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A novel design method based on flow pattern construction for flow passage with low flow drag and pressure drop

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HIGHLIGHTS

- A design method for flow passage is developed based on flow pattern construction.
- Flow pattern construction is considered as a variational problem.
- Virtual volume force is derived as the solution of the variational problem.
- Porous media model and VOF model combine in the construction process of flow pattern.

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ABSTRACT

A novel design method for flow passage with low flow drag and pressure drop was developed based on flow pattern construction. The specific flow pattern with minimum viscous dissipation rate represents low pressure drop in the flow passage. Thus, the fluid flow requires to be optimized as a variational problem subject to the minimum viscous dissipation rate principle, which is also considered as flow pattern construction. By using calculus of variations, the governing equations for the construction of the specific flow pattern were derived from the functional extremum problem represented by the Lagrange multiplier equation. After that, a computational fluid dynamics model was set up and applied in the solution procedure of the governing equations to generate the geometry of the flow passages based on the flow pattern construction. As the illustrative examples to validate the proposed design method, the geometries of flow passages were optimized in terms of pressure drop in a wide range of *Re* numbers.

1. Introduction

Drag reduction of fluid flow is a fundamental issue in the field of process engineering. Defective design of flow passages will cause high pressure drop, costly energy consumption and severe flow maldistribution in process industrial application. More deleterious consequence of the high pressure drop for example unscheduled maintenance may be encountered in some special cases. Therefore, more and more attentions have been focused on the hydrodynamics in the flow passages of structure packing, plate heat exchangers, fluid distributor, fuel cells, etc. (Bassiouny and Martin, 1984; Bassiouny and Martin, 1984; Miura et al., 2008; Tsai et al., 2009; Wang et al., 2014; Said et al., 2011; Zheng et al., 2000; Wang, 2008; Wang, 2010; Tondeur et al., 2011; Tonomura et al., 2004). Generally, in terms of engineering, pressure drop is considered as an important parameter which evaluates the performance of equipment, and how to reduce the flow drag or pressure drop becomes one of the most important aspects of equipment and process design in practice (Kulkarni et al., 2007; Choi and Graham, 1998; Li et al., 2001; Ou et al., 2004; Liu et al., 2006; Zehforoosh and Hossainpour, 2010; Wang and Wang, 2012; Butt et al., 2014; Safikhani et al., 2011).

So far, most of the drag reduction technologies such as inserting the baffles, guide vanes and fluid distributors were developed empirically. The empirical method proved to be effective on the case-to-case basis, but the diversity and complexity of the real-life flow process prevented its wide industrial applications. Besides the empirical method, some theoretical flow drag reduction approaches were proposed. In particular, past decades witnessed the development of topology optimization that is referred to as shape optimization for structural design. As the design guidance, topology optimization can provide engineers with satisfying preliminary designs for apparatus in early conceptual stage (Borrvall and Petersson, 2003; Gresborg-Hansen et al., 2005; Amstutz and Andrä, 2006; Pingen et al., 2007; Duan et al., 2008; Zhou and Li, 2008; Pingen et al., 2010). The sophisticated topology optimization methodology was developed based on a solid theoretical background; however, it is known to be so complicated because of the

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costly sensitivity analysis especially for complex flow patterns and geometries of flow passages. For practical consideration, flow drag and pressure drop reduction in industrial scale applications requires the method for shape optimization which avoids intensive computation expense. Fortunately, the attempts developing more convenient algorithm for structural design are being made recently. Wang et al. (2010) proposed a heuristic optimality criterion algorithm to optimize the channel shape design of low *Re* number fluid flow through a right angle elbow and a converging T-junction, respectively. The heuristic algorithm avoided the sensitivity analysis, and more importantly, gave a reasonable optimal design of the flow passage. Wang et al. (2014) then utilized this heuristic algorithm to reduce the flow resistance in the flat-type arborescent fluid distributor. Wang's work demonstrated the promising prospects of such heuristic algorithm in optimal design for complex structures. Avvari and Jayanti (2013) proposed another heuristic shape optimization method for air/gas ducting in power and process plants. Their optimization method proved to be effective for pressure drop reduction in highly turbulent flows. In addition to the heuristic algorithm, field synergy principle (Guo et al., 1998; Tao et al., 2002; Guo et al., 2005), which was developed originally for convective heat transfer enhancement, was extended to the drag reduction for fluid flow. In the paper of Chen et al. (2008), a virtual volume force was derived from the field synergy principle using calculus of variations and then applied to construct the specific flow pattern with minimum viscous dissipation rate. Hereafter, Chen et al. (2009) studied the heavy oil transport process from the viewpoint of field synergy and optimized the fluid flow in the passage in terms of flow resistance. In literatures, the construction of flow pattern using calculus of variations with specific optimization objective proved to be well applied in process intensification (Chien, 1984; Meng et al., 2005; Jia et al., 2012; Chen and Meng, 2008; Guo et al., 2015). It is of course the progress to construct a specific flow pattern which is helpful to the transport process, but we still lack the knowledge of how to design the optimal geometries of flow passages when the specific flow pattern was constructed a priori.

Most recently, the work of Li et al. (2014), which focused on the optimization approach for convective heat transfer enhancement in solar receiver, is noteworthy. In their paper, the authors not only constructed the flow pattern with specific optimization objective, but also concentrated on how a practically applicable optimal design of flow passage can be obtained from the constructed flow pattern.

However, in term of flow drag reduction, theoretical and easy-to-use design method for flow passage has rarely been reported in literatures despite intensive efforts devoted to this end. In view of this, a novel design method based on flow pattern construction for flow passages with low flow drag and pressure drop has been developed in this study. The flow pattern with minimum viscous dissipation rate represents low pressure drop in the flow passage, and thus the first step of the design method is to construct an optimal flow pattern with minimum viscous dissipation. For the purpose of the flow pattern construction, the fluid flow requires to be optimized as a variational problem subject to the minimum viscous dissipation rate principle. By using calculus of variations, the governing equations for the construction of the specific flow pattern are derived from the functional extremum problem represented by the Lagrange multiplier equation. As the innovation of this paper, the governing equations for the construction of specific turbulent flow are obtained based on the k-ε turbulence model, which have rarely been reported in literatures to the authors' knowledge. After the governing equations for the specific flow pattern were obtained, a CFD model that combines porous media model and volume of fluid (VOF) model has been set up and applied to the construction procedure of the specific flow pattern to generate the flow passage geometry with low pressure drop. The illustrative examples of fluid flow through the two-dimension flow passages are presented to demonstrate the validity of the proposed design method, using the CFD software Fluent.

2. Design method for flow passage

2.1. Governing equations for fluid flow

For steady-state incompressible laminar flows, the fluid flow can be described by a set of equations including the continuity and momentum equations.

$$\nabla \cdot (\rho U) = 0 \tag{1}$$

$$\nabla \cdot (\rho U U) = -\nabla P + \nabla \cdot \mu(\nabla U + \nabla U^T) + F \tag{2}$$

where F is the volume force.

In turbulent flows, the corresponding governing equations can be written as follows:

$$\nabla \cdot (\rho U) = 0 \tag{3}$$

$$\nabla \cdot (\rho U U) = -\nabla P + \nabla \cdot \mu_{eff}(\nabla U + \nabla U^T) + F \tag{4}$$

The turbulent influences are taken into account by introducing effective viscosity μ_{eff}, which is the sum of turbulent viscosity μ_t and molecular viscosity μ:

$$\mu_{eff} = \mu_t + \mu \tag{5}$$

Following the recommendation of Modi and Jayanti (2004), the standard k-ε two-equation turbulence model is employed to calculate turbulent viscosity μ_t:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{6}$$

where C_μ is a model constant, k is the turbulent kinetic energy, and ε is the turbulent dissipation rate. The turbulent kinetic energy, k, and its dissipation rate, ε, are calculated by the following transport equations, respectively:

$$\nabla \cdot (\rho U k) = \nabla \cdot [(\mu + \frac{\mu_t}{\sigma_k})\nabla k] + G_k - \rho\varepsilon \tag{7}$$

$$\nabla \cdot (\rho U \varepsilon) = \nabla \cdot [(\mu + \frac{\mu_t}{\sigma_\varepsilon})\nabla \varepsilon] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{8}$$

where G_k represents the generation of turbulent kinetic energy due to the mean velocity gradients; $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are model constants; σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively. For incompressible flows, the variation of turbulence kinetic energy due to buoyancy and fluctuating dilatation is neglected.

2.2. Flow pattern construction

The viscous dissipation in course of fluid flow denotes the mechanical energy loss, which is also considered as the required mechanical energy maintaining the fluid flow. Consequently, the fluid flow can be optimized by minimizing the viscous dissipation, as referred to as minimum viscous dissipation (MVD) principle in (Chen et al., 2008, 2009). According to the MVD principle, we have the following optimization objective function for fluid flow:

$$J_\phi = \iint_\Omega \phi \, \mathrm{d}S \tag{9}$$

where Ω is the flow passage, and the viscous dissipation function of incompressible Newtonian fluid takes the following form:

$$\phi = \mu_{eff}[(\nabla U + \nabla U^T) : \nabla U] \tag{10}$$