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Review

Multi-disciplinary, multi-objective and multi-scale constructal optimizations for heat and mass transfer processes performed in Naval University of Engineering, a review

Huijun Feng, Lingen Chen*, Zhihui Xie

Institute of Thermal Science and Power Engineering, Naval University of Engineering, Wuhan 430033, PR China
Military Key Laboratory for Naval Ship Power Engineering, Naval University of Engineering, Wuhan 430033, PR China
College of Power Engineering, Naval University of Engineering, Wuhan 430033, PR China

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ABSTRACT

This mini review paper summarizes the multi-disciplinary, multi-objective and multi-scale constructal optimizations for heat conduction and thermal insulation processes, fluid flow processes, convective heat transfer processes of fins, vascular networks and heat exchangers, mass transfer processes of porous mediums, heat and mass transfer processes of solid–gas reactors and solid oxide fuel cells as well as generalized transfer process performed in the Naval University of Engineering. The results show that the performances of transfer bodies are improved when model improvements are considered, therefore, the application values are considerable for designers. New optimal constructs of various transfer processes are obtained when different indexes are taken as the optimization objectives, and different optimal design schemes can be chosen according to practical design requirements. The flows of generalized transfer process include heat flow, mass flow, material flow, etc. Many optimal results of various transfer processes are special cases of the generalized transfer process. Performance improvements are made and different optimal design schemes are obtained in this review, which help to implement optimal designs of practical transfer processes and systems.

Contents

* Corresponding author at: Institute of Thermal Science and Power Engineering, Naval University of Engineering, Wuhan 430033, PR China.
E-mail address: lingenchen@hotmail.com (L. Chen).

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1. Introduction

Constructal theory [1–14] is a so powerful theory that it is widely used, ranging from engineering to geophysics and biology. Many scholars have studied various transfer systems by taking different optimization objectives based on this theory. Multi-disciplinary, multi-objective and multi-scale constructal optimizations have become the frontiers [1–14] of constructal theory. Constructal theory provides the theoretical bases for unified explanations for the generations of natural tissues and structures and the designs of various flow structures.

Such a powerful theory was put forward by Bejan [1], and was firstly applied into heat conduction optimization of the electronic device. The core of constructal theory is constructal law, which was described as follows [1]: "For a finite-size flow system to persist in time (to live), it must evolve such that it provides greater and greater access to the currents that flow through it". The configuration process of constructal theory is from small to large, which opposites to that of another classical theory – fractal theory. Constructal theory can be named as the thermodynamics of configuration problems in non-equilibrium systems, which is different from the thermodynamic optimizations without configuration evolutions. The research system of constructal theory locates among "volume" and "point", which is different from the "point" to "point" relationship based on least action principle.

Various flow systems have been studied and optimized based on constructal theory in recent years. The corresponding optimization objectives include maximum thermal resistance (MTR) [15,16], maximum temperature difference (MTD) [17], heat transfer rate (HTR) [18], heat loss rate (HLR) [19], flow resistance (FR) [20], maximum pressure drop (MPD) [21], exergy loss rate (ELR) [22], entropy generation rate (EGR) [23], etc. The MTR and MTD of heat conduction bodies [15–17] were minimized, and the heat conduction performances (HCPs) were evidently improved after constructal optimizations. The HTRs of T-shaped fins [18] and HLRs of multi-layer insulations [19] were maximized and minimized, respectively, which illustrated that different extremum conditions should be adopted according to different heat transfer problems. The FR and MPD of fluid flow bodies [20,21] were minimized, and the flow performances were evidently improved after constructal optimizations. Besides ELR and EGR, the optimization objectives above only can be used to evaluate the extremums of potential difference and flux for a single flow, therefore, the limitations of these optimization objectives are obvious. Furthermore, ELR and EGR can be used to evaluate the irreversible losses for multiple flow systems [22,23], therefore, the applications of these two optimization objectives are wide. Moreover, the performance indexes mentioned above are different, and different optimization results can be provided when different performance indexes are taken as the optimization objectives. These optimization results can satisfy different design requirements, which illustrates that constructal optimizations based on different optimization objectives are significant.

To further describe the performance of multiple heat transfer system, Guo et al. [24,25] proposed a new physical quantity called "entransy" and the entransy dissipation extremum principle (EDEP) to reflect the essence of heat transfer process. Entransy was defined as

$$E_{Vh} = Q_{Vh}T/2 \tag{1}$$

where Q_{Vh} is the constant volume heat capacity and T is the temperature of the object. The entransy dissipation rate per unit time and volume is

$$\phi_h = -\dot{q}\cdot\nabla T = k(\nabla T)^2 \tag{2}$$

where $\dot{q}$ is the heat flux vector and ∇T is the temperature gradient. Using the concept Entransy, EDEP was deduced as follows [24,25]: "for a fixed boundary heat flux, the heat conduction process is optimized when the entransy dissipation is minimized (minimum temperature difference); while for a fixed boundary temperature, the heat conduction process is optimized when the entransy dissipation is maximized (maximum heat flux)". Many transfer processes and systems have been optimized based on entransy theory [26–29], which promotes the developments of this theory. However, there are also some critical comments [30–45] to this theory, which have been replied by the corresponding authors [46–57].

Combining with various heat transfer optimization theories, such as entransy theory, entropy generation minimization theory [58–60] and constructal theory, this paper will summarize the works of constructal optimizations with different disciplines, optimization objectives and scales performed in the Naval University of Engineering. Comparisons of the optimal results obtained by different optimization objectives and scales will be implemented. A generalized transfer process will be optimized based on the summarized extremum principles.

2. Constructal optimizations for heat and mass transfer processes

Constructal optimizations for heat conduction and thermal insulation processes, fluid flow processes, convective heat transfer processes, mass transfer processes in porous mediums, heat and mass transfer processes as well as generalized transfer processes performed in the Naval University of Engineering will be presented in detail.

2.1. Heat conduction and thermal insulation processes

Since the first application of constructal theory into heat conduction problem by Bejan [1], different shapes of heat conduction assemblies were further considered by many authors. Ghodoossi and Egrican [16] found the deviation of approximate and exact solutions, and Wu et al. [17] solved the deviation based on equivalent of MTD. Variable cross-sectional conducting channels [61–63], variable angles [64–66] and nonuniform distributions [67,68] of conducting channels as well as releasing the premise of optimized last-order construct [69,70] were considered in the constructal optimizations of heat conduction problems, and the

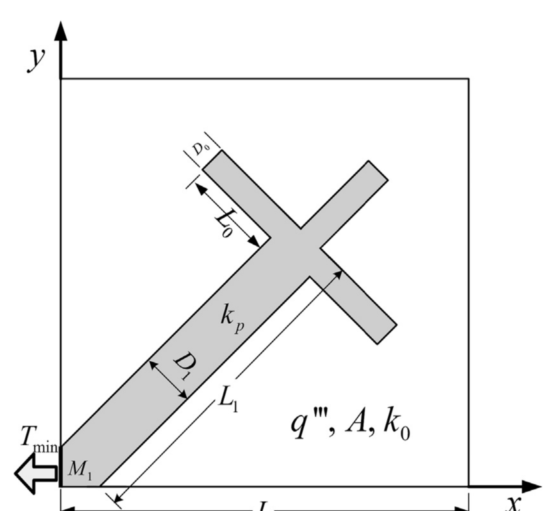

Fig. 1. Quarter of square body with "+" shaped HCP [74].