A NEW 3D-PRINTED ARTERIAL FLOW FACILITY

Andrea Zampiron, Elena Zarantonello, Andrea Marzellotta, Stefano Lanzoni, Francesca Maria Susin
Department of Civil, Architectural and Environmental Engineering
Università degli Studi di Padova
Via Marzolo 9, 35131, Padova, Italy
andrea.zampiron@unipd.it

ABSTRACT

In this work, we present the Padova Arterial Flow Facility (PAFF), which employs 3D-printed pipes to reproduce arterial flow conditions. Compared to commercial pipes, 3D printing provides the significant advantage of fabricating pipes with a virtually infinite choice of roughness elements, obstacles, and obstructions on their inner walls. The facility features four wall-pressure sensors installed along its length, enabling the measurement of streamwise time-averaged pressure gradients as well as the analysis of turbulent wall-pressure fluctuations. The PAFF also allows stereoscopic particle image velocimetry (PIV) measurements.

INTRODUCTION

In its simplest form, flow in arteries can be modeled as a smooth-wall pipe flow. Under this assumption, velocity statistical moments can be predicted using theoretical and (semi-) empirical relations. In reality, however, arterial flow is strongly influenced by disturbing elements such as bifurcations, curvature, obstructions (e.g., stenosis, a local narrowing of the artery), and wall roughness (e.g., stents or early stages of atherosclerosis). Thus, it is important to develop an experimental framework that allows us to recreate geometries and conditions similar to those that can be found in the human body arteries.

However, compared to other types of wall-bounded flows (turbulent boundary layers, closed-channel flows, and open-channel flows), experiments in pipes are characterized by limited access to the measurement section, which makes the installation of roughness elements particularly challenging. This motivated the development of a facility and a manufacturing procedure that overcome these limitations, enabling the insertion of arbitrary roughness elements inside the pipe.

In this abstract, we provide key information regarding PAFF, the 3D printing procedure and the pressure measurement setup. In the full paper, preliminary measurements and data analysis will be presented.

THE PADOVA ARTERIAL FLOW FACILITY (PAFF)

The PAFF is new a pipe facility located at the Cardiovascular Fluid Dynamics Laboratory of the University of Padova, which covers conditions typical of medium- to large-caliber arteries, i.e., from the coronaries to the aorta. The PAFF consists of a pipe with a diameter of $D = 20$ mm and a length of $L \approx 2.3$ m ($\approx 115D$, Figure 1). The pipe length was chosen to achieve developed flow conditions at the measurement section. Steady flow is generated using a centrifugal pump with a maximum flow rate of $\approx 400\ \mathrm{cm^3 s^{-1}}$, which is measured by an electromagnetic flow meter (Endress+Hauser Promag P 300). To achieve low flow rates, a bypass diverts part of the flow directly into the tank, while a valve is employed to accurately adjust the flow rate. A settling chamber removes any flow disturbances originating from the pump and the bypass (Draad, 1996; Draad *et al.*, 1998). A constant water level is maintained in the exit tank to ensure a constant pressure at the tube outlet (in a time-averaged sense). The free surface in the tank allows the removal of air bubbles from the fluid. The exit tank was designed to accommodate the development of the jet from the pipe outlet while containing the fluid volume, which is necessary to optimise the overall cost of refractive-index-matching fluid for subsequent PIV studies.

3D printing

The several components of the PAFF (i.e., settling chamber, pipe, and exit tank, Figure 1) were designed and fabricated in-house using a masked stereolithographic 3D printer (Elegoo Saturn 4 Ultra), featuring a build volume of $218.88 \times 122.88 \times 220\ \mathrm{mm^3}$, an $11{,}520 \times 5{,}120$ pixels LCD screen with a pixel size of $19 \times 24\mu$m, and a minimum vertical step size of 20μm. The chosen resin was the ANYCUBIC ABS-Like Resin PRO2. The printer can correctly reproduce all the required geometrical details. An example is the 1 mm-high triangular strips in a helicoidal pattern shown in Figure 1. The pipe is subdivided into 188.50 mm-long sections to fit the build volume of the printer. To enable stereoscopic PIV, a transparent measurement section is 3D-printed from a resin with a refractive index that matches that of the working fluid, specifically developed for this purpose.

Pressure measurement

Pressure measurements are carried out at the pipe wall at distances from the pipe inlet between $71D$ and $99D$, ensuring a good degree of flow development (e.g., Doherty *et al.*, 2007). Four pressure sensors (unamplified, uncalibrated, and uncompensated, with a maximum time response of $\approx 10^{-3}$ s, Honeywell 24PCAFA6G) are installed along the pipe (Figure 1). The pressure sensors were flush-mounted on the wall. Voltage signals from the sensors are acquired using a National Instruments 9237 module and a cDAQ-9174 with sampling frequency of 10MHz.

The sensors are employed to measure pressure losses along the pipe, which, in combination with flow rate measurements, provide friction factor estimates. In addition, they are used to study pressure fluctuations on the wall, providing statistical quantities such as moments, time correlations, frequency spectra, and structure functions. In Figure 2, we show distribution of variance ($\overline{p'p'}$), skewness and kurtosis of wall pressure turbulent fluctuations (p') as functions of the Reynolds number (Re) for turbulent flow conditions. As expected, the variance (Figure 2a) increases with Re as a result of increased turbulence levels. A mild increment can also be observed in the kurtosis (Figure 2b), indicating a tendency towards normality of the fluctuations, whereas no significant changes are observed in the skewness (Figure 2c).

CONCLUSIONS

We present a new 3D-printed pipe facility designed to reproduce arterial flow conditions. 3D printing offers flexibility in fabricating pipe sections with tailored wall roughness. Four pressure sensors enable the measurement of pressure gradients and turbulent wall-pressure fluctuations. The facility can be easily adapted to: (i) host a transparent measurement section combined with a working fluid of matching refractive index, allowing for stereoscopic particle image velocimetry (PIV) measurements in the presence of wall roughness; (ii) generate pulsating flow conditions through a piston or a numerically controlled valve; (iii) study flexible walls; and iv) to investigate heated walls. Finally, the high flexibility offered by its manufacturing procedures makes it possible to adapt the PAFF for studies in different fields.

ACKNOWLEDGMENTS

This work is funded by the European Union's Horizon 2022 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101107322 (CARE), by the European Union - NextGenerationEU and by the 2023 STARS Grants@Unipd programme. The authors acknowledge the support provided by ISR UniPD2017 – INCAS.

REFERENCES

Doherty, J., Ngan, P., Monty, J. & Chong, M. 2007 The development of turbulent pipe flow. In *16th Australasian Fluid Mechanics Conference, Crown Plaza, Gold Coast, Australia. 2–7 December 2007*.

Draad, A.A. 1996 Laminar-turbulent transition in pipe flow. In *Advances in Turbulence VI: Proceedings of the Sixth European Turbulence Conference, held in Lausanne, Switzerland, 2–5 July 1996*, pp. 371–374. Springer.

Draad, A.A., Kuiken, G.D.C. & Nieuwstadt, F.T.M. 1998 Laminar–turbulent transition in pipe flow for newtonian and non-newtonian fluids. *Journal of Fluid Mechanics* **377**, 267–312.

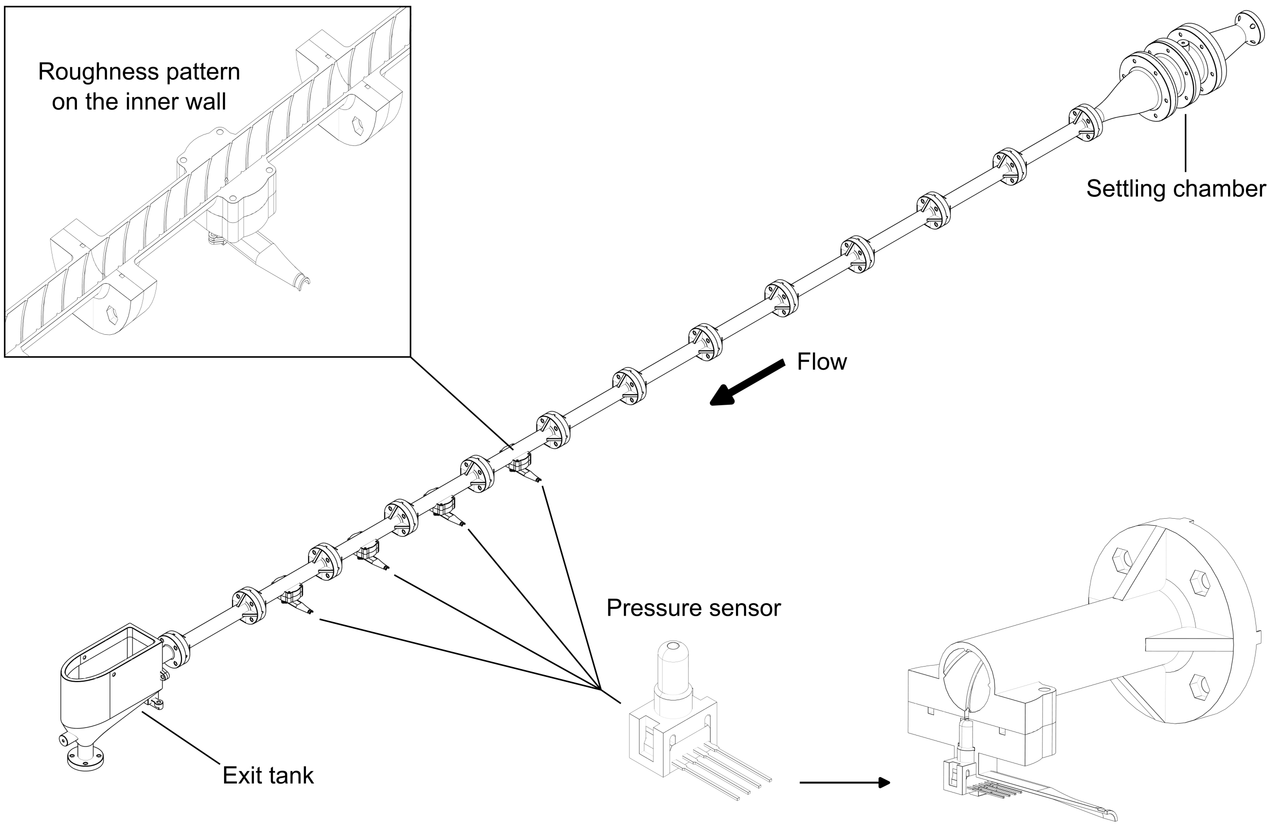

Figure 1. Overall view and details of the PAFF.

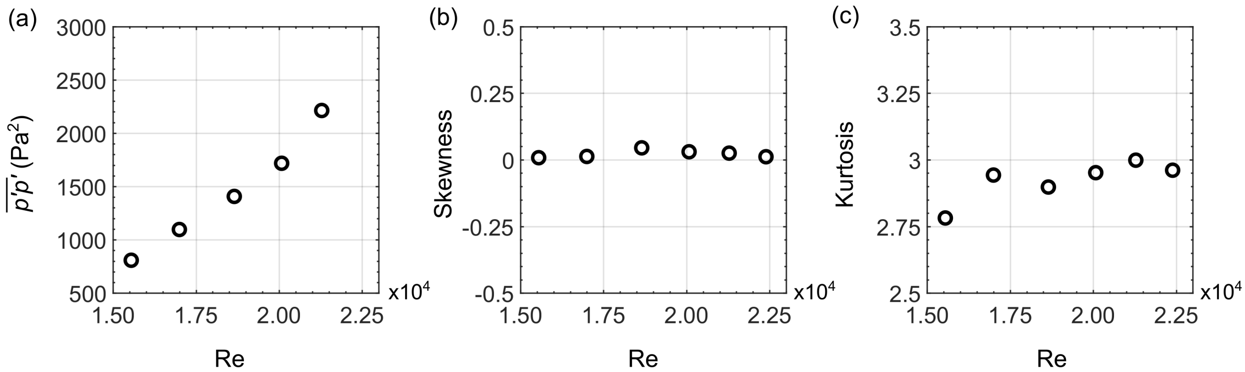

Figure 2. Distributions of (a) wall pressure variance ($\overline{p'p'}$), (b) skewness and (c) kurtosis as functions of the Reynolds number (*Re*).