International Journal of Heat and Mass Transfer 116 (2018) 9–15

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Review

The evolutionary design of cooling a plate with one stream

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ARTICLE INFO

Article history:
Received 5 May 2017
Received in revised form 29 August 2017
Accepted 30 August 2017
Available online 9 September 2017

Keywords:
Constructal design
Cooling
Electronics
Photovoltaics
Evolutionary design

ABSTRACT

Here we show the performance of a cooling system consisting of one stream that morphs while embedded in a square plate heated uniformly. Several configurations are considered in order to establish the evolutionary direction in which the thermal performance of the cooling system is improving. First, serpentine shapes are considered. The total length of serpentine length is fixed, and the number of meanders is varied. The stream inlet and outlet are free to migrate on the perimeter of the heated plate. The results show that the serpentine with four elbows maintains lower peak temperatures when the inlet and the outlet of the duct are positioned in the middle of the side of the plate. We report the configuration in which the thermal conductance is maximum. Second, we analyzed the effect of various loop cooling configurations such as square, circular and clover leaf. Each loop is centered on the center of the plate, and its length is free to vary. The minimum peak temperature is achieved when the length of the circular loop is $L_c = 2.5$ L, and when the length of the square loop is $L_c = 2.8$ L. The clover leaf designs show even better performance.

Contents

1. Introduction

Evolutionary design is a universal physics phenomenon, bio and non bio [1,2]. It is particularly evident in the evolution of technology. For example, the designs of compact heating or cooling systems evolve incessantly because they have a significant impact on the performance of numerous technologies. Specifically:

Higher peak temperatures in photovoltaic modules cause a decrease in conversion efficiency [3,4]. The efficiency of monocrystalline and polycrystalline silicon solar cells decreases by 0.45 percent per one degree temperature increase. The efficiency of amorphous silicon cells decreases by 0.25 percent per 1 K increase [5]. In packages of electronics, the peak temperature limits the operation and survival of the apparatus. The thermal performance of geothermal heat pumps depends on the design of its heat exchanger, which can be a single pipe or channels with arrays of serpentines and meanders [6–15]. Tree-shaped designs for conduction cooling were also proposed for decreasing peak temperatures [16–21].

In this paper we determine the relationship between peak temperature and heat flow configuration in a variety of morphing

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.08.122
0017-9310/

Nomenclature

c	specific heat of solid, J kg^{-1} K^{-1}
D_c	stream diameter, m
k_s	solid thermal conductivity, W m^{-1} K^{-1}
L	side length of heated body, m
L_c	stream length, m
N	number of meanders
q''	heat flux, W m^{-2}
Q	heat generation, W
$\tilde{T}$	dimensionless temperature difference, Eq. (2)
T_c	coolant temperature, K
T_{max}	peak temperature, K
x	coordinate, m
y	heated plate thickness, m

Greek symbols

ΔT	temperature difference, K
ρ	density, kg m^{-3}

designs with the objective of cooling a heat generating plate with one continuous stream. The design process is evolutionary. We treat this as a basic heat conduction problem, which is a simple model for PV modules cooling systems and for the ground heat exchanger design. The objective is to analyze the effect of the shape and layout of the cooling stream on the peak temperature in the heated domain. The ultimate objective is to determine the design direction in which thermal performance increases. A numerical approach is used throughout this study.

2. Serpentines

Consider the cooling of a heat generating plate, as shown in Fig. 1. The first design type is a serpentine-shaped fluid stream embedded in the plate, where the side length is L, and the plate thickness is y = 0.1 L. The diameter of the serpentine duct is fixed at D_c = 0.01 L, and its length L_c is assigned values from 2 L to 4 L. The shape of the serpentine is free to change.

We vary the shape of the serpentine by changing the number of elbows N, as shown in Fig. 2a. The flow rate through the meandering duct is assumed to be high enough so that the duct can be modeled as isothermal at T_c. A uniform heat flux is applied on the upper surface of the square plate. The remaining surfaces of the plate are insulated. The temperature distribution is governed by the heat conduction equation

$$\rho_s c u \nabla T = \nabla \cdot (k_s \nabla T) + Q \quad (1)$$

where ρ_s, c, and k_s are the solid density, the specific heat and the thermal conductivity, respectively. The convection term is neglected due to the isothermal duct flow assumption.

The peak temperature and its location in the conductive domain change as the serpentine configuration changes. In order to

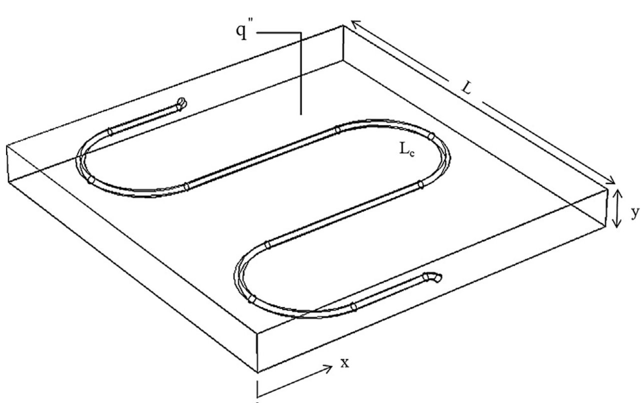

Fig. 1. Solid plate with heating from above, and with embedded serpentine cooling (N = 3 and L_c = 3 L).

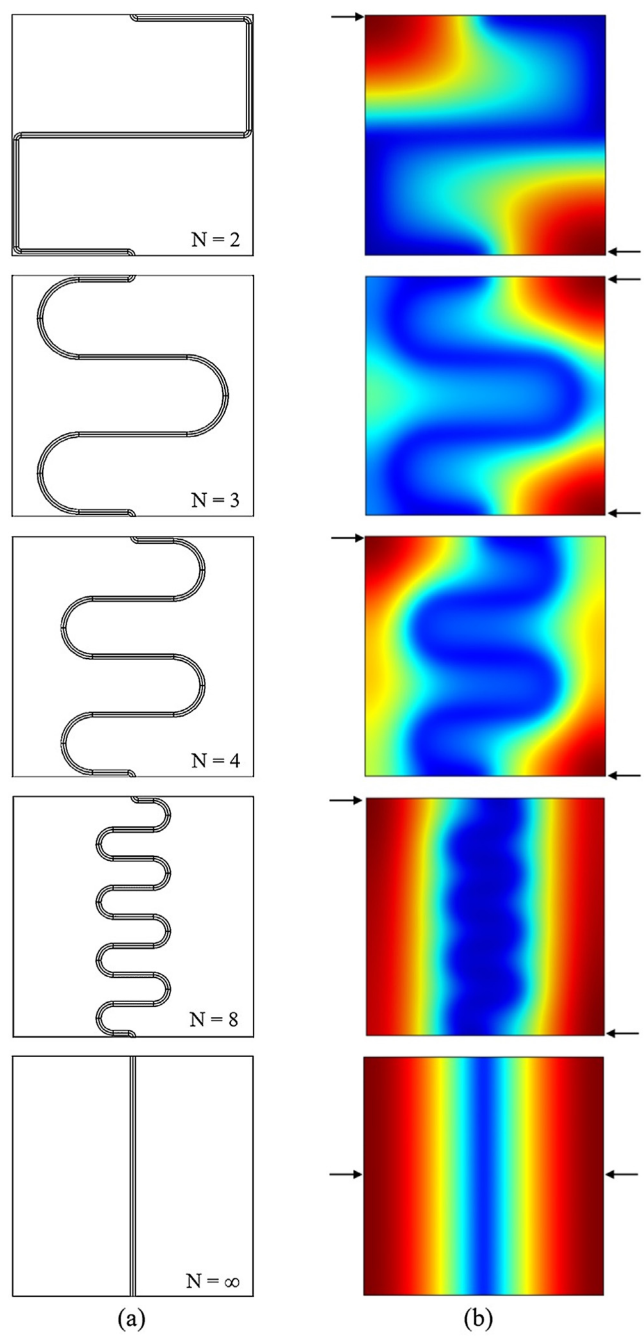

Fig. 2. (a) How the serpentine shape changes, and (b) the corresponding temperature fields as the number of elbows N changes while L_c = 3 L.