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An Evolutionary Optimization Method to Design Shapes of Flow Channels

Min Tao[a,b], Kai Guo[a,b,*], Hui Liu[a,b], Chunjiang Liu[a,b,*]

[a]School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, China
[b]State Key Laboratory of Chemical Engineering, Tianjin University, Tianjin 300072, China
guokaitianjin@163.com

This paper develops an evolutionary optimization method to design flow channel shapes and reduce the pressure drop. The optimization method includes three steps.
Firstly, an initial channel shape is given, and the original velocity field can be simulated numerically.
Then by adding a virtual body force to the original flow field, the optimal flow pattern can be constructed with minimum viscous dissipation.
Finally, the fluid cells having lower dynamic pressure are automatically substituted with the solid zones in the constructed flow pattern.
This process is repeated until the channel volume constraint is satisfied, and the optimal channel shape can be obtained. To demonstrate the validity of the multistep evolution optimization method, three numerical examples are presented, including a T-shape channel, a bend and a diffuser.

1. Introduction

Shape design of flow channels is a fundamental issue for fluid equipment in engineering applications, such as fluid distributors, fuel cells and reactors. Suitable design could reduce flow drag and save energy, even may improve the performance of equipment greatly. Therefore, considerable attentions have been focused on energy-efficient design of channel shape over the past years.
Based on the concept of design in nature, Bejan (1996) proposed the constructal theory, which contributes a lot to the development of channel shape optimization. Vargas et al (2007) and Ordonez et al (2004) introduced the constructal law to the field of fuel cells. They optimized the internal structure and external structure of fuel cells and reduced flow drag. Luo and Tondeur (2004) and later Luo and Tondeur (2005) applied the constructal law to design shapes of fluid distributors. Their optimal design improved the flow distribution and reduced flow resistance. Inspired by natural phenomenon fluvial erosion in river basins, Wang et al (2010) proposed a heuristic optimality criterion algorithm for shape design of fluid flow. They obtained optimal channel shapes by exchanging solid cells with fluid cells.
Recently, an optimization method based on the calculus of variations has attracted considerable attentions. The calculus of variations is a mathematical method to seek the extremum of the functional or the extremal function associated with the variational problem. So far, the method has been successfully applied to many fields such as enhancement for convective heat transfer (Chen et al, 2009a), drag reduction in fluid flow (Chen et al, 2008) and convective mass transfer (Chen et al, 2009b). It is noteworthy that Chen et al (2008) introduced the concept of field synergy principle (Tao et al, 2002) and presented the minimum mechanical energy dissipation principle for fluid drag reduction. In their research, a virtual body force was added, which could modify the flow field to an optimal flow pattern with minimum viscous dissipation. More recently, the idea of optimal flow pattern construction was employed to design heat conduction pathways (Guo et al, 2016a), heat transfer tubular (Guo et al, 2016b), two-dimensional flow channels (Guo et al, 2015a), three-dimensional flow channels (Tao et al, 2016), and intensify mixing process (Guo et al, 2015b).
The purpose of this work is to develop a multistep evolution optimization method based on flow pattern construction to research the proper channel design.

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2. Statement of the optimization method

In the present work, channel shape optimization is performed for two-dimensional steady, laminar incompressible fluid flow, and viscous heating has not been considered for simplicity.

2.1 Flow pattern construction

Before the multistep evolution optimization, an optimal flow pattern needs to be constructed. The optimal flow pattern is the flow field with minimum viscous dissipation, which ultimately determines the energy loss or pressure drop.
Flow pattern construction is based on the minimum mechanical energy dissipation principle (Chen et al, 2008). In mathematics, construction of the ideal flow pattern can be converted into a conditional extremum problem. The objective function of the extremum problem is the viscous dissipation and the constraint is the continuity equation. According to their work, necessary conditions are obtained as follows for the ideal flow pattern, i.e. Navier–stokes equations with a body force - Eq(1)) and the body force(Eq(2).

$$\rho \mathbf{V} \bullet \nabla \mathbf{V} = -P + \mu \nabla^2 \mathbf{V} + \mathbf{F} \tag{1}$$

$$\mathbf{F} = \rho \mathbf{V} \bullet \nabla \mathbf{V} \tag{2}$$

Where **F** is body force
When the body force **F** is added to the flow field, the optimal flow pattern can be constructed.

2.2 Multistep evolution optimization

The multistep evolution is the core of optimization process. Based on the flow pattern optimized in section2.1, the optimization method is developed.
In the multistep evolution process, the channel volume will continuously shrink to the shape with a predetermined value according to the evolution criterion. Here, dynamic pressure of fluid cells is selected as the evolution criterion, that is, a certain percentage of fluid cells having lower dynamic pressure in the constructed flow pattern will be substituted with solid zones where the fluid cannot flow through.
According to our practical calculation experience, the larger value of elimination rate in shape evolution procedure will make the evolution faster, but there is also an increasing possibility that the geometry will finally evolve to an undesirable shape in terms of pressure drop.
In the present work, an appropriate range of 1 % ~ 3 % for elimination rate per step is adopted considering both computation expense and accuracy.

2.3 Implementation of evolutionary optimization method

The evolutionary optimization procedure can be described in detail as follows:

Step 1 Specify the computation domain, the boundary conditions and the channel volume constraint, compute the initial flow field with **F = 0**

Step 2 Apply the body force **F** - Eq(2) to the initial flow field and construct the optimal flow pattern

Step 3 Substitute the fluid cells having lower dynamic pressure in the constructed flow pattern with solid zone, and generate a new channel shape

The optimal channel can be obtained by repeating Step 2 and Step 3 until the volume constraint is satisfied.

3. Numerical examples

In this section, three kinds of numerical examples are given to demonstrate the evolutionary optimization method. The working fluid is water. The parabolic velocity profile in fully developed laminar pipe flow is imposed at the inlet boundary. At the outlet boundary, the gauge pressure is set to zero. Non-slip boundary condition at the wall surface is adopted. The computation domains and boundary conditions are shown in Figure 1.
The CFD code Fluent 6.3 is utilized in our numerical computation. The velocity and pressure are linked using the SIMPLE algorithm with the convection and diffusion terms discretized using the QUICK scheme.

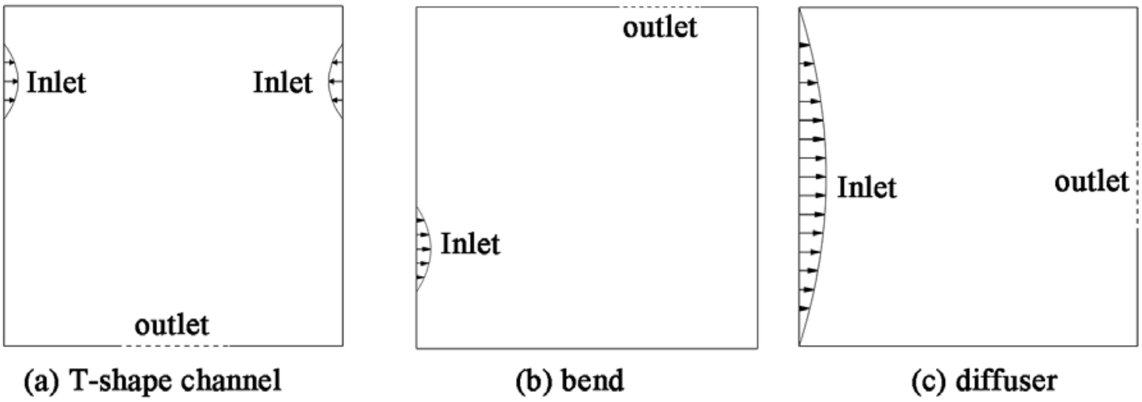

Figure 1: Computation domains and boundary conditions for a T-shape channel, a bend and a diffuser

3.1 Design of a T-shape channel

As a common junction structure for fluid distribution network, T-shape channel is usually selected as an elemental block for the self-assembly of compact constructal distributors. The mass flow rate of water through the inlet is 3.4×10^{-2} kg/s, corresponding to a Reynolds number of 50. The prescribed volume ratio α is 44.44 %. The total number of elements in the grid is 32,400, corresponding to a 'resolution' for the computation domain of 180×180.

From Figure 2, we can see that the vortexes disappear in the optimal flow pattern by the body volume force. According to the evolutionary procedure discussed in section 2.3, the channel shape is optimized to render the real flow field to approximate the optimal flow pattern by substituting the fluid cells with solid zones. Finally the optimal T-shape channel satisfying the volume constraint is shown in Figure 3.

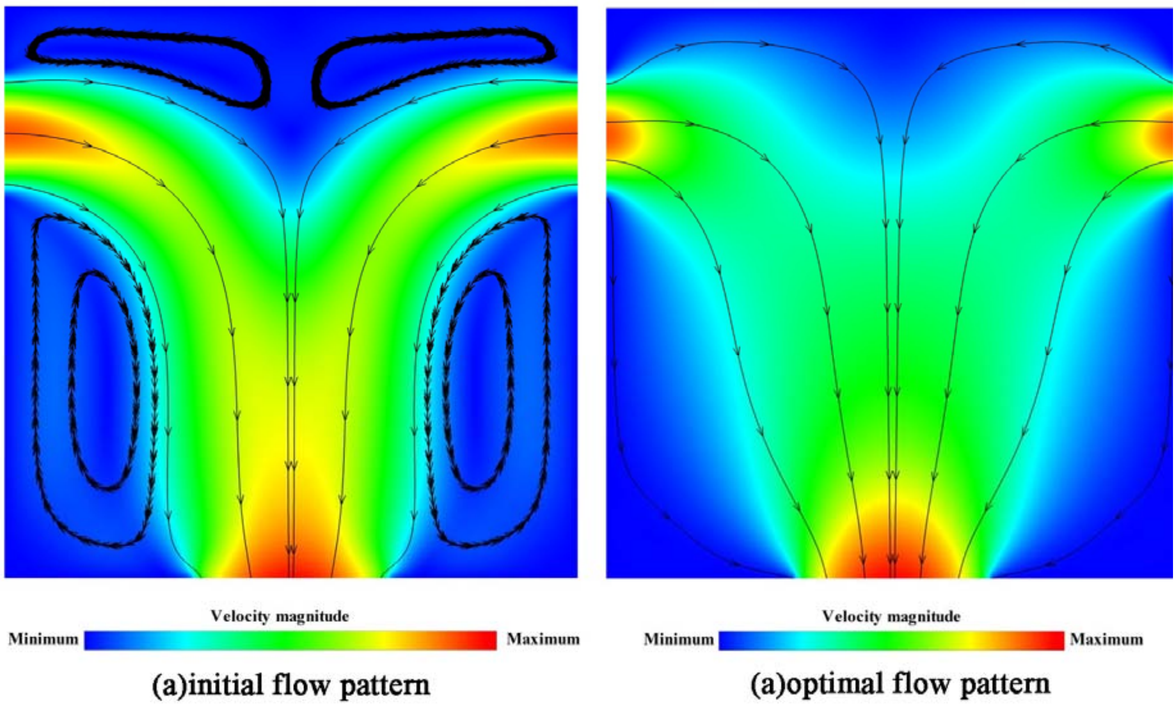

Figure 2: Comparison of initial and optimal flow patterns in initial computational domain when Re=50

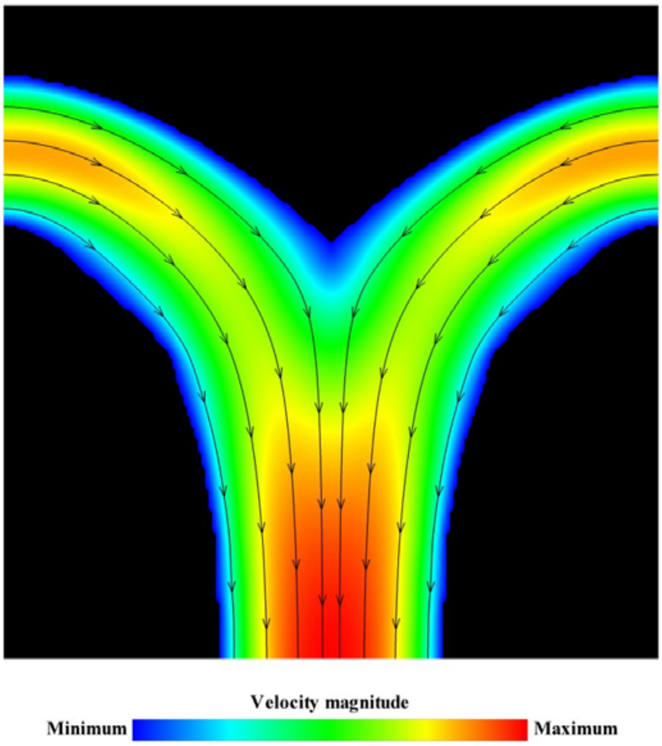

Figure 3: Optimal T-shape channel with flow field and streamlines

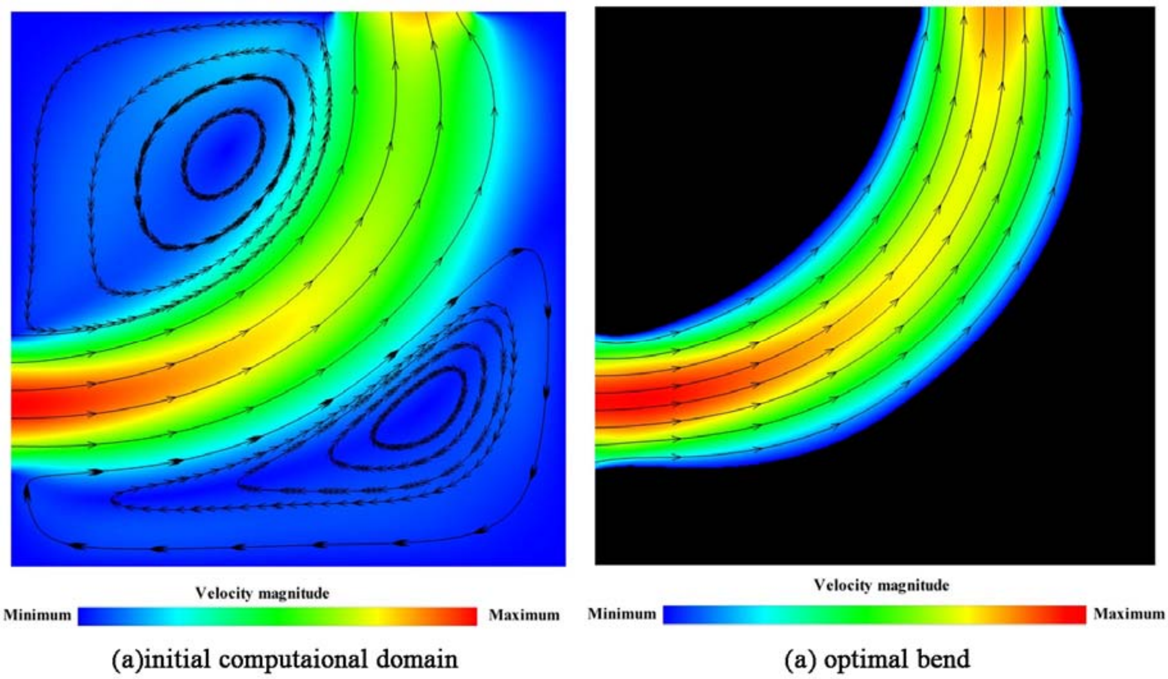

Figure 4: Comparison of the flow patterns in initial computational domain and optimal bend when Re=75

3.2 Design of a bend

Here, we consider the design of a two-dimension bend. The mass flow rate of water through the inlet is 5×10^{-2} kg/s, corresponding to a Reynolds number of 75. The predetermined volume ratio α is 35.42 %. The total number of elements in the grid is 230,440, corresponding to a 'resolution' for the computation domain of

480×480. The original flow field in computation domain reveals that there are two vortexes dissipating substantial mechanical energy. Obviously, most of the energy loss can be attributed to the singular effect in the zone where the flow direction changes sharply. With the evolutionary optimization procure being performing, the bend shape is successfully identified from the computation domain after 22 iterations. Compared with the original flow field, it can be seen that the vortexes do not exist anymore and the streamlines become smoother in Figure 4. That implies that the energy loss or pressure drop can be decreased greatly.

3.3 Design of a diffuser

Lastly, we take the example of a diffuser. The mass flow rate of water through the inlet is 3.6×10^{-2} kg/s, corresponding to a Reynolds number of 54. The prescribed volume ratio α is 50 %. The total number of elements in the grid is 22,500, corresponding to a 'resolution' for the computation domain of 150 × 150. After about 70 iterations, the optimized diffuser shown in Figure 5 is satisfying in comparison with the results (Duan et al, 2008).

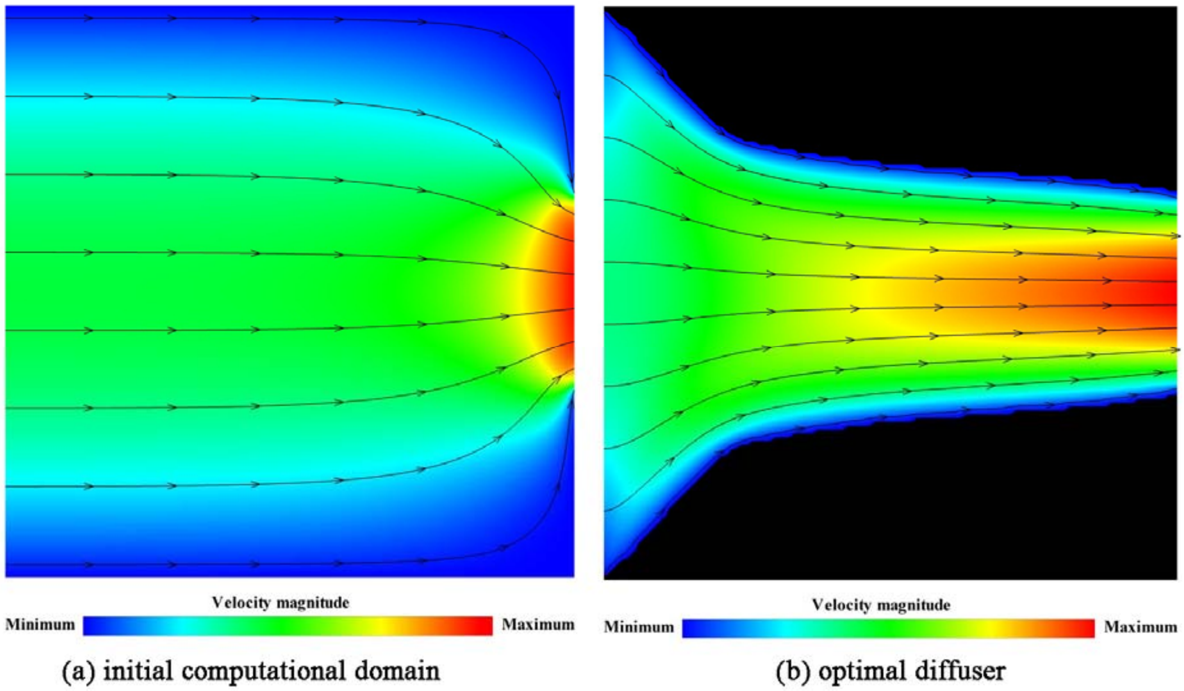

Figure 5: Comparison of the flow patterns in initial computational domain and optimal diffuser when Re=54

4. Discussions and conclusions

An evolutionary procedure combining flow pattern construction and multistep evolution is developed to optimize shapes of flow channels. The main conclusions are described as follows:

1. The multistep evolution optimization method is proposed. The optimal flow pattern is constructed firstly. Then the fluid cells are replaced continuously by the solid zones and optimal channel shape is generated.

2. Numerical examples are presented, including a T-shape channel, a bend and a diffuser. It proves that the optimal channel shapes are uniform with those reported in the literatures.

Therefore, validity of the optimization method can be confirmed.

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