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Topology optimization of the shear thinning non-Newtonian fluidic systems for minimizing wall shear stress

Jaeyub Hyun, Semyung Wang*, Sung Yang

School of Mechatronics, Gwangju Institute of Science and Technology, 261 Cheomdan-gwagiro, Buk-gu, Gwangju, 500-712, Republic of Korea

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ABSTRACT

This paper suggests the topology optimization process to minimize wall shear stress by considering shear thinning non-Newtonian fluid effects in the systematic design of fluidic systems dealing with blood. Topology optimization was originally developed for mechanical design problems, and within the last decade the method has been extended to a range of fluidic applications. In this paper, the Carreau–Yasuda constitutive equation model is used for shear thinning non-Newtonian fluid modeling. The fundamental idea is that the material density of each element or grid point is a design variable, thus, the geometry is parameterized in a pixel-like pattern. Then, material interpolation functions for inverse permeability and dynamic viscosity are used to ensure convergence of the solution and resolve non-linearity. In order to define wall shear stress on implicit boundary between solid and fluid (i.e., blood) occurring in fluidic topology optimization, the relaxation method of wall shear stress is first proposed in this study. We then apply the proposed fluidic topology optimization to actual fluidic systems dealing with blood (e.g., a femoral bypass graft). These design examples validate the efficiency of the proposed approach and show that topology optimization can be used for the initial conceptual design of various fluidic systems.

1. Introduction

The optimal design of the internal configuration or geometry pattern of fluidic systems dealing with blood (e.g., stent, femoral bypass graft, blood separation devices, etc.) is very important in improving system performance and from a durability perspective. Especially, minimizing wall shear stress plays a very important role in a fluidic system durability standpoint. Particularly, the importance of minimizing wall shear stress (WSS) is further emphasized in the bypass graft system because it correlates with robustness of the bypass graft and risk of re-stenosis at the anastomosis zone. We are interested mainly in the absolute and relative values of WSS from the design perspective. If the absolute value of WSS is increased, the RBC (i.e., red blood cell) in the blood explodes. This causes symptoms, such as anemia. Moreover, if the relative value of WSS (i.e., the spatial gradient of WSS) is increased, the flow tumbling (i.e., vorticity) phenomenon appears. This causes the risk of re-stenosis at the anastomosis. Hence the design optimization to reduce WSS in the bypass graft system is very important. In addition, the optimal anastomosis shape improves the success of the surgery. The ill-shaped bypass graft systems may also be prone to atherosclerosis development [1]. The design approaches can be classified into two groups: the first is to perform the repetitive manufacturing and experiment of the actual system until its required performance is satisfied (i.e., trial and error), and the second is to carry out design optimization based on computation fluid dynamics. In the former case, after manufacturing the actual systems, there are associated cost and time required for a subsequent analysis and experimental

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* Corresponding author. Tel.: +82 62 970 2390; fax: +82 62 970 2384.
E-mail address: smwang@gist.ac.kr (S. Wang).

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validation. In contrast, the latter case is extremely economical and efficient in terms of development of the final fluidic system. This study focuses on optimizing the structural design based on a numerical approach.

Many approaches for the design of fluidic systems have been reported, and extensive studies have been carried out over the past few decades. In general, a sizing/shape optimization process was employed for the fluidic system design dealing with blood. For instance, S. Pant et al. [2] applied a genetic algorithm to size the design of a coronary stent in order to minimize wall shear stress. T.J. Gundert et al. [3] presented a 3D-shape optimization for the control of spatial distribution of wall shear stress in a cardiovascular stent. Besides, M. Lei et al. [4] pointed to the design of optimal bypass graft geometries to minimize local wall shear stress gradient. L.C. Sousa et al. [5] performed the graft shape optimization to minimize the flow vorticities and induced reduced wall shear stress. C.F. Castro et al. [6] applied the self-developed multiobjective genetic algorithm to the vascular graft optimization in order to minimize the wall shear stress at the artery floor. These sizing/shape design approaches have merits of enabling a non-intuitive optimized shape to be easily obtained, however since only the initial boundaries can be changed, it is not possible to make holes in the structure. Therefore, only a limited number of optimally shaped systems can be realized.

A technique that provides a greater degree of freedom in the optimization design process is topology optimization, and it is thus selected for optimizing the fluidic systems in this study. Topology optimization in fluid mechanics was introduced by Borrvall et al. in 2003 [7]. They modified the Stokes equation with a Brinkman term to model flow through the application of inverse permeability. Since then, many studies have been proposed for fluidic topology optimization [8–11]. Recently, Y. Chen et al. [12] applied the topology optimization to a scaffold design for minimizing wall shear stress.

However, a common point in these studies is to use the Newtonian fluid modeling. This modeling can be a significant problem in the design of fluidic systems dealing with a shear thinning non-Newtonian fluid such as blood. In the literature, there are numerous topology optimization studies using the Newtonian fluid modeling, with relatively few studies employing shear thinning non-Newtonian fluid effects (e.g., shear thinning phenomenon). Lately, Pingen et al. [13] published a paper related to topology optimization by considering shear thinning non-Newtonian fluid effects using the Lattice Boltzmann Method (LBM); however, their numerical example was limited to the dual pipe with simple structure. Moreover, to our knowledge, although the topology optimization can be effective in femoral bypass graft design problems that consider wall shear stress as objective or constraint, no application has been reported so far.

Going one step further, this study presents a fluidic topology optimization for the conceptual design of actual fluidic systems dealing with blood (e.g., a femoral bypass graft system) when using a shear thinning non-Newtonian fluid such as blood. The objective is to minimize the wall shear stress on optimized channel boundary. Note that not only the formulation procedure itself, but also the physical interpretation of optimized results is important for practical applications.

In this respect, the main contributions of this study are classified into 4 parts: first of all, comparison and interpretation of a significant difference between Newtonian and shear thinning non-Newtonian fluid modeling in the design perspective, and a suggestion of the reasonable design approach through this. Second, the relaxations of wall shear stress on implicit interface boundary between solid and fluid. Third, the suggestion of the sequential topology optimization method in order to perform the design efficiently. Finally, the application of proposed fluidic topology optimization to real systems (e.g., a femoral bypass graft).

The remainder of this paper is organized as follows. Section 2 explains the governing equation and boundary conditions for shear thinning non-Newtonian fluid modeling, and builds a numerical model using the mixed finite element model and the Galerkin method. In particular, this section compares Newtonian and shear thinning non-Newtonian fluids through a simple backward-facing step example. Section 3 then presents the standard topology optimization problem and carries out a design sensitivity analysis using an analytical method. In addition, the relaxation method of wall shear stress on the implicit interface boundary between solid and fluid (i.e., blood) is proposed. Next, Section 4 presents several numerical examples based on the proposed topology optimization approach, and shows that topology optimization can be successfully applied to the design of fluidic systems. In Section 5 we draw the conclusions and discuss findings of the study.

2. Shear thinning non-Newtonian fluids and mixed finite element modeling

In this section, we discuss the shear thinning phenomena, one of the main features of shear thinning non-Newtonian fluids and constitutive equations used to accurately describe their effect. The governing equation, boundary conditions, and finite-element model are defined prior to a numerical simulation of a shear thinning non-Newtonian fluid. In addition, we mention the differences between Newtonian and shear thinning non-Newtonian fluids through a simple backward-facing step example.

2.1. Constitutive equations for shear thinning non-Newtonian fluids

In general, the stress in a fluid is proportional to the rate of strain. Here, the proportionality parameter is known as viscosity, and is a function of strain. If the relation between stress and strain is linear, then the fluid is referred to as Newtonian; if the relation is non-linear, the fluid is shear thinning non-Newtonian. Shear thinning non-Newtonian fluids have a non-linear constitutive behavior, and a typical characteristic of a non-Newtonian fluid is its shear thinning effect, i.e., the viscosity decreases with an increased shear rate. Blood is a representative example of shear thinning non-Newtonian fluids that display the shear thinning effect; Fig. 1 explains the shear thinning non-Newtonian mechanism of blood. The figure depicts the