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ON THE ENHANCEMENT OF HEAT TRANSFER IN A BACKWARD-FACING STEP USING POROUS BAFFLES

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Abstract. *The backward-facing step geometry is frequently employed not only to assess the accuracy and effectiveness of numerical models, but also to examine fundamental flow and heat transfer characteristics, and the influence of various configurations, on a wide range of problems, because of its resemblance to real-world and more complex geometries. One area of interest is heat transfer, which is the focus of this work. In this study, porous baffles are installed downstream of a backward-facing step to enhance heat transfer from the heated bottom wall to the colder incoming flow. The position, size of the baffle and Darcy number are adjusted and simulated using a two-dimensional finite volume method. The flow is assumed to be steady, incompressible, and laminar. Genetic algorithms are employed to determine the optimal set of parameters that enhance heat transfer. Given the computational cost associated with evaluating the objective function, obtaining results has proven to be challenging, requiring the parallel computation of the objective function to reduce the computational time needed for each generation of the optimization process. The results indicate that placing the baffle in a manner that deflects the flow from the entry to the bottom heated wall significantly improves heat transfer.*

1 INTRODUCTION

Optimizing fluid flow and heat transfer has long been a research focus with applications in engineering, industry, and environmental sciences [1, 2, 3]. Additionally, the backward-facing step, a configuration present in a wide range of problems, is commonly used to examine phenomena such as flow separation, recirculation and flow reattachment [4]. This work investigates heat transfer enhancement in a backward-facing step channel with a heated bottom wall by placing a porous baffle downstream of the sudden expansion. Porous baffles are widely used to enhance heat transfer in numerous applications, such as solar collectors [5], heat exchangers [6], electronic cooling [2, 7, 8], chemical reactors [9], and microfluidics [10]. In this work, the flow and heat transfer in a backward-facing step channel are simulated using a two-dimensional finite volume method, the position and size of the baffle, as well as the Darcy number are varied to optimize heat transfer. A similar work has recently been presented in [11], although that research considers a discrete number of deterministic and predefined combinations of parameters, not answering which set of parameters leads to the best heat transfer performance of the system. There are also other studies that examine the benefits of placing porous baffles along a backward-facing step channel to increase heat transfer [12, 13], but also only simulating a limited set of conditions.Various optimization methods, from gradient-based algorithms to genetic algorithms, have been applied to fluid flow and heat transfer problems [14]. This study employs genetic algorithms [15], a metaheuristic optimization method inspired by natural selection and genetics, to efficiently explore the parameter space. In fluid flow and heat transfer optimization, different objective functions can be used based on the specific problem and design goals. These functions include entransy [16] and entropy [17]. Due to the high computational cost, in this work, parallel computing is employed to expedite the evaluation of the objective function and reduce optimization time. This study aims to optimize heat transfer in a backward-facing step with a heated bottom wall using porous baffles and genetic algorithms, contributing to the understanding of the use of porous media for heat transfer enhancement and of the application of genetic algorithms to fluid flow and heat transfer optimization problems.

2 Method

In this study, a two-dimensional backward-facing step with a porous baffle is simulated. The baffle is placed adjacent to the top wall (next to the entry flow from the smaller channel), and its position, height, width, and Darcy number are the parameters to be optimized. The flow is assumed to be steady, incompressible, and laminar, and the heat flux in the bottom wall is fixed at 1 kW/m^2. The optimal set of parameters that enhances heat transfer and reduces pressure drop is determined using genetic algorithms [15]. In this study, the finite volume method is applied to simulate fluid flow and heat transfer in a porous medium while considering the fluid as incompressible. The pressure-velocity coupling is addressed using the SIMPLE (Semi-Implicit Method for Pressure-

Linked Equations) scheme [18], which iteratively corrects the pressure field to ensure mass conservation. The hybrid scheme is employed for the convection terms, while the central difference scheme is adopted for the diffusion terms, effectively representing spatial derivatives. Figure 1 shows a sketch of the domain in study.

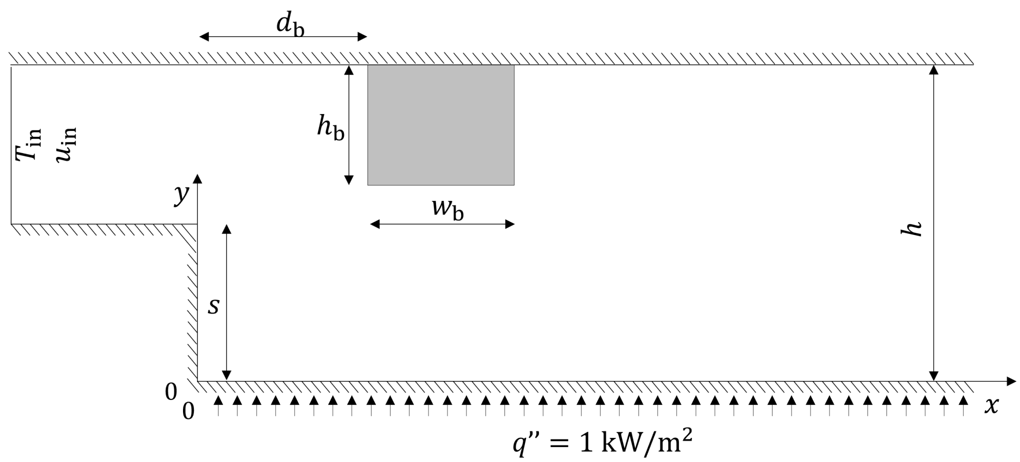

Figure 1: Sketch of the computational domain, featuring the parameters.

In figure 1, the channel has a wider height, h, of 0.02 m and a step height, s, of 0.01 m, furthermore, the total length, L, of the channel is 0.5 m and the entry is 0.04 m length. The geometric parameters used in the optimization are: d_b, the porous baffle distance from the step, and h_b and w_b, its height and width. Fluid enters on the left with a uniform temperature, T_in, and parabolic velocity profile with average value, u_in.
The methodology incorporates 2D volume-averaged governing equations, for the conservation of mass, momentum in the x and y directions, and energy:

$$\vec{\nabla} \cdot \vec{u} = 0 \tag{1a}$$

$$\vec{\nabla} \cdot \left(\rho \vec{u} \otimes \vec{u} - \mu \vec{\nabla} \vec{u}\right) = -\vec{\nabla}\left(p + p_\epsilon\right) \tag{1b}$$

$$\vec{\nabla} \cdot \left(\rho c_\mathrm{p} \vec{u} T - k_\mathrm{eff} \vec{\nabla} T\right) = 0 \tag{1c}$$

where $\vec{u}$ is the velocity vector, ρ is the density of the fluid, c_p is the specific heat of the fluid, μ the fluid viscosity, p the pressure and T is the temperature. Moreover, thermal equilibrium between the fluid and solid phases of the baffle is assumed, and a single energy equation describes the thermal behavior of the porous medium. The effective thermal conductivity of the porous baffle, k_{eff} is modeled as a linear relationship between the conductivity of the fluid, k_f, and of k_s.
The Forchheimer equation [19], accounting for both viscous and inertial effects, is employed to model the pressure drop within the porous medium, $\vec{\nabla} p_\epsilon$,

$$\vec{\nabla} p_\epsilon = \vec{u}^T \left(\frac{\mu}{K} + \frac{F\rho}{\sqrt{K}} \|\vec{u}\| \right) \tag{2}$$

where the permeability K, computed from the Darcy number of the baffle, Da, and the inertial factor F, are given by

$$\mathrm{Da_b} = \frac{K}{s^2}. \tag{3a}$$

$$F = \frac{1.75}{\sqrt{150}} \frac{1}{\epsilon^{3/2}} \tag{3b}$$

In this study, the average Nusselt number, $\overline{\mathrm{Nu}}$, serves as the objective function to evaluate the performance of the system. The Nusselt number is computed along the heated bottom wall of the backward-facing channel, providing insight into the convective heat transfer characteristics of the fluid flow in this region. This choice of objective function allows for an effective assessment of the thermal performance of the system. The equation for calculating the average Nusselt number is presented as follows:

$$\overline{\mathrm{Nu}} = \frac{1}{L} \int_0^L \mathrm{Nu}\; dx. \tag{4}$$

Here, L represents the total length of the wider channel and,

$$\mathrm{Nu} = \frac{q'' s}{k_\mathrm{f} \left(T_\mathrm{w} - T_\mathrm{in} \right)}. \tag{5}$$

Throughout the optimization process, a fixed Reynolds number of 200 is maintained, ensuring consistency in the flow conditions being studied. The equation for calculating the Reynolds number is

$$\mathrm{Re} = \frac{\rho u_\mathrm{in} s}{\mu}. \tag{6}$$

The optimization parameters are bounded by the intervals:

- $d_\mathrm{b} \in [0.02, 0.08]$ [m];
- $h_\mathrm{b} \in [0.002, 0.018]$ [m];
- $w_\mathrm{b} \in [0.002, 0.08]$ [m];
- $\mathrm{Da_b} \in [0.001, 0.1]$.

The constant values of the properties assumed along the work are presented in Table 1. The genetic algorithm is used with a population of 40 individuals, which, initially, is randomly generated, a mutation rate of 0.25 and a crossover probability of 0.8. Elitism is activated so that the best solution found in each generation is not lost. Convergence is considered achieved when the number of objective function evaluations exceeds 1,000.

Property		Value
ρ	$[\mathrm{kg.m^{-3}}]$	1.225
c_p	$[\mathrm{kJ.kg^{-1}.K^{-1}}]$	1.006
μ	$[\mathrm{N.m^{-1}.s^{-1}}]$	1.7894×10^{-5}
k_f	$[\mathrm{W.m^{-1}.K^{-1}}]$	0.0242
k_s	$[\mathrm{W.m^{-1}.K^{-1}}]$	202.4
ϵ	$[-]$	0.9

Table 1: Properties used in simulations.

3 Results

Figure 2 illustrates the convergence of the genetic algorithm, by showing the best individual's average Nusselt number value and each of the respective parameters in each generation.

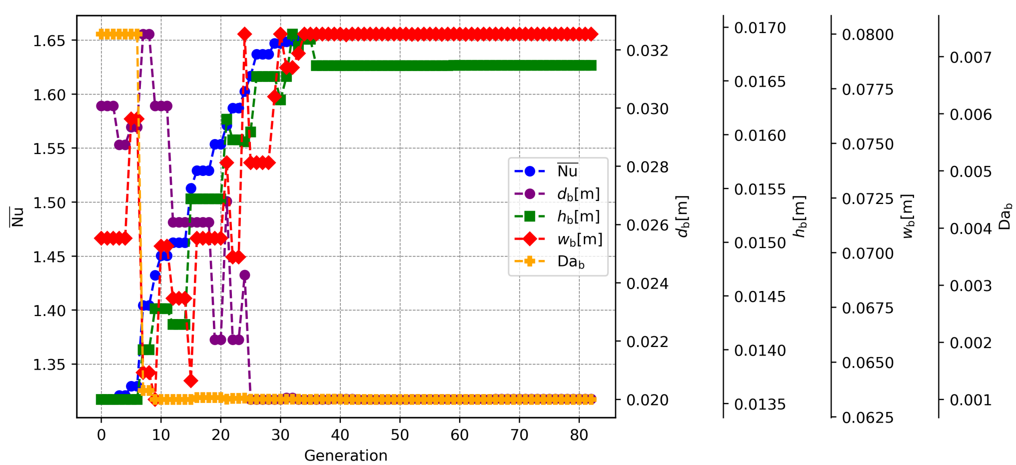

Figure 2: Genetic algorithm convergence plot. The best individual's average Nusselt number and respective parameters are presented.

After 82 generations, a Nusselt number of 1.66 was achieved for a porous baffle height value of 0.01676 m. Due to the computationally intensive nature of the objective function, which requires about 30 minutes per evaluation on a computer with a 3.3 GHz processor, the parallel computation was employed to simultaneously evaluate the fitness values of 20 individuals. However, as the height of the porous baffle increased, so did the velocity beneath the baffle, which made convergence in the CFD-solving process more challenging. Figure 3 presents the contour plot of the temperature and velocity vectors for the best solution found in the optimization process.

At the time of writing, the optimization has still not reached convergence. However,

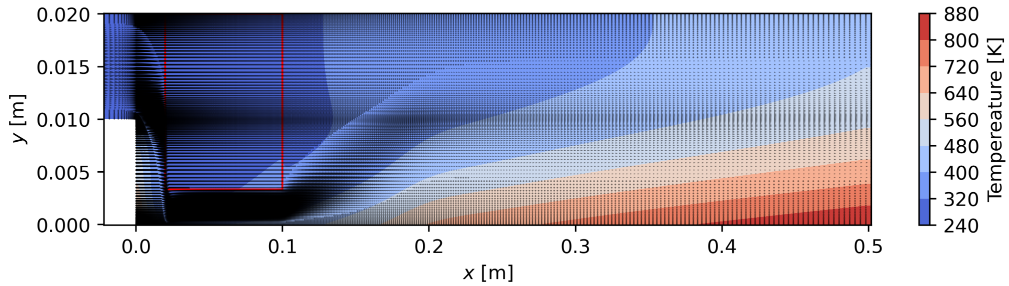

Figure 3: Contour plot of the temperature and velocity field representation for the best case found in the optimization.

despite the small number of generations, the optimal solution is already converging. It was found that the best solution so far is the one in which both the distance of the baffle to the entry and the Darcy number are the lowest possible, the porous baffle is the widest possible and the height of the porous baffle occupies 84% of the wider channel. Apparently, the height that maximizes the Nusselt number appears to be dependent on the Darcy number, width, and distance parameters. This is an interesting relation that needs to be confirmed and that may be useful in future works.

4 CONCLUSIONS

This study presents an optimization of the positions, dimensions and properties of a porous baffle placed on a two-dimensional backward-facing step channel to enhance heat transfer. The results show that positioning the baffle to deflect the flow from the entry to the bottom and heated wall is an effective strategy for enhancing heat transfer. The use of genetic algorithms was found to be an efficient method for optimization. The study provides a useful insight into the use of porous baffles for enhancing heat transfer in backward-facing steps and can be extended to more complex geometries. In future works, the use of similar pre-computed solutions as an initial condition for new CFD simulations may help reduce computational time, since these solutions are closer, taking less time to obtain convergence and, thus, reducing the overall challenge.

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