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Constructal wavy-fin channels of a compact heat exchanger with heat transfer rate maximization and pressure losses minimization

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HIGHLIGHTS

- A type of wavy-fin of compact heat exchangers is designed by constructal theory.
- Both pressure drop minimization and heat transfer maximization are considered.
- The optimal geometrical parameters of wavy-fin channels are found.
- The optimal configuration has a decrease of 54% in pressure drop.
- The heat transfer rate of the optimal configuration is enhanced by around 26%.

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ABSTRACT

In this paper a new generation of wavy-fin channels of a compact heat exchanger is investigated based on the Constructal Theory with maximizing the heat transfer rate and minimizing the pressure losses. Three dimensionless variables such as the channel space, the wavelength ratio and the amplitude ratio of two wavy walls are considered to find the optimal configuration of wavy-fin channels for the compact heat exchanger applied in a heat recovery system of a microturbine. Two dimensional numerical simulations are conducted to obtain the steady laminar heat transfer and pressure drop characteristics by using Computational Fluid Dynamics (CFD). All of the CFD simulations are carried out for a sufficiently long time so that the initial conditions are completely convected out of the channels and have no effects on simulated results. The results show that the new generation of wavy-fin channel can help to reduce the pressure drop by more than 54% and to enhance the heat transfer rate by around 26%. The optimal design regions of the three dimensionless parameters are also provided so as to help design wavy-fin heat exchangers.

1. Introduction

Over the past few decades considerable attention has been devoted to heat transfer enhancement in thermal devices due to increased demands by industry for efficient and cost-effective heat exchange equipments. In this area, the passive methods are preferred over the active techniques. The former is more realistic and do not require extra power. A feasible approach to designing heat exchanger should also consider material usage and energy savings. Other design constraints are; the size of the device, its weight, and even its manufacturing simplicity. The wavy channel is one such passive method to improve heat transfer characteristics. Although these configurations can obtain the substantial benefit of enhanced heat transfer, the increase in pressure drop is one of critical problems.

One of the most recent techniques to find the optimal configuration with much better thermal performance is constructal design [1]. This method emerges from Constructal theory now a growing field in thermal science. Constructal theory is based on the constructal law which is a new law of physics. This principle states that if a flow system is endowed with sufficient freedom to change its configuration, the system exhibits configurations that provide progressively better access routes for the currents that flow. A time arrow is associated with the sequence of flow configurations that make up the existence of the system. In other words, the system

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Nomenclature

a	amplitude (m)
f	friction factor
h	convective coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	length (m)
Nu	Nusselt number
NTU	number of transfer unit
P	pressure (Pa)
Pr	Prandtl number
q	heat transfer rate (W)
Re	Reynolds number
S	spacing between wavy surfaces (m)
T	temperature (K)
u, v	velocity components (m/s)
U	free-stream velocity (m/s)

Greek symbols

α	constructal efficiency
ε	effectiveness
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
ΔP	pressure drop (Pa)
λ	wavelength (m)

Subscripts

w	wall
i	inlet
o	outlet
∞	free-stream

Superscripts

$(\tilde{\ })$	dimensionless variables

shape and internal flow architecture do not develop by chance, but result from the permanent struggle for better performance and therefore should evolve in time. From a geometric point of view, natural systems that display an enormous variety of shapes are far from being perfect. Geometric perfection means symmetry. However, it is almost impossible to find the perfect geometric form in animate systems because they are far from equilibrium. So, non-equilibrium means flow asymmetry and imperfection. Imperfection is either geometric or physical. The actual form of natural systems is the result of optimal distribution of imperfection. Constructal law applied to engineered systems helps designers to find the configurations that have optimal distribution of imperfection.

Constructal designs of various heat exchangers are emerged based on the so-called constructal theory [2–6]. Zimparov et al. [2] studied on the performance of balanced two-streams parallel flow heat exchangers, where each stream flow as a tree network through its allotted space. They developed the relationships between effectiveness (ε) and number of heat transfer units (NTU) for several parallel tree flow configurations. Besides, they compared the thermal performance of the parallel flow configurations with counter flow configuration. Luo et al. [3] proposed an idea of coupling constructal distributions/collectors with a mini cross flow heat exchanger to solve the problem of flow misdistribution. Raja et al. [4] analyzed a multi-block heat exchanger by applying the constructal theory. Numerical simulations were conducted at different values of heat capacity rate ratios on finned and unfinned constructal heat exchangers, whose the heat transfer areas were kept to be the same. It was showed that effectiveness of the constructal heat exchangers (both finned and unfinned) were higher by around 20% compared to that of the conventional cross flow heat exchangers. Luo et al. [5] studied experimentally the effects of constructal distributors built on binary pattern of pores and on flow equidistribution in a multi-channel heat exchanger. Thermal performance and pressure drop were determined with different assembly configuration of constructal distributors, conventional pyramid distributors and a mini cross flow heat exchanger. Among all tested assembly configurations, the configuration whose the inlet was equipped with a conventional pyramid distributor and the outlet was equipped with a constructal collector showed a relatively better thermal performance as well as low pressure drops under experimental conditions considered. Azad and Amidpour [6] performed an optimization of shell and tube heat exchanger by reducing the total cost of the heat exchanger based on constructal theory. It was reported that the overall heat transfer coefficient was increased, and the capital cost required for making the heat transfer surface is reduced. Moreover, the operational energy costs involving pumping power in order to overcome frictional pressure loss were minimized. Martins et al. [7] introduced a general computational model for regenerators fed by a hot fluid stream on one side, whereas the other side was a fluid mixture, in which one of the components undergoes a phase change. They also proposed a model to simulate numerically the behavior of the regenerator working under different operating and design conditions.

Constructal theory is also applied into the design of other heat transfer channels. For examples, Luo et al. [8] presented some examples of multi-scale components by using the constructal theory such as heat exchangers, fluid distributors, coupling of fluid distributor to heat exchanger, and mixer and its coupling to a microreactor. Bejan and Lorente [9] focused on the flow configuration based on the constructal theory. The global performance was maximized by balancing and arranging the various flow resistances in a flow system which was free to morph. Ghaedamini et al. [10] investigated the svelteness as an important factor which illustrates the importance of bifurcation angle effect on pressure drop and flow distribution uniformity in tree-shaped networks. It was showed that the flow uniformity was enhanced while the effect of bifurcation angle on pressure drop was diminished as the svelteness was increased. Norouzi and Amidpour [11] obtained the best dimensions and arrangements of flow in heat recovery system by the constructal theory. Lee et al. [12] used the constructal theory to minimize the global pressure drop in a comb-like channel network with self-heating and self-cooling. Xie et al. [13] carried out a constructal optimization of line-to-line vascular networks by considering the minimization of dimensionless overall entropy generation rate per unit heat transfer load as the optimization objective. The constraints of fixed total area were occupied by the vasculature and the fixed total volume of channels. They presented the analytical correlations and numerical examples of the dimensionless overall entropy generation rate and the dimensionless overall entropy generation rate per unit heat transfer load versus the number of assembly levels, the dimensionless mass flow rate and the dimensionless pumping power. They also reported that the comprehensive performance of the vasculature was improved with the increase of the number of assembly levels, but such increase