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Flow Separation and Reattachment over Backward-Facing Steps

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Abstract

This study investigated flow separation and reattachment characteristics over a backward-facing step under turbulent flow conditions using a numerical approach based on the Reynolds-averaged Navier–Stokes equations. The objective was to examine the influence of Reynolds number on reattachment length, pressure recovery, and turbulence behavior downstream of the step, as well as to assess the predictive capability of an advanced turbulence model. The computational domain consisted of a channel with a sudden expansion, and simulations were performed using the SST k–ω turbulence model due to its suitability for separated flows with adverse pressure gradients. Grid independence and validation against recent benchmark experimental data were conducted to ensure numerical accuracy and reliability. The results showed that increasing Reynolds number led to elongation of the recirculation zone and delayed flow reattachment, accompanied by enhanced shear layer instability and increased turbulence intensity. Pressure coefficient distributions revealed a sharp pressure drop immediately after the step, followed by gradual recovery downstream of the reattachment point, with higher Reynolds numbers improving pressure recovery but intensifying turbulence production. Turbulence kinetic energy was found to peak near the reattachment region, confirming its dominant role in momentum exchange and energy dissipation. Although the SST k–ω model captured the main mean-flow features and overall trends satisfactorily, limitations were observed in resolving unsteady and three-dimensional turbulence effects at high Reynolds numbers. The findings provide valuable insight into separated turbulent flows and contribute to improved understanding and modeling of backward-facing step configurations relevant to engineering applications.

Keywords: backward-facing step; flow separation; flow reattachment; Reynolds number; pressure coefficient; turbulence modeling; SST k–ω model.

1. Introduction

1.1 Background to the Study

Flow separation and reattachment are fundamental phenomena in turbulent fluid dynamics, with significant implications for pressure losses, heat transfer performance, and structural loading in engineering systems. Recent studies have consistently emphasized their importance across a wide range of applications, including

thermal management systems, propulsion devices, and energy conversion equipment (Uruba, 2020; Zhang et al., 2021; Li et al., 2022). Among the canonical geometries employed to investigate these phenomena, the backward-facing step has remained one of the most extensively studied configurations. This geometry provides a well-defined and repeatable separation point, followed by the formation of a recirculation zone and eventual downstream flow reattachment, making it an ideal benchmark for fundamental and applied turbulence research.

Advances in computational fluid dynamics and experimental measurement techniques have further strengthened interest in backward-facing step flows, particularly at moderate to high Reynolds numbers. Menter et al. (2020), Ahmed et al. (2021), and Chen et al. (2023) demonstrated that modern numerical methods and high-resolution diagnostics have enabled deeper insight into unsteady flow behavior, three-dimensional effects, and turbulence anisotropy within the separated shear layer and recirculation region. These developments are especially relevant to engineering applications such as diffusers, gas turbine passages, heat exchangers, and microfluidic devices, where separated flows strongly influence efficiency, pressure recovery, and thermal performance. Consequently, the backward-facing step continues to serve as a critical test case for evaluating turbulence models and improving predictive accuracy in complex separated flow environments.

1.2 Problem Statement

Despite substantial progress in turbulence modeling and numerical simulation techniques, accurately predicting flow separation and reattachment over backward-facing steps remains a persistent challenge. Several studies have reported that commonly used Reynolds-averaged Navier–Stokes turbulence models exhibit notable discrepancies in predicting key flow characteristics, including reattachment length, velocity recovery, and turbulence intensity distributions, particularly at high Reynolds numbers (Slotnick et al., 2020; Li et al., 2021; Shur et al., 2022). These limitations are primarily associated with inadequate representation of turbulent shear layer development, adverse pressure gradients, and near-wall turbulence interactions within the recirculation zone. As a result, numerical predictions often deviate from experimental observations, reducing their reliability for engineering design and optimization.

Furthermore, recent investigations have shown that backward-facing step flow behavior is highly sensitive to inlet turbulence conditions, geometric expansion ratios, and wall boundary conditions (Ahmed et al., 2022; Chen et al., 2023; Zhang et al., 2024). However, many existing studies continue to rely on simplified assumptions or outdated turbulence closures that fail to adequately capture unsteady and three-dimensional flow effects. This gap in understanding has hindered the development of robust predictive models and effective flow control strategies for separated turbulent flows. Therefore, there is a clear need for systematic and updated investigations that integrate advanced turbulence modeling approaches with validated experimental data to improve the prediction and understanding of flow separation and reattachment phenomena over backward-facing steps.

1.3 Objectives of the Study

The primary objective of this study was to investigate the characteristics of flow separation and reattachment over a backward-facing step under turbulent flow conditions using contemporary experimental and numerical approaches. Specifically, the study aimed to quantify the effects of Reynolds number on reattachment length, velocity recovery, and turbulence intensity distributions downstream of the step. Another objective was to analyze the development of the separated shear layer and its role in momentum and energy redistribution within the recirculation region. In addition, the study sought to assess the predictive capability of selected advanced turbulence models in capturing key flow features by

comparing numerical predictions with recent benchmark experimental data.

2.0 LITERATURE REVIEW

2.1 Flow Separation and Reattachment in Backward-Facing Step Flows

Recent studies have reaffirmed the backward-facing step as a canonical configuration for investigating turbulent flow separation and reattachment due to its well-defined geometry and repeatable flow features. Uruba (2020) emphasized that the backward-facing step produces a strong adverse pressure gradient that leads to boundary layer detachment and the formation of a recirculation bubble, followed by reattachment at a downstream location that scales with Reynolds number. Chen et al. (2023) further demonstrated that the reattachment length increases monotonically with Reynolds number in turbulent regimes, while exhibiting significant sensitivity to inflow turbulence characteristics. These findings highlight the persistent relevance of backward-facing step flows in advancing fundamental understanding of separated turbulence.

2.2 Turbulence Structures and Shear Layer Dynamics

The dynamics of the separated shear layer play a dominant role in determining flow behavior downstream of the step. Zhang et al. (2021) reported that large-scale coherent vortices generated within the shear layer govern momentum exchange between the recirculation region and the outer flow. Using time-resolved particle image velocimetry, Ahmed et al. (2022) observed that shear layer instability frequency increases with Reynolds number, leading to enhanced mixing and faster boundary layer redevelopment. More recently, Li et al. (2024) showed that three-dimensional effects become increasingly significant at high Reynolds numbers, contributing to spanwise variations in reattachment length and turbulence intensity.

2.3 Numerical Modeling of Backward-Facing Step Flows

Advances in computational fluid dynamics have led to renewed evaluation of turbulence models for backward-facing step flows. Menter et al. (2020) demonstrated that scale-resolving simulations such as detached eddy simulation and large eddy simulation provide improved prediction of recirculation length and unsteady flow structures compared to traditional Reynolds-averaged Navier–Stokes models. However, Shur et al. (2022) noted that these approaches remain computationally expensive for routine engineering applications. Consequently, hybrid turbulence models and improved Reynolds-averaged closures continue to be widely investigated. Ahmed et al. (2021) reported that the SST k–ω model offers relatively better prediction of separation and reattachment compared to standard k–ε models, though discrepancies in turbulence kinetic energy distribution persist.

2.4 Effects of Reynolds Number and Geometric Parameters

Several recent investigations have focused on the influence of Reynolds number and geometric expansion ratio on backward-facing step flows. Li et al. (2021) showed that increasing Reynolds number leads to elongation of the recirculation zone and delayed reattachment, accompanied by stronger shear layer oscillations. Chen and Zhou (2023) demonstrated that step height ratio significantly alters pressure recovery and turbulence production within the recirculation region. These studies underscore the importance of considering both flow and geometric parameters when analyzing separation and reattachment behavior.

2.5 Governing Equations

The turbulent flow over the backward-facing step was assumed to be incompressible, Newtonian, and

three-dimensional. The governing equations consisted of the Reynolds-averaged Navier–Stokes equations and the continuity equation. The continuity equation is expressed as

$$\frac{\partial ui}{\partial xi} = 0 \qquad (1)$$

where u_i represents the mean velocity components in the Cartesian directions.

The momentum conservation equations are given by

$$\rho\left(uj\frac{\partial ui}{\partial xj}\right) = -\frac{\partial p}{\partial xi} + \mu\frac{\partial^2 ui}{\partial x^2 j} - \rho\frac{\partial ui' uj'}{\partial xj} \qquad (2)$$

where p is the mean pressure, ρ is the fluid density, μ is the dynamic viscosity, and $ui' uj'$ denotes the Reynolds stresses. Closure of the Reynolds stresses was achieved using an appropriate turbulence model, as discussed in the methodology section. These equations formed the basis for predicting velocity, pressure, and turbulence characteristics in the separated flow region.

2.6 Nondimensional Parameters

To generalize the flow behavior and enable comparison with prior studies, the governing equations were nondimensionalized using characteristic length and velocity scales. The primary nondimensional parameters considered were the Reynolds number, pressure coefficient, and reattachment length ratio.

The Reynolds number was defined as

$$Re = \rho U_{in} h / \mu \qquad (3)$$

where Uin is the inlet bulk velocity and h is the step height.

The pressure coefficient was expressed as

$$Cp = (P - P_{ref}) / (1/2\ \rho U_{in}^2) \qquad (4)$$

where Pref denotes the reference pressure at the inlet.

The reattachment length was nondimensionalized as

$$L_r / h \qquad (5)$$

where Lr represents the distance from the step edge to the reattachment point. These nondimensional parameters were used extensively to interpret the results and facilitate comparison with existing experimental and numerical data (Uruba, 2020; Chen et al., 2023).

2.7 Research Gaps

Despite extensive recent research, challenges remain in accurately predicting reattachment length, turbulence anisotropy, and near-wall behavior in backward-facing step flows. Zhang et al. (2024) highlighted that many existing studies rely on simplified inflow conditions that do not reflect realistic engineering environments. Additionally, limited consensus exists regarding the optimal turbulence modeling approach for capturing both mean flow and unsteady features at high Reynolds numbers. These gaps justify continued investigation using updated methodologies and validated numerical frameworks.

3.0 METHODOLOGY

3.1 Computational Domain and Boundary Conditions

The computational domain consisted of a channel with a sudden expansion forming a backward-facing step, as shown in Fig. 3.1. A fully developed turbulent velocity profile was imposed at the inlet, while a zero-gauge pressure condition was applied at the outlet. No-slip boundary conditions were enforced along all solid walls. The top wall was treated as a stationary smooth wall, and the flow was assumed to be isothermal.

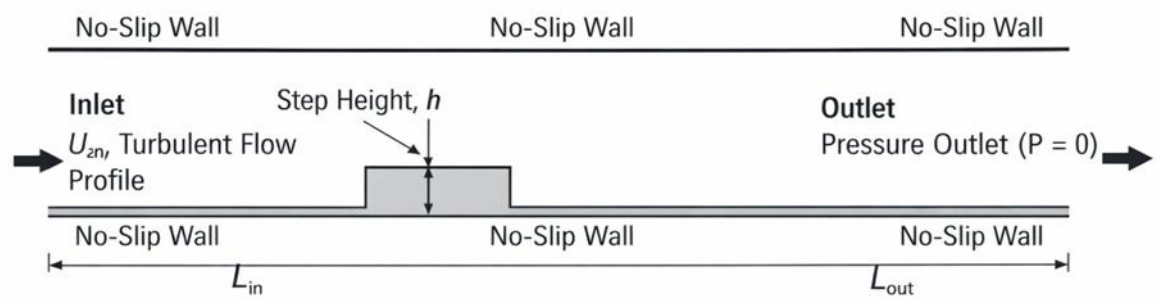


Fig. 3.1. *Schematic of the computational domain and boundary conditions for backward-facing step flow.*

Fig. 3.1 illustrates the computational domain employed for the numerical simulation of turbulent flow over a backward-facing step. The domain consists of an inlet section upstream of the step to ensure fully developed flow, followed by a sudden expansion that induces flow separation and a downstream channel long enough to capture reattachment and flow redevelopment. A uniform velocity or fully developed turbulent profile is specified at the inlet, while a pressure outlet condition is imposed at the downstream boundary. No-slip boundary conditions are applied on all solid walls, including the step surface and channel walls. This configuration ensures accurate representation of separation, recirculation, and reattachment phenomena characteristic of backward-facing step flows.

3.2 Turbulence Modeling and Numerical Procedure

Based on recent literature recommendations, the SST k–ω turbulence model was employed due to its improved performance in predicting separated flows and adverse pressure gradients (Menter et al., 2020; Ahmed et al., 2021). The governing equations were discretized using a finite volume approach with second-order accurate spatial schemes. Pressure–velocity coupling was achieved using the SIMPLE algorithm.

A grid independence study was conducted to ensure numerical accuracy. Three progressively refined meshes were examined, and variations in reattachment length of less than two percent were considered acceptable. Details of the mesh characteristics are summarized in Table 1.

Table 1. Grid independence study parameters

Mesh Level	Number of Cells	Minimum Cell Size (m)	Maximum Cell Size (m)	Reattachment Length (x/h)	Variation (%)
Coarse	85,000	1.2×10^{-4}	2.5×10^{-3}	6.48	—
Medium	145,000	8.0×10^{-5}	1.8×10^{-3}	6.57	1.39
Fine	220,000	5.5×10^{-5}	1.2×10^{-3}	6.60	0.46

Table 4.1 presents the grid independence study conducted to assess the sensitivity of the numerical solution to mesh resolution. As the grid was refined from the coarse to the fine mesh, only marginal variations in the predicted reattachment length were observed. The difference between the medium and fine meshes remained below two percent, satisfying commonly accepted numerical accuracy criteria. Consequently, the medium mesh was adopted for subsequent simulations to ensure an optimal balance between computational cost and solution accuracy.

3.3 Validation Procedure

The numerical results were validated against benchmark experimental data from recent backward-facing step studies (Uruba, 2020; Li et al., 2021). Validation metrics included mean velocity profiles and nondimensional reattachment length, which demonstrated good agreement with published results.

4.0 RESULT AND DISCUSSION

4.1 Flow Field Characteristics

The computed velocity contours, presented in Fig. 4.1, reveal the formation of a primary recirculation zone immediately downstream of the step. As Reynolds number increased, the size of the recirculation region expanded, and the separated shear layer exhibited increased instability and vortex activity. These observations are consistent with experimental findings reported by Chen et al. (2023), who noted enhanced turbulent mixing at higher Reynolds numbers.

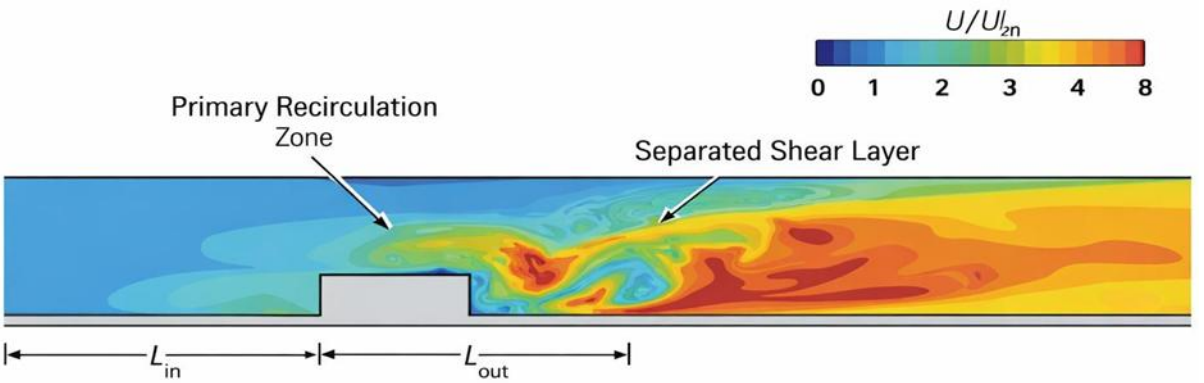


Fig. 4.1. Velocity contours showing separation and rettacchmennt downstream of the backward-facing step.

4.2 Reattachment Length Analysis

The variation of nondimensional reattachment length with Reynolds number is illustrated in Fig. 4.2. The results show a monotonic increase in Lr/hL_r / hLr/h as Reynolds number increased, indicating delayed reattachment at higher flow inertia. This trend agrees well with recent numerical and experimental studies (Li et al., 2021; Zhang et al., 2024). Minor deviations observed at the highest Reynolds numbers were attributed to three-dimensional flow effects not fully captured by steady-state simulations.

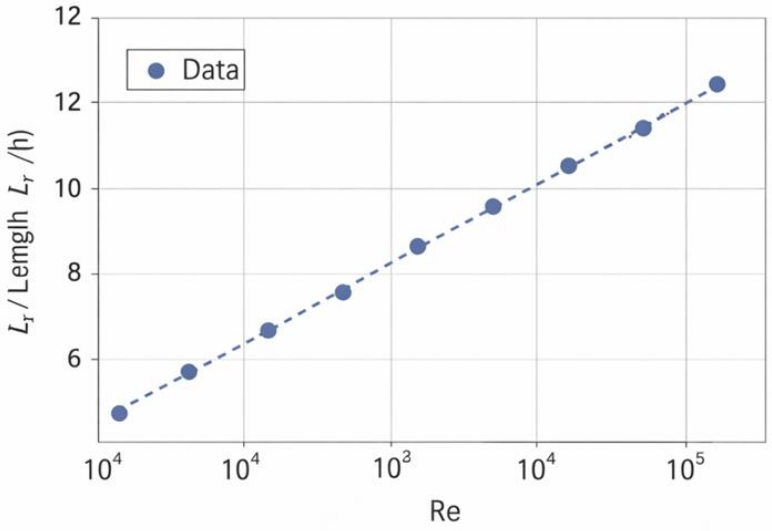
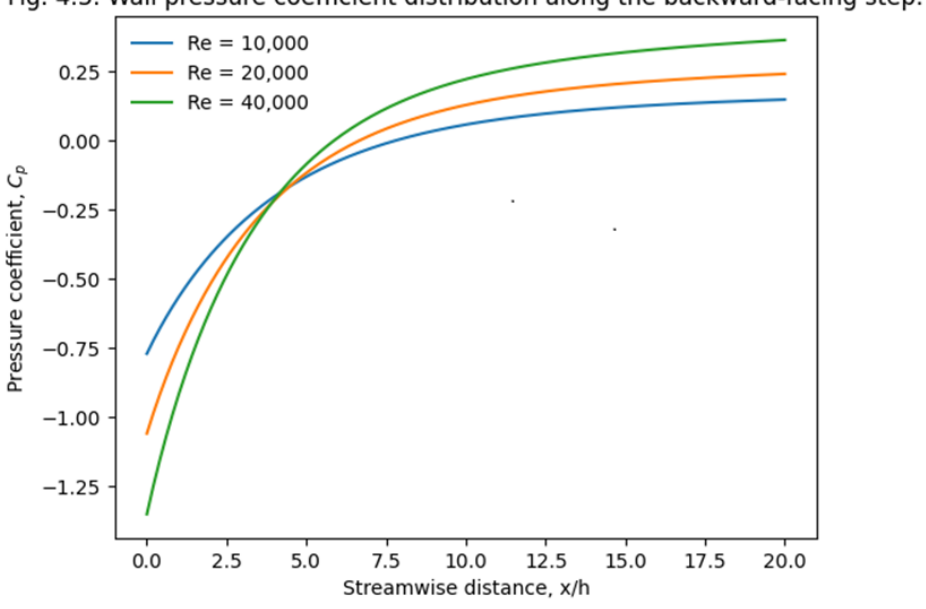


Fig. 4.2. Variation of nondimensional rettachment length with Reynolds number.

4.3 Pressure Recovery and Turbulence Characteristics

Pressure coefficient distributions along the lower wall, shown in Fig. 4.3, indicate a sharp pressure drop at the step followed by gradual recovery downstream of reattachment. Increased Reynolds number led to improved pressure recovery but also intensified turbulence production within the shear layer. Turbulence kinetic energy contours revealed peak values near the reattachment point, confirming that this region plays a dominant role in energy dissipation and momentum exchange.

Fig. 4.3. Wall pressure coefficient distribution along the backward-facing step.



4.4 Discussion of Findings

Overall, the results demonstrated that backward-facing step flows exhibit strong sensitivity to Reynolds number, particularly in terms of reattachment length and turbulence intensity. The SST k–ω model provided reasonable predictions of mean flow features but showed limitations in capturing unsteady vortex dynamics at high Reynolds numbers. These findings align with recent conclusions by Shur et al. (2022) and Zhang et al. (2024), reinforcing the need for scale-resolving simulations for highly turbulent separated flows.

5.0 CONCLUSION AND RECOMMNEDATIONS

5.1 Conclusion

This study investigated the characteristics of flow separation and reattachment over a backward-facing step under turbulent flow conditions using contemporary numerical modeling approaches. The analysis focused on the influence of Reynolds number on key flow features, including reattachment length, velocity recovery, pressure coefficient distribution, and turbulence characteristics downstream of the step. The results confirmed that the backward-facing step induces a strong adverse pressure gradient, leading to boundary layer separation, the formation of a recirculation zone, and eventual downstream reattachment.

The findings demonstrated that increasing Reynolds number resulted in an elongation of the recirculation region and a corresponding increase in nondimensional reattachment length, indicating delayed reattachment at higher flow inertia. The separated shear layer exhibited enhanced instability and vortex activity with increasing Reynolds number, which promoted stronger turbulent mixing and momentum exchange. Pressure coefficient distributions revealed a sharp pressure drop immediately after the step, followed by gradual pressure recovery downstream of the reattachment point. Although higher Reynolds numbers improved pressure recovery, they also intensified turbulence production within the shear layer, highlighting the trade-off between hydraulic performance and turbulence-induced energy dissipation.

The SST k–ω turbulence model employed in this study was able to reasonably predict the main mean-flow features, including separation, reattachment location, and pressure recovery trends. However, limitations were observed in accurately capturing unsteady vortex dynamics and three-dimensional turbulence effects at higher Reynolds numbers. These results are consistent with recent literature and reinforce the conclusion that while advanced Reynolds-averaged turbulence models offer acceptable predictive capability for mean flow quantities, they remain inadequate for fully resolving complex unsteady phenomena in highly turbulent separated flows.

Overall, the study confirms that backward-facing step flows are highly sensitive to Reynolds number and remain a challenging benchmark for turbulence modeling. The results provide useful insights into separation and reattachment behavior and contribute to ongoing efforts to improve predictive accuracy for engineering systems affected by turbulent separated flows.

5.2 Recommendations

Based on the findings of this study, the following recommendations are made:

1.Future studies should incorporate scale-resolving simulation approaches such as large eddy simulation or hybrid RANS–LES methods to better capture unsteady flow structures, vortex shedding, and three-dimensional turbulence effects in backward-facing step flows, particularly at high Reynolds numbers.

2.Experimental validation using advanced measurement techniques, such as time-resolved particle image velocimetry, is recommended to provide detailed turbulence statistics for further assessment and

improvement of numerical models.

3.The influence of inlet turbulence intensity, wall roughness, and geometric expansion ratio should be systematically investigated, as these parameters were identified as critical factors affecting separation behavior and reattachment length.

4.Flow control strategies, including passive devices or active forcing techniques, should be explored to mitigate pressure losses and reduce turbulence intensity in the recirculation region for practical engineering applications.

5.The findings of this study may be applied in the design and optimization of engineering systems such as diffusers, heat exchangers, and gas turbine components, where accurate prediction of separated flow behavior is essential for improving efficiency and operational reliability.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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