator.

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To facilitate the connection of air hoses to the ports, we included circular, conical caps in our model. To maintain consistency throughout the study, the same geometry was retained in the numerical simulation, fig.4.

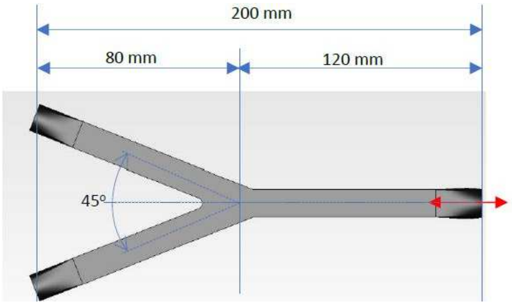

Fig. 4. The geometry of the square bifurcation and the dimensions. Same bifurcation geometry is used in the numerical simulations.

We collected flow rate and pressure data within the bifurcation model through our experimental setup, which was monitored continuously for a duration of approximately one minute (fig. 5). The data extracted from this duration of the experiment allowed us to gain insights into the flow characteristics and pressure variations within the bifurcation.

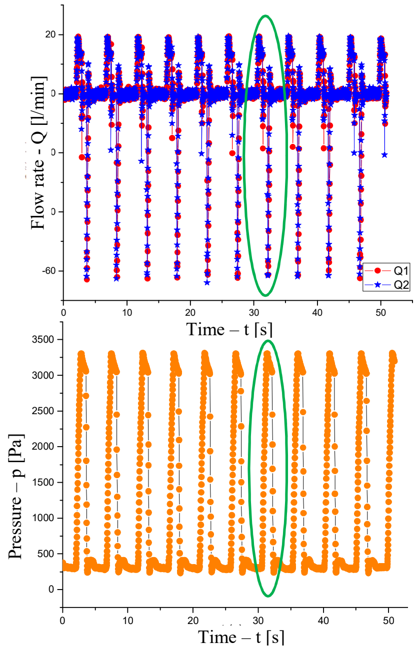

Fig. 5. Measured flow rates and pressure data for a duration of approximately one minute. The inhalation-exhalation cycle is marked with green and is represented in the figure 6.

Due to the similarity of the flow rate and pressure waveforms, we specifically chose a single cycle of inspiration and expiration to represent a complete breathing cycle.

Three regions stand out distinct: I – inspiration, II – transient, III - expiration (marked in Fig.6), limited by repaus areas, R.

This data was then used as the input for the subsequent numerical simulation. By focusing on one complete cycle, we were able to obtain a more detailed and accurate analysis of the flow and pressure characteristics within the bifurcation model.

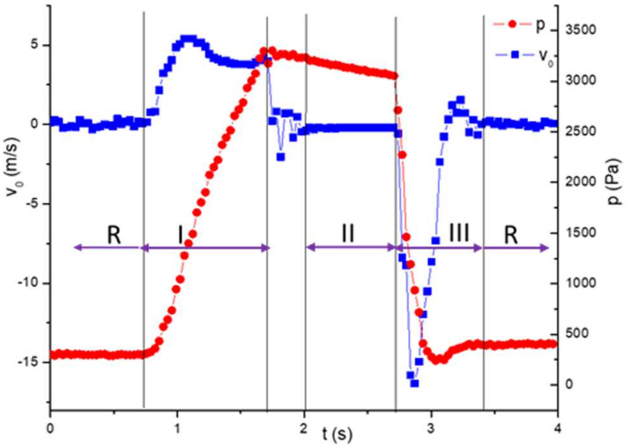

Fig. 6. The measured data over a single breathing cycle. These variations are used as boundary conditions for the unsteady airflow in the test bifurcation.

During the data collection process, we also introduced smoke into the experimental setup to aid in the visualization of flow patterns (fig. 7).

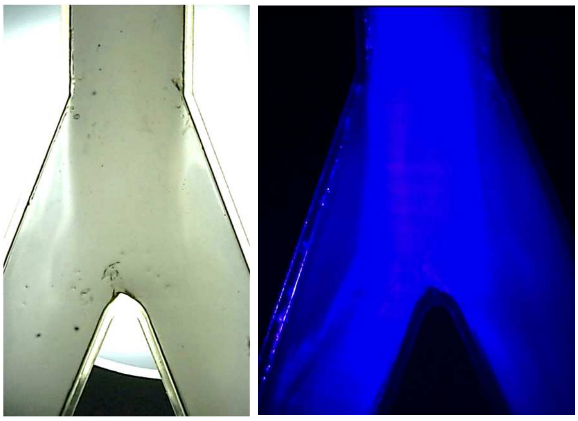

Fig. 7. Flow pattern visualization

III. NUMERICAL STUDY

The 3D simulations were performed with the ANSYS Workbench 2021R1 – Fluid Flow (Fluent) program; the air flow regime is unsteady with the following boundary conditions: the variation of velocity at the inlet is v_=v_ (t) and the variation of pressure at the outlets is $p = p(t)$, given by the diagram from figure 6.

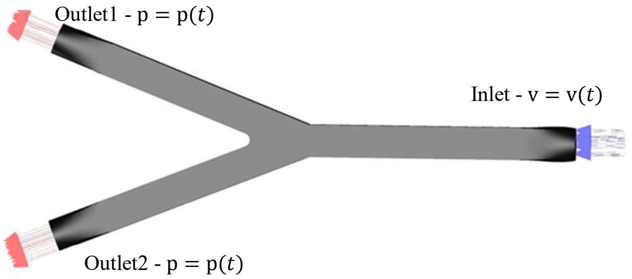

Fig. 8. Computation flow domain and boundary conditions

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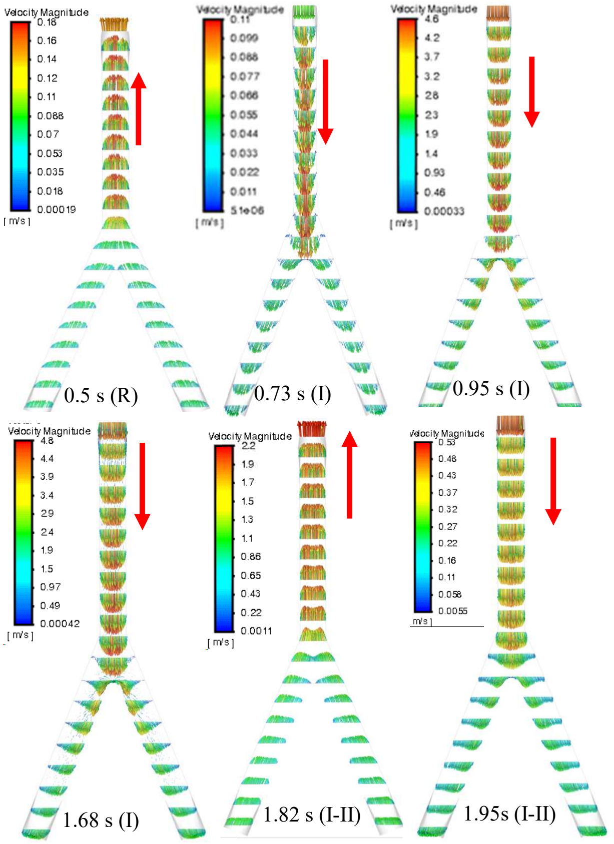
The solutions of the motion equations being obtained with the standard $k-\varepsilon$ model. For the CFD simulation the k-ε turbulence model was used. The residual value of the governing equations was 10-6. The domain discretization contains 2.1 million cells, with 4.2 million faces and 392067 nodes.

The properties of air at normal conditions were considered in this study: density is 1.225 kg/m³, the viscosity is 1.7894×10^{-5} Pas.

The evolution at various time steps of the velocity vectors distribution in a different plane positioned at the 10 mm distance in bifurcation are shown in the figures 9 and 10.



0.5 s (R) 0.73 s (I) 0.95 s (I)

1.68 s (I) 1.82 s (I-II) 1.95s (I-II)

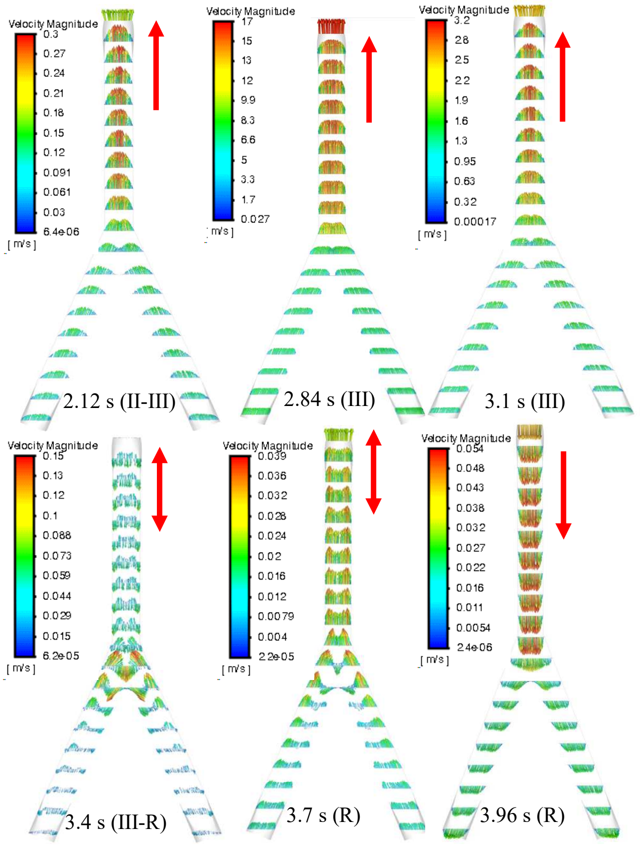
Fig. 9 The velocity vectors distributions on normal planes to the flow in the region R, I (inspiration), and zone I-II between inspiration and transient.

Can be noted that the maximum velocities during exhalation have much higher values compared to those during inspiration.

Between the regions are transition zones characterized by turbulent flows where the transported flows change their direction or have very low values.

To validate the numerical model used in this study, the particle trajectories of the smoke visualizations and the simulations were compared.

The comparison showed a strong correlation between the two, indicating that the model is appropriate for this application (fig. 11). This validation process is important to ensure that the numerical simulation accurately represents the physical system being studied.



2.12 s (II-III) 2.84 s (III) 3.1 s (III)

3.4 s (III-R) 3.7 s (R) 3.96 s (R)

Fig. 10. The velocity vectors distributions on normal planes to the flow in the zone between transient and expiration II-III, expiration III, zone between transient and expiration III-R and pause zone.

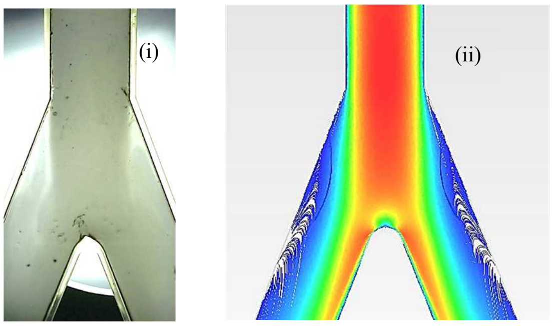


Fig. 11 Comparison between experimental (i) and numerical (ii) flow spectrum in the bifurcations.

IV. CONCLUSIONS

From this study, we can conclude that the experimental setup was successful in measuring flow rate and pressure characteristics of airflow through a 3D-printed bifurcation model with a 45-degree angle between branches. The smoke visualization also provided useful information on flow patterns.

These experimental results were then used to drive a numerical simulation which was validated by comparing it to the smoke visualization results. The validation showed that the numerical model was suitable for this application. Overall, this study demonstrates the importance of experimental validation

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in numerical modeling of airflow through bifurcations and the usefulness of smoke visualization in providing qualitative data on flow patterns.

The study was focused to the experimental and numerical investigations of the airflow in a bifurcation. The numerical results were compared to experiments under identical conditions.

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REFERENCES

[1] C. Peng et al., “The impact of the geometric characteristics on the hemodynamics in the stenotic coronary artery,” *PLoS One*, vol. 11, no. 6, Jun. 2016.

[2] M. Boumpouli, E. L. Sauvage, C. Capelli, S. Schievano, and A. Kazakidi, “Characterization of Flow Dynamics in the Pulmonary Bifurcation of Patients with Repaired Tetralogy of Fallot: *A Computational Approach,*” *Front Cardiovasc Med*, vol. 8, Sep. 2021.

[3] G. Pennati *et al.*, “Computational fluid dynamics models and congenital heart diseases,” *Frontiers in Pediatrics*, vol. 1, no. FEB. Frontiers Media S.A., Feb. 01, 2013.

[4] J. Li *et al.*, “Multifunctional Artificial Artery from Direct 3D Printing with Built-In Ferroelectricity and Tissue-Matching Modulus for Real-Time Sensing and Occlusion Monitoring,” *Adv Funct Mater*, vol. 30, no. 39, Sep. 2020.

[5] C. M. Rodkiewicz, “Nombre de Reynolds caracteristique d’un embranchment,” *Journal of Hydraulic* Research, vol. 12, no. 2, pp. 241–252, 1974.

[6] M. A. Lieben, I. Balásházy, T. Heistracher, and W. Hofmann, “Air Flow and Particle Deposition Patterns in Bronchial Airway Bifurcations: The Effect of Different CFD Models and Bifurcation Geometries,” 1996.

[7] Malve M. et al., “FSI analysis of a human trachea before and after prosthesis implantation”, *J. Biomech. Eng.* 133(7), 2011.

[8] A. Pandal-Blanco, R. Barrio-Perotti, R. Agujetas-Ortiz, A. Fernandez-Tena, “Implementation of a specific boundary condition for a simplified symmetric single-path CFD lung model with OpenFOAM”, *Biomechanics and Modeling in Mechanobiology*, vol. 18, pp. 1759–1771, 2019.

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