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Topology Optimization for Vortex-type Fluidic Diode in Hybrid Loop-Pool Type SFRs

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1. Introduction

Fluidic diode (FD) is a simple passive device having different flow resistance according to its flow direction. Recently, this fluidic diode has been proposed as a key safety flow control device in pool reactor auxiliary cooling system (PRACS) of Hybrid Loop-Pool type SFRs. Fluidic diode restricts flow in forward direction under normal operation, while it allows backward flow under loss of forced circulation (LOFC) transient condition [1]. Performance of fluidic diode are generally defined by diodicity (Di), a ratio of pressure drop in forward and backward directions.

A vortex-type fluidic diode is most common design and it is composed of a circular chamber with an axial port at center and a tangential port on the side. A general geometry of the vortex-type fluidic diode can be seen in Fig. 1. In reverse flow mode in Fig. 1 (a), flow comes from tangential port and generate swirl flow inside the chamber which make significant pressure loss. In forward flow mode in Fig. 1 (b), on the contrary, flow comes from axial port and flow directly to tangential port and leads to relatively low pressure loss. This concept has been studied from several decades ago. An experiment for vortex throttles was conducted to compare the performance of the round-edged design and square-edged one [2]. A new design modified from basic one was suggested and analyzed through CFD study and experiments. Factors affecting its performance was analyzed and design guide lines were proposed [3,4]. Several studies have been conducted to analyze the modified design and flow characteristics have been founded. A detailed CFD study with large eddy simulation (LES) was performed and flow characteristics related with internal recirculation zone (IRZ) were founded [5]. Thus one can expect that vortex-type fluidic diode has potential for further improvement. In this study, vortex-type fluidic diode design with topology optimization technique was conducted to improve its performance.


(a) (b)

Fig. 1. General gemetry of vortex diode [6].

2. Topology Optimization

Topology optimization is one of the optimization techniques for seeking out material distribution given domain and constraints. This topology optimization was first introduced in the material science and currently expanding its area to other research fields such as heat transfer and fluid flow [7-9]. In topology optimization, material distribution is generally expressed as density function (γ) for each grid. Thus, the main purpose of topology optimization is to find out optimal density function which can minimize a certain objective function in the given domain. In principle, density function should have a discrete number, 0 for solid region and 1 for fluid region. However, it is practically assumed to be a continuous function ranging between 0 and 1 for numerical stability.

In the topology optimization, the following form of continuity equation is used for solving incompressible flow.

$$\nabla \cdot \boldsymbol{u} = 0 \qquad (1)$$

However, the Navier-Stokes equation with an additional Darcy friction force term is used as momentum equation as below. The Darcy friction force term applies virtual force on the fluid flow in the optimization domain. It is assumed that Darcy friction force is proportional to the velocity.

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u}\right) = -\nabla p + \mu \nabla^2 \boldsymbol{u} + \boldsymbol{f} \qquad (2)$$

$$\boldsymbol{f} = -\alpha \boldsymbol{u} \qquad (3)$$

The coefficient alpha (α) is a degree of impermeability and expressed in terms of density function (γ). The value of alpha is generally penalized using the following convex and q-parameterized interpolation function. [7]

$$\alpha(\gamma) = \alpha_L + (\alpha_U - \alpha_L)\frac{q(1-\gamma)}{q+\gamma} \qquad (4)$$

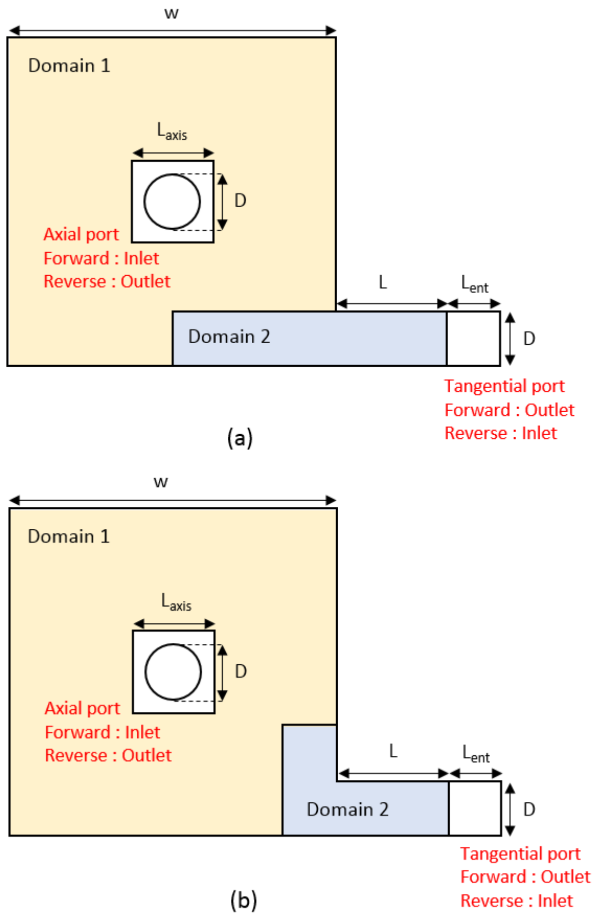
In this equation, the value of α_L set as zero and the value of α_U set as a very large number. Therefore, in fluid region (γ = 1), the value of alpha becomes zero, leading the momentum equation (2) to the general Navier-Stokes equation. On the other hand, in solid region (γ = 1), the value of alpha becomes very large by suppressing the fluid flow due to its large flow resistance. In the intermediate region (0 < γ < 1), the alpha has value between α_L and α_U. However, the parameter q penalizes the alpha value to 0 or 1 because of its non-linear feature.

The parameter q determines the degree of penalization. As q becomes smaller, the relation between α and γ becomes non-linear.

3. Design of SFR Vortex-type Fluidic diode

3.1. Optimization method

Topology optimization was conducted for the vortex-type fluidic diode focusing on the main chamber and the tangential port. Diodicity (Di) was used as an objective function to be maximized. The selected 2D domain is shown in Fig. 2. The chamber domain was defined as a square in order to have large degree of freedom in the optimization process. The rectangular domain was attached next to the chamber domain to reflect tangential port region. The axial port was simply assumed as circle at center of chamber domain. In the forward flow mode, the inlet velocity boundary condition was assigned at the axial port (center circle), and the pressure condition was assigned at the rectangular port end. In the reverse flow mode, a pressure outlet condition was assigned at the axial port (center circle), and velocity inlet boundary condition was assigned at the rectangular port end. An inlet Reynolds number was set as 300 in this study. The non-dimensional geometrical parameters in the optimization domain was selected as follows : 6.0 for aspect ratio of the chamber (w/D), and 3.0 for aspect ratio of the tangential port ((L+L_{ent})/D). The chamber aspect ratio was selected according to previous result [2].



(a)

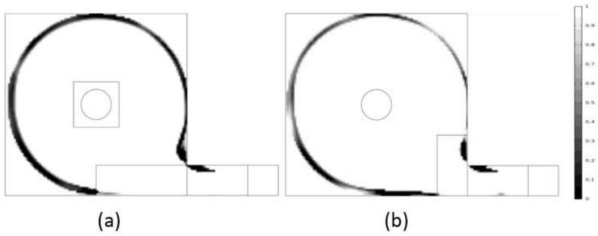
(b)

Fig. 2. Optimization domain and Inlet/Outlet boundary

In this study, whole optimization domain was divided in two regions, the chamber domain (domain 1) and the tangential port domain (domain 2). Optimization for the two domains were conducted independently. Optimization was first conducted only for the domain 1. Then subsequent optimization was conducted in the whole domain using the result obtained in the previous step as an initial condition. Division of two domains is seen in Fig. 2. The parameters of the penalization function was selected as follows : $1 \times 10^8 \sim 5 \times 10^8$ for α_U, 0.1 ~ 0.2 for q, and 0.0 for α_L. The value of initial density function for each grid was set as 1.0, (= fluid), in the whole domain.

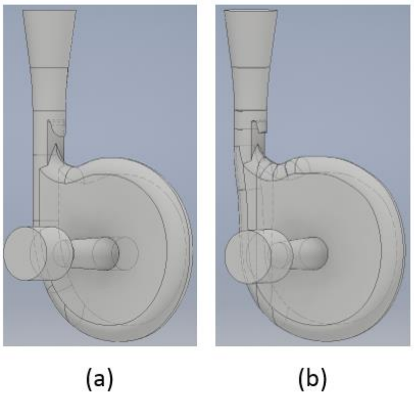
3.2. Result and post-processing

The topology optimization results were finally obtained as shown in Fig. 3. According to the result, the diodicity (Di) was increased from 15.47 to 19.247 in the domain division (a), to 21.284 in the domain division (b). Based on optimization results, the 3D geometries of the vortex-type fluidic diode port were obtained as shown in Fig. 4. The edges in the chamber were rounded and the sharp edges and rough surfaces were smoothed. A diffuser was attached to the end of each port.



(a) (b)

Fig. 3. Optimization result



(a) (b)

Fig. 4. 3D geometry for CFD analysis

4. Conclusion

The design of the vortex-type fluidic diode for hybrid loop-pool type SFRs was optimized using novel topology optimization technique. The optimization was conducted in simplified 2-D domain and finally the diodicity of the fluidic diode has been improved by 37%. As further works, the following tasks are on-going and will be performed.

1) Validation using detailed 3-D CFD analysis and performance evaluation.
2) Further design improvement based on parametric study for axial port location, size shape, and etc.

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