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Performance optimization of a channel flow problem using shape functions

Gustavo M. Hobold [a], Alexandre K. da Silva [a,b,*]

[a] Department of Mechanical Engineering, Federal University of Santa Catarina, Florianópolis, SC 88040-900, Brazil
[b] Federal University of Santa Catarina, Ararangua, SC 88906-072, Brazil

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ABSTRACT

This study explores the use of shape functions on the boundary condition optimization of a forced convection channel flow subjected to an axial heat flux distribution. The goal is to determine the heat flux distribution that minimizes the coolant overheating and simultaneously reduces the computational optimization efforts. The calculations are implemented in a 2-D homemade code, which solved the conservation equations of mass, momentum and energy, while coupling the optimization variables, here represented by the multiple coefficients of the shape functions, with a genetic algorithm. Generally speaking, two types of shape functions were used: unbiased and biased. In the former, the optimization procedure is responsible for obtaining the optimal coefficients for Legendre shape functions, while in the latter, scaling-based power laws are used to construct shape functions. The results computed for both biased and unbiased shape functions show that not only higher performance levels (i.e., less overheating) can be obtained with the present formulation when compared with the techniques employed so far in the available literature (e.g., constant discrete heat flux heaters along the channel), but it also significantly reduced computation efforts. More specifically, the biased shape functions outperform the unbiased formulation by lowering the maximum plate temperature as much as 20% with respect to the standard constant heat flux case, while simultaneously reducing the computational time by a factor of over 4.
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1. Introduction

The performance optimization of engineering systems with respect to their transport phenomena behavior has been considered extensively while addressing different exchange mechanisms, optimization methods and objective functions. More specifically, with respect to heat transfer mechanisms, forced convection-based problems are often explored due to the existing tradeoffs commonly observed when accounting for heat transfer rate and pumping power [1,2]. As for the optimization methods, gradient-based and bio-inspired (e.g., genetic algorithm) techniques have been successfully applied to a variety of thermal-fluids related problems [3–5]. Furthermore, regardless of the physical principle ruling the heat transfer process or the optimization methodology employed, the selection of the proper figure of merit is crucial, as the attempt to optimize an ill-posed figure of merit leads to a sensitivity analysis [6].

With the goal of improving heat transfer performance, progress has been achieved towards, for example, the conception of novel working fluids (e.g., nanofluids, supercritical carbon dioxide and refrigerants) and geometry optimization [7–12]. With respect to the latter, researchers have found that topology optimization can be accomplished, for instance, by the implementation of shape functions, often polynomials, which are expected to mimic the behavior of global optima [7,13–15]. On the other hand, boundary conditions, particularly those of Neumann-type, can be optimized using discrete constant functions to search for optimal heat transfer distributions and heater spacing [4,16].

Generally speaking, a common observation is that the number of independent variables (i.e., degrees of freedom) being simultaneously optimized is, to a certain extent, proportional to the quality (i.e., how high or low) of the absolute value obtained for the figure of merit under consideration [1,2,13]. Therefore, during the optimization of complex systems, there is an urge to increase the number of degrees of freedom. However, despite the apparent benefits, the number of degrees of freedom that can be considered is often limited by the computational efforts required to solve the constitutive set of equations representing the problem [5,17]. Under these conditions, researchers must find a compromise

* Corresponding author at: Department of Mechanical Engineering, Federal University of Santa Catarina, Florianópolis, SC 88040-900, Brazil. Tel.: +55 (48) 3721 9937.

E-mail address: a.kupka@ufsc.br (A.K. da Silva).

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Nomenclature

a	shape function coefficient [–]
b	shape function coefficient [–]
D	diameter [m]
f	normalized heat flux distribution [–]
g, h	inadequate heat flux distribution [–]
h'	integrated inadequate heat flux distribution [–]
H	shape function, integrated inadequate heat transfer distribution [–]
k	index
L	length
p	pressure [Pa], number of shape functions [–]
q'	heat flow per unit length [W/m]
q''	heat flux [W/m^2]
Nu	Nusselt number [–]
Pe	Péclet number [–]
T	temperature [K]
u,v	velocity components [m/s]
U	mean velocity [m/s]
x,y	Cartesian coordinates [m]

Subscripts

b	bulk
h	hydraulic
i	index
in	inlet
k	index
L	length
m	mean
s	surface

Superscript

$\sim$	dimensionless

Greek Symbols

ϕ	general shape function [–]
τ	normalized computational time [–]
ξ	mapping variable [–]
Ξ	number of boundary condition elements [–]

between the number of degrees of freedom and the quality of the optimization process with respect to the global optimum.

In addition to the difficulty encountered during the optimization process of multivariable problems, constraints are particularly expensive to solve [1,6]. Search methods often rely on internalization of constraints so that they are intrinsically treated (e.g., by penalization) [6]. Hence, it is evident that the optimization methodology of expensive problems, such as the ones relying on the solution of a non-linear differential equation, should attempt to deal with constraints internally. Furthermore, the above discussion can be complemented by realizing that, when considering highly complex systems, optimization theory studies have shown that a global maximal or minimal value is arguably unobtainable [6,18]. Nevertheless, it is also important to realize that higher complexity levels (i.e., number of degrees of freedom) create systems with robust features [1].

Therefore, new optimization techniques that can improve convergence rates of optimization processes applied to complex systems are always welcome. In that respect, the present study proposes the boundary condition optimization (i.e., the local heat flux) of an internal forced convection problem (i.e., channel flow) using shape functions, which are often used in finite element methods [19–21]. In the methodology developed, the goal is to obtain the optimal heat flux distribution on the channel wall which leads to the lowest overheating scenario (i.e., minimized maximum temperature within the channel), with the least computational effort. For that the boundary conditions are divided in discrete elements, each being represented by a group of functions, of which coefficients are then optimized. In order to further reduce computational time, the methodology to be presented is able to treat all non-linear constraints internally.

2. Modeling

In this paper, the optimal heat flux distribution of a symmetrically heated channel, which is internally cooled by forced convection and subjected to a fixed total heat transfer rate per unit of length, is determined. Shape functions are used to obtain a channel's optimized Neumann boundary condition distribution that minimizes the overheating (i.e., $T_{\max}$) anywhere within the domain. In order to demonstrate the effectiveness of this method in comparison with optimized results based on constant heat flux heaters as studied by Ref. [16], two classes of problems are considered. First, a developing thermal entrance length with a hydrodynamic fully developed parallel plate flow (Case 1), which is known as the Graetz problem [2], is studied. Second, the hydrodynamic and thermally developing flow along a parallel plate channel is considered (Case 2). The parallel plate domain is shown in Fig. 1.

For Case 1, the energy equation, Eq. (1), is solved with a fully developed laminar parabolic profile. For Case 2, both the energy and Navier–Stokes equations, which are respectively represented in Eqs. (1) and (2), are solved for a constant velocity inlet. In both formulations, the equations are solved in their dimensionless forms in such a way that the representative dimensionless parameters (e.g., Peclét or Reynolds and Prandtl numbers) control all thermal and hydrodynamic parameters. The non-dimensionalization parameters are shown in Eq. (3). Additionally, the distance between the parallel plates is taken as 0.05 L (i.e., $\mathrm{Re}_{D_h} = 0.1\mathrm{Re}_L$).

$$\tilde{\mathbf{u}} \cdot \nabla\tilde{T} = \frac{1}{\mathrm{Pe}_L}\nabla \cdot \nabla\tilde{T} \tag{1}$$

$$\tilde{\mathbf{u}}\nabla \cdot \tilde{\mathbf{u}} = -\nabla\tilde{p} + \frac{1}{\mathrm{Re}_L}\nabla \cdot \nabla\tilde{\mathbf{u}} \tag{2}$$

$$\tilde{x} = \frac{x}{L};\ \ \tilde{\mathbf{u}} = \frac{u}{U};\ \ \tilde{p} = \frac{p}{\rho U^2};\ \ \tilde{T} = \frac{T - T_{in}}{q'/k} \tag{3}$$

Both Eq. (1) and Eq. (2) are solved numerically on a Cartesian structured grid using a Finite Volume code developed in-house. As shown in Fig. 1, the boundary conditions of the energy equation are Dirichlet on the west border, Neumann (heat flux) on the north border, symmetry on the south border and outflow (locally parabolic) on the east border. For the solution of the Navier–Stokes equations, the PRIME (PRessure Implicit, Momentum Explicit) method is used on a staggered grid, see Refs. [22,23], along with Dirichlet boundary conditions on the west, south and north borders, and outflow on the east border. For both equations, the hybrid interpolation scheme is employed. It is worth mentioning that the Navier–Stokes equations were applied and solved on the entire domain (i.e., channel length versus plate-to-plate spacing), while the energy equation made use of symmetry and was only solved on half of the domain.

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