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Constructal design of a semi-elliptical fin inserted in a lid-driven square cavity with mixed convection

A.L. Razera [a], R.J.C. da Fonseca [a], L.A. Isoldi [b], E.D. dos Santos [b], L.A.O. Rocha [c], C. Biserni [d,]*

[a] Department of Mechanical Engineering, Federal University of Rio Grande do Sul – UFRGS, Sarmento Leite Street, 425, Porto Alegre, RS, Brazil
[b] Ocean Engineering Graduate Program, School of Engineering, Federal University of Rio Grande – FURG, Italia Avenue, km 8, 96201-900 Rio Grande, RS, Brazil
[c] Mechanical Engineering Graduate Program, University of Vale do Rio dos Sinos – UNISINOS, São Leopoldo, RS, Brazil
[d] Dipartimento di Ingegneria Industriale, Università degli Studi di Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

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ABSTRACT

The present study is focused on the geometric optimization, according to Constructal Design, of a semi-elliptical morphing fin, i.e. a fin that can vary its dimensions, inserted into a lid-driven square cavity under mixed convection. The fluid flow is considered incompressible, two-dimensional, laminar and at the steady state. Conservation equations of mass, momentum and energy are solved numerically by means of the Finite Volume Method. Moreover, buoyancy forces are modeled with Boussinesq approximation. The main purpose here is to maximize the dimensionless heat transfer rate between the heated fin and the surrounding flow for different Reynolds ($Re_H = 10$, 10^2 and 10^3) and Rayleigh ($Ra_H = 10^3$, 10^4, 10^5 and 10^6) numbers keeping constant the Prandtl number ($Pr = 0.71$). The studied domain has two constraints (areas of fin and cavity) and one degree of freedom given by the aspect ratio between the height and length of the fin (H_1/L_1), which is evaluated in three different surfaces of the cavity and four different area fractions of the fin. Results showed that the optimal configurations presented a gain in the thermal performance on the order of 40% in relation to other geometries. Finally, it is worth to mention that the optimal shapes here discovered are highly influenced by Reynolds and Rayleigh numbers.

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1. Introduction

The increasing requirement for miniaturization of structures in heat transfer removal, especially in electronic packages, makes the search for cooling solutions in these systems an important topic to be investigated. Convection heat transfer in cavity flows with inserted fins can ideally represent cooling in rooms, cars, solar panels and space between fins in heat exchangers. Therefore, several strategies have been employed to improve the thermal performance in these systems [1,2]. In this context, studies related to flow inside cavities have been carried out continuously over the years. Several works have been developed in order to obtain a better understanding of the fluid-dynamic behavior of isothermal flows inside cavities, under different flow regimes [3–8]. The lid-driven cavity flow is one of the most investigated problem in fluid dynamics framework; the "relative" computational simplicity is counterbalanced by complex physics phenomena such as the formation of main vortex, reattachment and detachment of boundary layers and possible secondary vortices.

Moallemi and Jang [9] studied numerically the effect of the Prandtl number on heat transfer by mixed convection in a square cavity with movement of superior surface, where it was observed that the effects of buoyancy were more evident for larger Prandtl numbers. Prasad and Koseff [10] evaluated, by means of the experimental investigation, the heat flux by mixed convection in a rectangular cavity with water. Their results indicated that the heat transfer rate is partially affected by the Richardson number variation. Sivasankaran et al. [11] observed the effects of the cavity slope on the heat convection behavior of the system. In addition to the above described studies, Refs. [12–19] treated mixed convective flows in similar domains. More specifically, the study of fins or obstacles in flows inside lid-driven cavities has been the subject of a precise literature. Chamkha et al. [20] analyzed the flow of the air through mixed convection inside a cavity with a square cylinder heated at its center by investigating the effect of the geometric variation of the cavity, as well as the Reynolds and Richardson numbers. Similarly, Oztop et al. [21] evaluated the effect of mixed convection in a cavity with a circular body in its interior. More recently, Gibanov et al. [22] investigated the heat transfer by mixed convection in a cavity with a conductive solid heated therein. Other important studies deserved attention

* Corresponding author.
E-mail address: cesare.biserni@unibo.it (C. Biserni).

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Nomenclature

A	area of the cavity [m^2]
A_f	area of the fin [m^2]
c_p	specific heat [J kg^{-1} K^{-1}]
H	cavity height [m]
h	convective heat transfer coefficient [W m^{-2} K^{-1}]
H_1	ellipse vertical semi axis length [m]
k	thermal conductivity [W m^{-1} K^{-1}]
L	cavity length [m]
L_1	ellipse horizontal semi axis length [m]
Nu_H	Nusselt number based on cavity height
P	pressure [N m^{-2}]
Pr	Prandtl number
Ra_H	Rayleigh number based on cavity height
Re_H	Reynolds number based on cavity height
T	temperature [K]
T_∞	bulk temperature [K]
u	velocity in the x-direction [m s^{-1}]
u_{us}	velocity of the upper surface [m s^{-1}]
v	velocity in the y-direction [m s^{-1}]
x, y	spatial coordinates [m]

Greek symbols

α	thermal diffusivity [m^2 s]
β	thermal expansion coefficient [K^{-1}]
ν	kinematic viscosity [m^2 s]
ρ	density [kg m^{-3}]
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ϕ	area fraction

Subscripts

f	fin variable
max	maximum
min	minimum
o	once optimized

Superscripts

(~)	dimensionless variables
(¯)	spatial-averaged variables

[23–25]. In general, cavities and fins represent ideally several engineering problems so that the geometric optimization of morphing geometries has always been attractive for researchers. One possible option in order to evaluate the design in this kind of problem is to employ Constructal Design, which is a method based on the physical principle named Constructal Law. Firstly proposed by Bejan [26] in 1997, the Constructal Law of design and evolution postulates that, for any finite animated or inanimated flow system, to persist in time (to survive), its design must evolve in such way to easily the internal streams that flow through the thermodynamic system [27,28]. In engineering, Constructal Design has been applied for geometric evaluation of several problems, as fundamental heat transfer, renewable energy and, even, solid mechanics ("flow of stresses") [29–36]. For the application of Constructal Design, it must be defined an objective function (i.e. a performance indicator), constraints (which can be physical and geometrical) and degrees of freedom that arise in the closure of equation system defined by constraints and geometrical variables. A detailed explanation and main steps related with the application of Constructal Design and Exhaustive Search (used in the present work) was presented in Ref. [37]. Recently, the Constructal Law has been applied for the solution of several research topics related to flow with heat transfer in cavities. Dos Santos et al. [38] employed the Constructal Design method to evaluate the effect of the geometry of a rectangular fin inserted into the bottom wall of a lid-driven square cavity, over heat exchange between the fin and the surrounding forced convective flow. The fin geometry was evaluated for different Reynolds numbers, considering a fixed Prandtl number ($Pr = 0.71$). Similarly, Ref. [39] treated the same geometric configuration for different Reynolds and Rayleigh numbers, thus studying the effects of fin geometry on the heat transfer. Aldrighi et al. in Ref. [40] investigated the heat transfer by forced convection in a system composed of a cavity with a heated rectangular fin inserted in lower and lateral (upstream and downstream) surfaces, according to the Constructal Design method. Afterwards, Razera et al. in Ref. [41] evaluated the heat transfer by mixed convection for different conditions of flow, in a system that combines a square cavity and a triangular fin inserted in its bottom wall.

In this context, the present work is aimed at the geometric optimization of a morphing fin inserted into a lid-driven square cavity bathed by mixed convective flow. The effect of aspect ratio between the height and length of the fin (H_1/L_1) over heat transfer rate between the heated fin and fresh surrounding flow has been numerically investigated. Moreover, the fin is mounted in three different placements of the cavity (lower, downstream and upstream surfaces). The influence of different Reynolds ($Re_H = 10$, 10^2 and 10^3) and Rayleigh ($Ra_H = 10^3$, 10^4, 10^5 and 10^6) numbers, as well as, different fraction of areas of the fin inserted in the cavity ($\phi = 0.05$, 0.1, 0.2 and 0.3) over the thermal performance and optimal shapes are also evaluated. It is worth mentioning that these problems have not been investigated yet in Refs. [39–41], even using "basic" rectangular and triangular fins. Here it is studied a semi-elliptical fin with variable aspect ratio. The extended surface is firstly considered in the lower plane of the cavity and then it is supposed to be located into the cavity sidewalls, i.e. upstream and downstream. The mixed convective flow is considered two-dimensional, laminar, incompressible and at the steady state. For estimation of buoyancy forces, the Boussinesq approximation is contemplated. In this sense, conservation equations of mass, momentum and energy are numerically solved with the Finite Volume Method, more precisely employing the software ANSYS FLUENT 14.0 [42,43].

2. Mathematical modeling

This paper proposes to evaluate, numerically, the thermal and fluid-dynamic behavior of a system that combines a lid-driven square cavity and a heated semi-elliptical fin. The main objective is to obtain the geometries that lead to the maximization of the heat transfer rate between the heated fin and the surrounding flow, which is at a lower temperature. As already mentioned, the extended surface is initially supposed to be located in the lower wall of the cavity and thereafter an evaluation of the fin inserted into the sidewalls of the cavity (upstream and downstream) will be performed. A schematic computational domain with boundary conditions and geometric variables of the studied problem is presented in Fig. 1. The mixed convection, laminar and incompressible flows at steady-state with constant thermophysical properties are modeled by continuity, momentum (in *x* and *y* directions) and energy conservation equations, which are given in coherence with Ref. [44]:

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