Enhanced Finned Tube Heat Exchanger Design through Topology Optimization

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Abstract

Finned tube heat exchangers are widely used in air conditioning systems. Various fin structures have been proposed and studied in literature to enhance their heat transfer performance. However, enhancement in heat transfer is often accompanied by pressure drop penalty. This study utilized a numerical method, topology optimization, to design novel fin structures for enhancing heat transfer performance while maintaining pressure drop as low as possible. In the optimization process, volume constraints were applied to add fins into the original finned tube with the assumption that increased heat transfer areas would lead to better heat transfer performance. Minimizing pressure drop was set as the objective so that the fins were added in a manner that could achieve better overall performance. Finally, the performance of the optimized fin structures was validated through full 3D conjugate heat transfer simulation.

Keywords: Topology optimization; finned tube heat exchanger; increased heat transfer areas; minimize pressure drop

1. Introduction

The finned tube heat exchanger is an important component in air conditioning systems for heat transfer between refrigerants and air. Improving its air-side heat transfer is the main potential for increasing its efficiency since the thermal resistance of air-side is 5-10 times of that of refrigerants side [1]. Thus, various fin structures have been proposed in literature to enhance air-side heat transfer, such as wavy fins [2] and louver fins [3].

Different from these experience based designs, topology optimization, a mathematical optimization method, could generate non-conventional designs. It was initially developed for designing mechanical elements that can withstand given loads with minimum amounts of materials [4]. In 2003, Borrvall and Petersson [5] tuned it to include physics of fluid flow and demonstrated successful application in flow path designs with minimized pressure drop. Following this pioneering work, Gersborg-Hansen et al. [6] extended the flow region from Stokes flow to incompressible laminar viscous flow. More similar studies could be seen in [7-9].

In topology optimization, the design domain is treated as fictitious porous media and its local porosity is represented by a design variable which varies continuously from 0 to 1. If a point is occupied with solid, the design variable will take a value of 0. If a point is occupied with fluid, the design variable will take a value of 1. In this way, the initial problem of designing flow paths is transferred as a problem of optimizing design variable fields, which is continuous and allows utilizing gradient-based optimization methods.

In this work, topology optimization is utilized to improve the performance of a plain plate finned tube heat exchanger. With the idea that heat transfer could be enhanced by increasing heat transfer areas, extra fins are introduced by exerting a volume constraint during optimization. Minimizing pressure drop is set as the objective to avoid high pumping power penalties. The fluid dynamics modelling is described in section 2. Formulation and implementation of topology optimization are presented in section 3. Section 4 gives the results and discussion, followed by conclusions in section 5.

2. Fluid dynamics modelling

A periodically repeating portion of original finned tube is shown in Fig. 1. The tube diameter is 6.7 mm and the fin is 19 mm long. Air flows across the tube in x direction, and the computational domain is extended by 19 mm at the outlet to avoid back flow problem in simulation. The top and bottom surfaces are fin walls and both sides are set as symmetry boundary conditions.

Due to manufacturing restrictions, introduced fins could not be on the edges. Thus, only parts of the air paths are assigned as design domains as highlighted in Fig. 1.

In the design domain, governing equations include the continuity equation and the modified Navier-Stokes equation:

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

$$\rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\nabla P + \mu \nabla^2 \boldsymbol{u} - \alpha \boldsymbol{u} \quad (2)$$

Where $\boldsymbol{u}$ is the velocity vector, P is the pressure, ρ is the air density, and μ is the air dynamic viscosity. $\alpha\boldsymbol{u}$ is the Brinkman friction force term initiated from the treatment of fictitious porous media. α is a function related to local porosity.

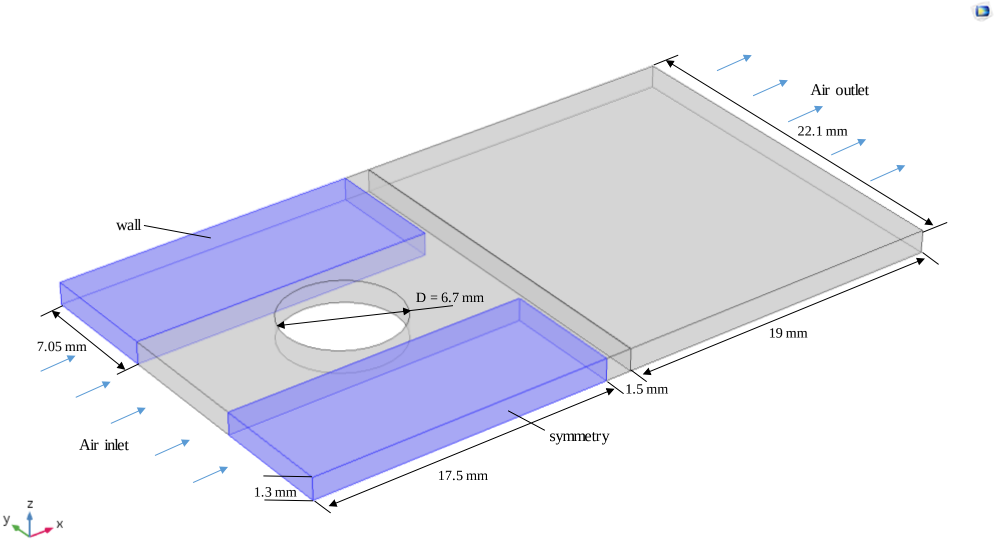


Figure 1. Computational domain and dimensions of the original finned tube

$$\alpha(\mathbf{r}) = \alpha_{min} + (\alpha_{max} - \alpha_{min})\frac{q[1-\gamma(\mathbf{r})]}{q+\gamma(\mathbf{r})} \qquad (3)$$

Where $\mathbf{r}$ is the local coordinate, $\gamma(\mathbf{r})$ is the local design variable, q is a parameter that controls the convexity of this function. α_{max} and α_{min} are the maximum and minimum values of α, respectively. For elements with $\gamma = 0$, according to this function, α will take the value of α_{max}, which is set as 10^5, resulting in a large friction force so that those elements work as solid. For elements with $\gamma = 1$, α will take the value of α_{min}, which is set as 0, thus retaining the normal Navier-Stokes equation and those elements are considered as fluid.

For other simulation domains, the governing equations are normal continuity and Navier-Stokes equations.

3. Topology optimization

3.1 Problem formulation

The principle of this optimization work is to increase heat transfer areas with low pressure drop penalties. Thus, minimizing pressure drop is set as the objective, and a volume constraint is applied to generate fins. The optimization formulation is summarized as followings:

Minimize: ΔP
Subject to: $0 \le \gamma(\mathbf{r}) \le 1$ (4)
$\int_\Omega \gamma(\mathbf{r}) d\Omega \le \bar{V}$ (5)
Governing equations

where $\bar{V}$ is the predefined maximum volume occupied by fluid.

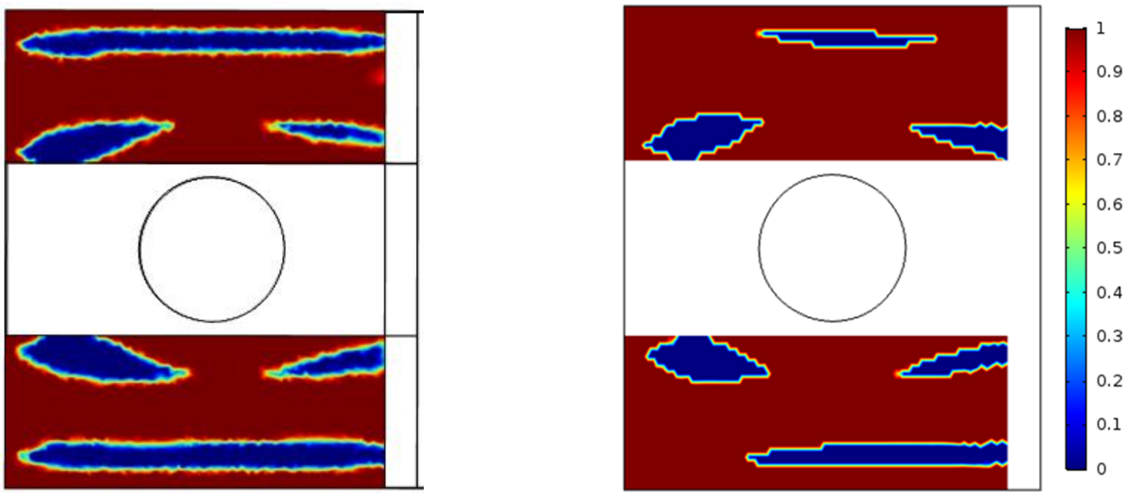
3.2 Implementation of topology optimization

Single phase laminar flow module and optimization module of COMSOL Multiphysics 5.2a are utilized in this study. The inlet velocity under optimization is 2 m/s. For the volume constraint $\bar{V}$, two cases are studied: 75% and 85% of the design domain areas. To gain a uniform profile along z direction for consideration of manufacturing, γ is kept the same for elements with the same (x,y) coordinates through the “General Extrusion” function in COMSOL.

Initially, the whole design domain is set as $\gamma = 1$. Then the fluid dynamics problem is solved, and the objective and constraints are evaluated. Their sensitivities with respect to the design variable field are also computed, based on which the design variable field is updated through GCMMA optimization method [10] in COMSOL. The new design variable field will result in a new flow field and it is updated iteration by iteration following the same process. To govern the process of convergence to a well separated 0/1 design variable field, the convexity parameter q is gradually increased during the optimization process.

4. Results and discussion

The final optimized design variable fields are shown in Fig. 2. In each design domain, 3 fins are generated in streamline shapes.



(a) (b)

Figure 2. Topology optimized design variable fields of (a) 75% and (b) 85% volume constraint

To examine the performance of the topology optimized finned tube heat exchanger, standard CFD analysis has to be performed. The profiles of the new fins are firstly extracted by a level curve of $\gamma = 0.5$, smoothed and reconstructed as Fig. 3.

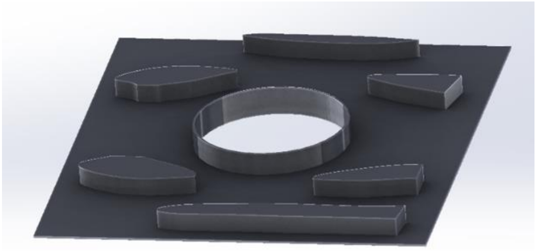


Figure 3. Reconstructed fin structure based on the optimization result of 85% volume constraint

The solid material is aluminium with a thermal conductivity of 205 $\mathrm{W/m \cdot K}$. In CFD analysis, air inlet temperature is 307.47 K and inlet velocity varies from 1 m/s to 3 m/s. The tube wall temperature is set as a constant of 318.57 K. As air flows through the finned tube, it will be heated up by fins and the center tube wall. The amount of heat absorbed is an index for the heat transfer performance. Another important parameter for evaluating finned tube heat exchangers is the pumping power, which is calculated as the product of the volume flow rate and the pressure drop. Smaller pumping power and higher heat absorption rates are favourable.

When comparison with the original plain plate fin configuration, as shown in Fig. 5, the heat absorbed in the topology optimized structure is always higher under the same pumping power or the pumping power is always lower if the same amount of heat has to be absorbed. This operation characteristic verifies the usefulness of the optimized structure.

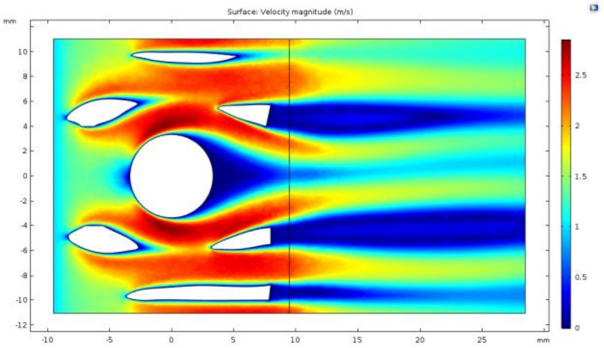


Figure 4. Velocity profile of the optimized structure of 85% volume constraint at inlet velocity of 1 m/s

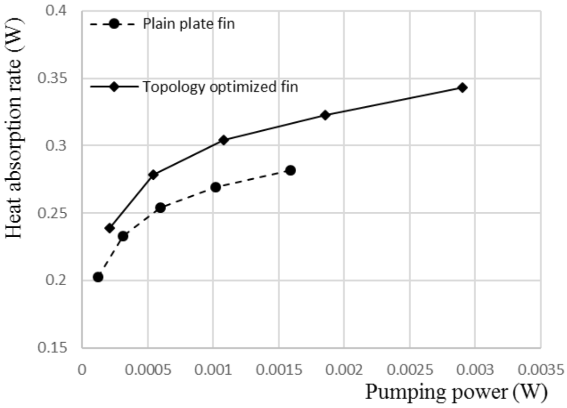


Figure 5. Performance comparison of the optimized structure over the original plain plate fin structure

It should be noticed that topology optimization could also cope with coupled fluid flow and heat transfer problems with interpolation of thermal conductivities between solid and fluid. For example, Joe Alexanderson et al. [11] successfully designed 3D large scale heat sinks based on natural convection by topology optimization. However, cooperating heat transfer physics induces extra interpolation functions and convexity parameters. Based on the authors' experience, the convexity parameters have to be set in good pairs with each other and need to gradually change during optimization process to govern the process of convergence to discrete 0/1 results. No standard guidelines for choosing these parameters make the problems more difficult, which normally require massive work of trial and errors to obtain meaningful structures. This issue calls for further research for topology optimization of coupled fluid flow and heat transfer problems.

5. Conclusions

In this study, topology optimization is utilized to design high thermal performance finned tube heat exchangers. By imposing a volume constraint and setting minimizing pressure drop as the objective, new fins structures are generated, significantly increasing heat transfer areas with low pumping power penalties. Comparing to original plain plate fins, the optimized structure achieves higher heat transfer rates under the same pumping power requirements. Therefore, this work shows the great potential of designing thermofluid equipment with topology optimization facilitated by COMSOL Multiphysics.

Reference

[1] C. C. Wang, C. J. Lee, C. T. Chang and S. P. Lin, Heat transfer and friction correlation for compact louvered fin-and-tube heat exchangers, International Journal of Heat and Mass Transfer, vol. 42, no. 11, pp. 1945-1956 (1999).

[2] T. Kuvannarat, C. C. Wang and S. Wongwises. Effect of fin thickness on the air-side performance of wavy fin-and-tube heat exchangers under dehumidifying conditions. International journal of heat and mass transfer, vol 49, no. 15, pp. 2587-2596, (2006)

[3] C. C. Wang, K. Y. Chen, J. S. Liaw and C. Y. Tseng, An experimental study of the air-side performance of fin-and-tube heat exchangers having plain, louver, and semi-dimple vortex generator configuration, International Journal of Heat and Mass Transfer, vol. 80, pp. 281-287 (2015).

[4] M.P. Bendsøe, N. Kikuchi, Generating optimal topologies in structural design using a homogenization method, Comput. Methods Appl. Mech. Eng. 71 197–224 (1988).

[5] T. Borrvall, J. Petersson, Topology optimization of fuids in Stokes flow, Int. J. Numer Methods Fluids. 107 77–107 (2003).

[6] A. Gersborg-Hansen, O. Sigmund, R. Haber, Topology optimization of channel flow problems, Struct. Multidiscip. Optim. 30 (3) 181–192 (2005).

[7] L.H. Olesen, F. Okkels, H. Bruus, A high-level programming-language implementation of topology optimization applied to steady-state Navier–Stokes flow, Int. J. Numer. Meth. Engng. 65 975–1001 (2006).

[8] C. Othmer, T. Kaminski, R. Giering, Computation of topological sensitivities in fluid dynamics : cost function versatility, in Proceedings of ECCOMAS CFD 2006 (2006).

[9] N. Aage, T.H. Poulsen, A. Gersborg-Hansen, O. Sigmund, Topology optimization of large scale stokes flow problems, Struct. Multidiscip. Optim. 35 175–180 (2008).

[10] K. Svanberg, MMA and GCMMA – Fortran versions March 2013, Royal Institute of Technology, pp. 1-23 (2013).

[11] Alexandersen, J., Sigmund, O. and Aage, N., Large scale three-dimensional topology optimisation of heat sinks cooled by natural convection. International Journal of Heat and Mass Transfer, 100, pp.876-891 (2016).