Enhancing Heat Transfer in Backward-Facing Step Using Strategic Fin Placement and Forced Convection

I.BOUALEM [1], N.BOUHAMRI[2], M.BOUHAFS[3], I.DJELLID[4], F. BOUZIT[5]

[1,2,3,4]Lab of Industrial Production and Maintenance Engineering, Institute of Maintenance and Industrial Safety, University of Oran2 Mohamed Ben Ahmed;P.B 1015 El M'naouer 31000 Oran Algeria

E-mail: boualem.ikram.31@gmail.com, noured_bh@yahoo.fr, mohamedbouhafs@yahoo.fr ikramdjellid09@gmail.com.

[5]Nationa Laboratory of Maritime Sciences and Engineering LSIM Faculty of Mechanical Engineering, University of Science and Technology of Oran, Mohamed Boudiaf, El Mnaouar, B.P.1505, 31000, Oran, Algeria.

E-mail: faycal.bouzit@yahoo.fr.

Abstract: This study investigates the cooling performance of a backward-facing step using forced convection with air, systematically studying the impact of strategically positioned fins to enhance heat transfer. Numerical simulations were conducted varying Reynolds numbers between 50 and 200 while maintaining a constant Prandtl number (Pr = 0.71), focusing on configurations with up to three fins. Deploying three fins in specific positions resulted in a significant 45% increase in average Nusselt number compared to configurations without fins. Optimal heat transfer occurred near the fins and step, emphasizing critical temperature gradients crucial for effective cooling. These findings emphasize the importance of optimizing fin placement for maximizing heat transfer in engineering applications.

Keywords: Heat transfer-backward facing - Forced convection- Nusselt number-Fin- laminar flow.

1. INTRODUCTION

Cooling systems are indispensable in modern engineering applications, pivotal for managing heat dissipation in electronic devices, power plants, and various industrial processes. Among the techniques employed, forced convection over backward-facing steps stands out due to its effectiveness in enhancing heat transfer under controlled fluid dynamics (Alhasan et all., 2024).

Backward-facing steps are characterized by abrupt expansions in ducts or channels, causing flow separation, recirculation zones, and reattachment points downstream (Kumar et all ., 2023). These flow features significantly influence heat transfer characteristics and the overall efficiency of cooling systems (jin et all., 2024).

Understanding and optimizing heat dissipation over such configurations are critical for improving thermal management and system performance.

Recent research has explored various strategies to augment heat transfer over backward-facing steps. Studies have investigated the deployment of fins at strategic locations to manipulate airflow and enhance convective heat transfer (kumar and vangadesan.,2019).

Additionally, the integration of circular cylinders has been explored for its ability to disrupt boundary layer formation and promote heat transfer enhancement (Kumar et al., 2012).

The application of magnetohydrodynamic (MHD) forced convection using ferrofluids and magnetic fields has shown promise in enhancing cooling efficiency by leveraging magnetic forces to control fluid behavior and heat dissipation (Toumi et al., 2022). Nanofluids, which consist of nanoparticles dispersed in conventional fluids, have also emerged as a cutting-edge coolant due to their superior thermal conductivity and enhanced convective heat transfer properties in microchannels (Salimefendigil et al., 2017; Klazy et al., 2022).

Furthermore, advancements in computational techniques like the Lattice Boltzmann method have facilitated the optimization of microstructural modifications such as dimples and ribs on channel surfaces. These modifications aim to manipulate fluid flow patterns to further enhance heat transfer efficiency over backward-facing steps (yousefi et all., 2023)

This paper investigates the cooling performance of a backward-facing step using air and forced convection, with a focus on the strategic placement of fins to optimize heat transfer. Building upon previous research, the study aims to contribute insights that can advance the design and efficiency of cooling systems in engineering applications.

In summary, the intricate interplay between fluid dynamics, heat transfer mechanisms, and advanced cooling techniques over backward-facing steps underscores the significance of ongoing research in improving thermal management strategies across various industrial and technological domains. This paper aims to contribute to this evolving field by presenting a comprehensive analysis of cooling strategies tailored to backward-facing step configurations.

2. PHYSICAL PHENOMENON

2.1. Description of backward facing step configuration

In the present work, a 2D numerical study of the forced convection of a laminar flow using air as Fluide , on a backward facing step containing a single couple fins on top wall placed in certain position, the physical configuration with boundary conditions are presented in (Fig. 1) The height of the backward facing step is (2H) and the height of the channel is 50H. the length of the fin is (H) and the epaisseur is (H/20) where the position is at (11H,26 H,32H) with H=100(um).
At the inlet Tc =293(k) represents the cold flow and parabolic velocities are imposed.
At the lower wall downstream Th = 300(k) is the hot temperature. The other walls are adiabatic and have no slip velocity . The boundary conditions are presented in (Tab. 1.)

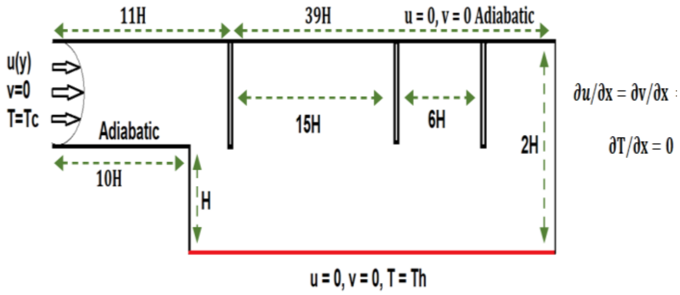

Figure 1. Schematic diagram of the backward facing step with boundary conditions.

2.2. The mathematical equations

The partial differential equations (PDEs) that govern the conservation laws for mass, momentum, and energy are fundamental to understanding fluid dynamics and heat transfer in various engineering applications(ouizi et all.,2024) . These equations, expressed in dimensional form, form the backbone of our analysis for forced convection over backward-facing steps. The conservation of mass, also known as the continuity equation, ensures that the mass of the fluid remains constant over time as it flows through a control volume. This principle is mathematically represented by the continuity equation, which, for an incompressible fluid, is given by:

$$\partial u/\partial x = \partial v/\partial y = 0 \qquad (1)$$

Here, u and v are the velocity components in the x and y directions, respectively.

The conservation of momentum is captured by the Navier-Stokes equations, which describe the motion of fluid substances (Zhang et all.,2024) For a two-dimensional, incompressible flow, these equations are split into two components: one for the x-direction (horizontal) and one for the y-direction (vertical). The x-momentum equation is expressed as:

$$\rho[u\,\partial u/\partial x + v\,\partial u/\partial y = [-\partial \rho/\partial x + \mu(\partial^2 u/\partial x^2 + \partial^2 u/\partial y^2) \quad (2)$$

And they-momentum equation is:

$$\rho[u\,\partial u/\partial x + v\,\partial u/\partial y = [-\partial p/\partial y + \mu\,(\partial^2 u/\partial x^2 + \partial^2 u/\partial y^2) \quad (3)$$

In these equations, ρ represents the fluid density, p is the pressure, and μ is the dynamic viscosity of the fluid. These equations account for the convective acceleration (change in fluid velocity within the flow field) and the viscous forces acting within the fluid, which are essential for capturing the behavior of fluid flow over backward-facing steps (Kumar and Dhiman.,2016).

The conservation of energy, crucial for analyzing heat transfer, is governed by the energy equation. For a fluid with constant properties, the energy equation in two dimensions is given by:

$$[u\,\partial T/\partial x + v\,\partial T/\partial y] = \alpha(\partial^2 u/\partial x^2 + \partial^2 u/\partial y^2) \qquad (4)$$

In this equation, T denotes the temperature, and α\alphaα is the thermal diffusivity of the fluid, defined as $\alpha = k/\rho cp$, where k is the thermal conductivity and cp is the specific heat capacity at constant pressure. The left-hand side of the equation represents the convective heat transfer, while the right-hand side represents the conductive heat transfer within the fluid. These PDEs collectively form the mathematical framework necessary for simulating and understanding the complex interactions of fluid flow and heat transfer in forced convection scenarios over backward-facing steps. By solving these equations with appropriate boundary and initial conditions, we can predict the behavior of the fluid and the effectiveness of various cooling strategies, such as the addition of strategically placed fins to enhance heat transfer. This understanding is critical for optimizing cooling designs in practical engineering applications, including electronic cooling systems and heat exchangers (coskun et all.,2021).

Table 1. Boundary conditions

The inlet	$u = u(y), v = 0, T = T_c$
The downstream bottom wall	$u = 0, v = 0, T = T_h$
The outlet. n is the surface normal direction coinciding with the x axis at the outlet	$\partial u/\partial n = \partial v/\partial n = \partial T/\partial n = 0$
Other walls are adiabatic and the velocity is no-slip.	$u = v = \partial T/\partial n = 0$
Fin adiabatic	$\partial T/\partial n$
Fin velocity components	$u = 0, v = 0$

Compute of the average and local Nusselt number Convection is one of the methods of heat transfer. The term convection refers to the heat transfer processes that occur between a surface and a moving fluid when they are at different temperatures (Boruah et all.,2020)

. To measure the intensity of heat transfer in the fluid due to its movements and to characterise the heat exchange between the fluid and the wall, the Nusselt number is used. The local Nusselt number on the hot wall is calculate as fol- lows:

$$Nu = hL/k \quad (5)$$

Nu is the Nusselt number.
h is the convective heat transfer coefficient for air.
L is a characteristic length (such as the step height).
k is the thermal conductivity of air.

Convective Heat Transfer Coefficient

$$h = qw/Th - Tc \quad (6)$$

- qw is the heat flux on the heated wall.
- Th is the temperature of the heated wall.
- Tc is the temperature of the cold flow (inlet temperature).

Heat Flux on the Heated Wall
qw stands for heat flux on the heated wall

$$qw = -k \cdot (Th - Tc)/L \cdot (\partial\theta/\partial y) \quad (7)$$

- qw is the heat flux on the heated wall.
- k is the thermal conductivity of the fluid (air).
- Th is the temperature at the hot wall.
- Tc is the temperature of the fluid (cold flow).
- L is a characteristic length.

$$Nu = k/kf \cdot (\partial\theta/\partial Y) \quad (8)$$

The average Nusselt number on the hot wall is calculated as follows(Xie et all.2019):

$$Nuavg = \int_0^{Ls} NudX \quad (9)$$

- Nuavg is the average Nusselt number.
- Ls is the total length of the heated part.
- X is the dimensionless length along the heated part

3. RESULTS AND DISCUSSION

The main objective of this study is to investigate heat transfer in a backward-facing step configuration. Therefore, a numerical investigation is undertaken to analyze the forced convection of air flow over a backward-facing step containing multiple fins attached to and fixed on the top wall of the step, with a constant bottom wall temperature. The control parameter, Reynolds number (Re), is considered, and the specific position and number of fins are key parameters that enable us to study their effect on the quality of heat transfer. To validate our numerical study, we compare the results obtained with those from a previous study(Alhasan et all.,2024) . The validation is done using local Nusselt numbers for Pr = 0.71 and Re = 150 (Fig. 2). The validation plot (Fig. 2) shows that our results closely match those of the reference study, demonstrating excellent consistency and very acceptable agreement

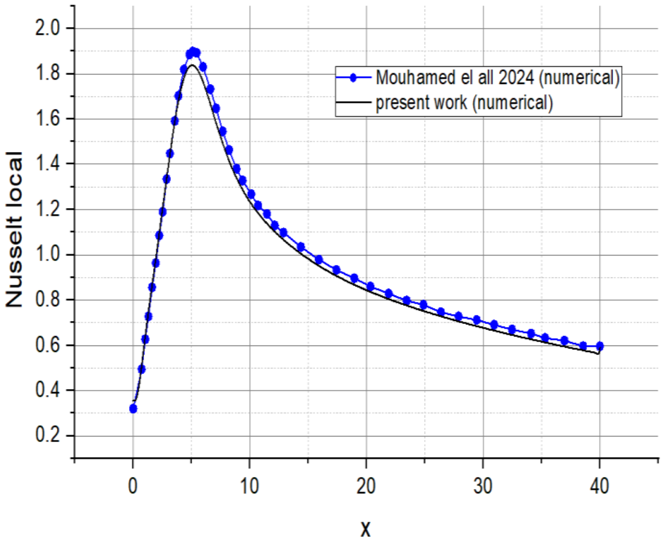

Figure 2.Validation of local Nusselt number for Re=150 with Muhammed et all 2024 .

The values of the control parameter are taken as the Reynolds number between(50 and 200), and the Prandtl number (Pr) is set to 6.2. Simulations were carried out for several fin numbers (between 1 to 3) in specific positions. The results are therefore voluminous, and for this reason, it was chosen to present the streamline contours and isotherms for the most significant fin number and position. Results obtained by numerical simulations for the study of forced convection of air flow in a backward-facing step geometry containing fins fixed on the top wall are analyzed qualitatively through the contours of isotherms and streamlines, which are presented in Figure 3 and4. Additionally, quantitative analysis is made by calculating the average Nusselt number, presented in Figure 5 , and the local Nusselt number, presented in Figure 6 .

Fig. 3 highlights different positions and numbers of fins, with Pr = 0.71 and Re = 150. The contours in Fig. 3 show weak forced convection in the absence of fins, indicating that the amount of heat transmitted is small. We notice in the streamlines (Fig. 3) the presence of a vortex that slows down air flow circulation. With the presence of fins, the streamlines show that fins in certain positions guide the fluid towards the bottom wall and increase the vortex created in the dead zones. Consequently, the isotherms show that the thermal layer in the duct is thicker compared to the absence of fins.
This leads us to conclude that thermal heat transfer has improved due to the number of fins in these specific positions.

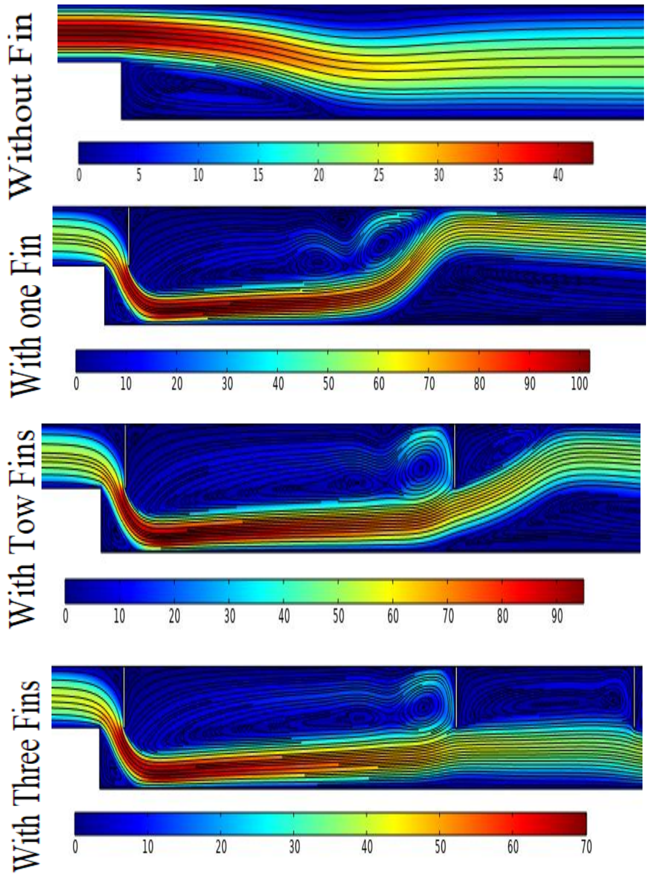

Figure 3.Effect of different fin positions on streamline for Re=150, Pr = 0.71.

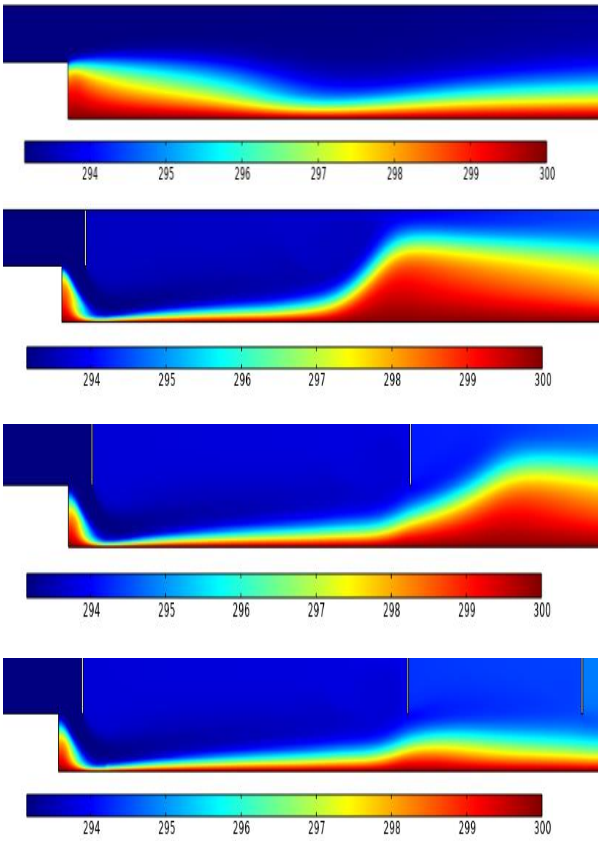

Figure 4. Effect of different fin positions on isotherm for Re=150, Pr = 0.71.

In this part, the analysis of the results of average Nusselt number variation as a function of Reynolds number and certain fin positions is presented. The study of air movement behavior and the quality of heat transfer in the duct is conducted for specific positions with different numbers of fins. The variation of the average Nusselt number as a function of different Reynolds number (50, 100, 150, 200) with Pr = 0.71 is presented in Figure 5 shows that the best heat transfer rate by forced convection is achieved when the average Nusselt number reaches its maximum value of 1.6400, while it takes a smaller value when Re = 200. To conclude, increasing the Reynolds number and the absence of fins increases the average Nusselt number. The effect of fin position and Reynolds number on the average Nusselt number is analyzed.

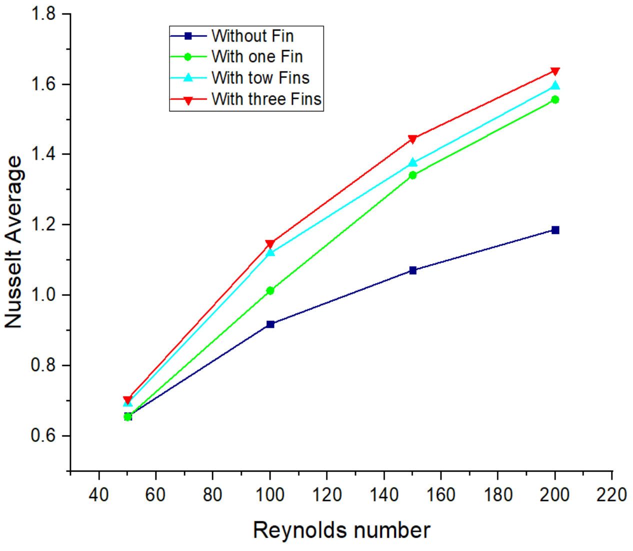

Figure 5. Effect of different fin positions on Local Nusselt number along the heated wall for Re=150 ,Pr = 0.71

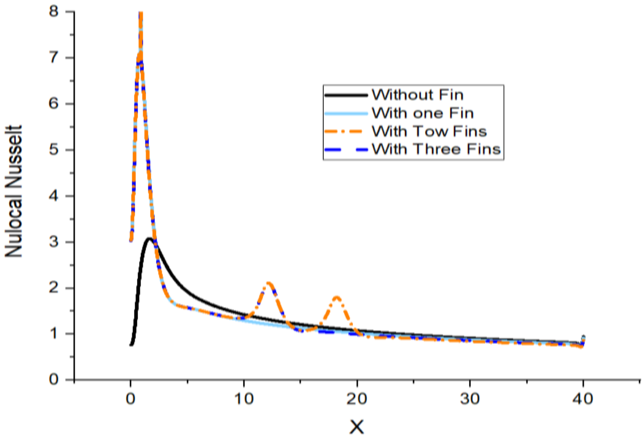

Figure 6. Effect of different fin positions on average Nusselt number for Re=150, Pr = 0.71

Figure 6present the evaluation of the local Nusselt number as a function of Reynolds number (Re = 150). The local Nusselt number is calculated along the hot bottom wall to show the development of heat transfer at this wall. In Fig. , it is observed that the local Nusselt number distribution is maximum in the vicinity of the fins and the backward-facing step (from X = 0 up to X = 14.25), (from X = 10 up to X = 15), and (from X = 15 up to X = 20). This part corresponds to a strong temperature gradient, causing cooling of the heated plate. After the obstacle (0 < X < 14.25), (10 < X < 15), (15 < X < 20), the local Nusselt number starts to decrease and takes minimum values as the X displacement towards the duct exits, indicating a lower temperature gradient.

4. CONCLUSIONS

This study aimed to investigate the cooling performance of a backward-facing step using air and forced convection, with a particular focus on the strategic addition of fins in specific positions to enhance heat transfer. The results demonstrated that increasing the Reynolds number generally led to improved heat transfer, especially when fins were employed. The strategic placement of fins significantly enhanced heat dissipation by effectively redirecting airflow and creating thicker thermal boundary layers along the duct.

The deployment of three fins in carefully selected positions resulted in a remarkable 45% improvement in the average Nusselt number compared to the configuration without fins. The highest heat transfer rates were observed near the fins and the step, indicating the presence of strong temperature gradients crucial for efficient cooling. This enhancement is attributed to the fins' ability to direct the airflow towards the bottom wall, thereby increasing the convective heat transfer coefficient and improving overall thermal performance.

In conclusion, the optimization of fin placement is critical for enhancing heat transfer efficiency in backward-facing step configurations. These findings offer valuable insights for developing advanced cooling strategies in various engineering applications, such as electronic cooling systems and heat exchangers, where effective heat removal is paramount. The study underscores the importance of geometric modifications in achieving superior thermal management.

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