BRIDGING THE GAPS IN HEMOLYSIS PREDICTION: GENERALIZED k-ω MODEL OPTIMIZATION AND STRAIN-BASED APPROACH.

Ilaria Guidetti (1), Katharine H. Fraser (2), Maria Laura Costantino (1), Francesco De Gaetano (1)

1. *Department of Chemistry, Material and Chemical Engineering, Politecnico di Milano, Milan, Italy*
2. *Department of Mechanical Engineering, University of Bath, Bath, United Kingdom*

Introduction

Computational prediction of blood damage is still a challenge, hindering the possibility of reducing the design and development time of cardiovascular devices. Since 2008, the FDA is promoting interlaboratory studies aimed at defining a standard for conducting computational fluid dynamics (CFD) simulations and using hemolysis models [1]. Despite efforts, fast and accurate CFD predictions are still a challenge, and a universal hemolysis model has not yet been developed. This study addresses the first shortcoming optimizing the parameters of a Reynolds-averaged Navier-Stokes (RANS) turbulence model and the second implementing a strain-based hemolysis model that accounts for red blood cell (RBC) deformation.

Methods

A 2D axisymmetric model for the sudden expansion (SE) and the conical diffuser (CD) configurations of the FDA nozzle is employed to solve the device flow field with ANSYS Fluent 2021. The tunable parameters of the generalized k-ω (GEKO) turbulence model are optimized for the application and ANSYS Post-CFD 2021 is used to extract the pathlines to implement the Lagrangian hemolysis models. Pathlines are tracked either forward from the inlet, backward from the outlet, or from recirculation zones, normally excluded from path-tracking. Both the stress and the strain-based hemolysis models are implemented in MATLAB® 2023 using a damage dose to account for RBCs' shear history, following the damage accumulation method of Grigioni, and are evaluated with the power-law parameters from Torner and Tobin works [2]-[4]. The stress-based model uses a von Mises-like equivalent shear stress while the strain-based describes the RBC as a deforming droplet through an evolution equation. This model accounts for the tank treading motion and the relaxation time of the RBC membrane and is derived from Arora [5].

Results

The optimized GEKO model parameters improved the flow field prediction, matching the experimental pressure drop with a mean absolute percentage error of only 0.97%. Only two of the power-law parameters sets reported by Torner (FZ and HO) yield modified index of hemolysis (MIH) values in the magnitude order of the experimental results for both models, with the FZ set providing the best results [3]. The inclusion of the recirculation regions (Figure 1) in the path-tracking allows to improve the hemolysis estimation and resolve the prediction errors of the other methodologies. The MIH obtained with the FZ set and this path-tracking method, are shown in Figure 2. Both hemolysis models have similar trends; however, the strain-based is able to correctly predict the MIH for the two conditions at 6 L/min (SE6 and CD6) and slightly overpredicts the 5 L/min condition (CD5).

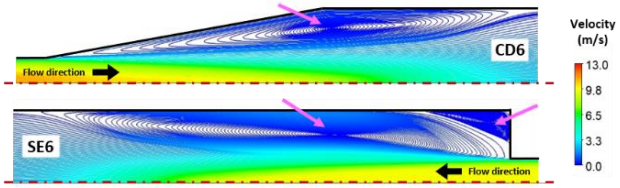

Figure 1: Recirculation regions in the diffuser and in the expansion at 6 L/min (CD6 and SE6 conditions).

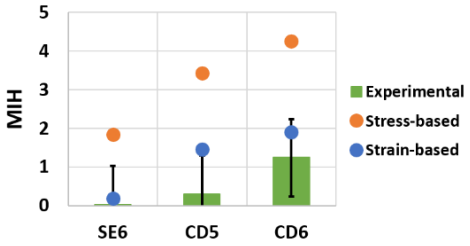

Figure 2: Modified index of hemolysis (MIH) obtained experimentally and with the stress and the strain-based models considering also the recirculation regions.

Discussion

This study improves RANS models prediction capability providing a set of optimized parameters for the GEKO model and introduces a methodology that uses a 2D axisymmetric Lagrangian model for assessing hemolysis in a 3D domain. The results indicate the strain-based model as a viable candidate for the development of a hemolysis model for a wide range of cardiovascular devices. Furthermore, this work explores the impact of recirculation zones and emphasizes the complexities inherent in Lagrangian methods. This lays the groundwork for enhancing hemolysis predictions by incorporating a more comprehensive approach that includes recirculation zones and underscores the necessity for an in-depth examination of the strain-based model and power-law method parameters.

References

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