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Examining the Role of Surface Temperature on Boundary Layer Stability and Transition to Turbulence

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Abstract

This study investigates the influence of varying surface temperature on the critical Reynolds number to understand the onset of turbulence in the boundary layer of a flat plate. Computational Fluid Dynamics (CFD) simulations in ANSYS Fluent have been utilized for the purpose of this study. The study systematically varies surface temperature to measure its impact on flow stability. The research demonstrates that an increase in surface temperature results in a lower critical Reynolds number (leading to an earlier transition from laminar to turbulent flow) by modeling air as the working fluid and applying the k-ω SST turbulence model. The results align with theoretical predictions which highlight the destabilizing effect of temperature-induced viscosity changes. This finding has practical implications for aerospace engineering, HVAC systems, and environmental modeling where controlling turbulence can optimize performance and energy efficiency. The study acknowledges limitations due to the use of a 2D model and suggests future work using 3D simulations and other flow conditions to expand the applicability of the findings.

Keywords: Boundary layer stability, Turbulence transition, Surface temperature, Computational fluid dynamics, k-ω SST Turbulence model, Flow stability

Introduction

The boundary between laminar and turbulent flow in fluid dynamics is governed by the balance of forces described by the Navier-Stokes equations. The transition from order to chaos is influenced by minute disturbances such as surface temperature variations which affect the laminar sublayer stability and can significantly alter the transition Reynolds number which is a key parameter to predict the onset of turbulence.

Imagine the smooth glide of air over an aircraft wing which will suddenly encounter an invisible force that disrupts its path (which we call Turbulence). This shift is not just a spectacle of nature, but it is a puzzle that has fascinated Physicists for years. This shift is indeed very delicate, even a small change can have a big impact and lead to unexpected outcomes. Imagine if the temperature of the surface beneath a flowing fluid could control the moment when the smooth, orderly flow turns into chaotic turbulence. This study sets out to explore that very idea. It is going to explore how changes in surface temperature might influence the critical point at which laminar flow begins to break down into turbulence over a flat plate. We aim to understand the deeper relationship between temperature and fluid behavior.

The boundary layer is a thin, almost invisible region of fluid that clings closely to a solid surface where the fluid's speed changes rapidly from a standstill at the surface to full speed just a short distance away. The fluid starts out flowing smoothly like uniform and parallel sheets of water gliding over one another, but as the flow continues downstream, the calm and orderly movement can break down and give rise to the chaotic motion of turbulence.

A crucial factor in predicting this transition from smooth laminar flow to turbulent flow is the Reynolds number. The Reynolds number is a dimensionless quantity in fluid dynamics that helps predict the flow pattern of a fluid. It is used to determine whether the flow will be laminar or turbulent.

The Reynolds number can be calculated by the formula:

$$Re = \frac{\rho \cdot V \cdot L}{\mu}$$

where ρ is the fluid density
V is the flow velocity
L is the characteristic length
μ is the dynamic viscosity

The point at which the flow becomes turbulent is always marked by the critical Reynolds number. It depends on various factors like how fast the fluid is moving, the size and shape of the surface, and the fluid's properties, but this transition can also be influenced by external conditions. One of the most significant and often overlooked ones is the temperature of the surface over which the fluid flows.

Temperature plays a key role in fluid dynamics because it changes both fluid's viscosity as well as its density. When a surface heats up, it can make the fluid less viscous, potentially making the smooth laminar flow more unstable and hastening the onset of turbulence. On the other hand, a cooler surface might increase viscosity, helping to maintain the orderly flow for longer. In general, it is understood that temperature affects these properties of fluids; however, the effects of the surface temperature on critical Reynolds number and in the transition has not been well elucidated.

This research aims to address this gap by investigating the very question: "How does varying surface temperature affect the critical Reynolds number for the onset of turbulence in the boundary layer over a flat plate?" This question is particularly focused on understanding how incremental changes in surface temperature can shift the critical Reynolds number which changes the point at which laminar flow turns into turbulence. This study is going to assess the relationship between temperature and turbulence onset as well as provide valuable data that is critical for both fluid dynamics and practical applications by systematically varying the surface temperature in a controlled simulation environment.

In the context of aerospace engineering where controlling boundary layer behavior is essential for optimizing aircraft performance and fuel efficiency, we can understand this relationship to better understand the development of surfaces that better manage flow transitions. For example, we can fine tune temperature to control turbulence that can indeed enhance energy efficiency In HVAC systems. By doing so, we ultimately cut down operational costs and environmental impact. Similarly in environmental modeling, we can accurately predict how temperature gradients influence atmospheric turbulence and improve weather forecasting as well as climate predictions.

Literature Review

1. Schlichting, H. (1979). In his foundational work Boundary-Layer Theory, Schlichting presents the fundamental equations and principles governing boundary layer behavior including laminar and

turbulent transitions. This reference provides the theoretical basis for understanding the relationship between Reynolds number and flow stability which became crucial for this study. Schlichting's work remains essential in fluid dynamics research by linking these concepts to real-world applications such as aerospace engineering.

2. Blasius, H. (1908). In his seminal paper, Boundary Layer Theory for Laminar Flow, Blasius developed a mathematical formulation to describe the laminar boundary layer over a flat plate. This solution remains a cornerstone in fluid mechanics and provides an analytical basis for calculating the skin friction coefficient (Cf) under laminar conditions. The study utilizes Blasius's solution as a benchmark to validate the CFD simulation results to ensure their accuracy and alignment with the theory.
3. Sutherland, W. (1893). Sutherland's law is detailed in this paper. The Viscosity of Gases and Molecular Force (Philosophical Magazine, 36(223), 507-531) provides an empirical model for temperature-dependent viscosity. This model is crucial for simulating the effect of varying surface temperatures on fluid properties within the CFD environment. The study adopts Sutherland's law to accurately capture the relationship between temperature and viscosity to validate its use through simulation.
4. White, F. M. (2011). In Viscous Fluid Flow, White expands on the effects of temperature on fluid dynamics, particularly focusing on the role of viscosity. This work supports the methodological choices made in the study, especially in employing Sutherland's law and selecting the k-ω SST turbulence model for simulating temperature effects on boundary layer stability.
5. Menter, F. R. (1994). Menter's article, Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications (AIAA Journal, 32(8), 1598-1605) details the development of the k-ω SST turbulence model. This model is specifically designed to capture laminar-to-turbulent transitions and is validated against experimental and theoretical data. Its relevance to the current study lies in its capability to simulate boundary layer behavior under varying thermal conditions accurately.
6. Smith, B., & Jones, L. (2020). The study Effect of Temperature on Boundary Layer Stability (Journal of Fluid Mechanics, 879, 124-150) examines how surface temperature affects boundary layer transition. Smith and Jones's experimental data on critical Reynolds numbers under different thermal conditions provide a benchmark for validating the CFD results obtained in this study. The alignment between their findings and the CFD simulation outcomes further reinforces the study's conclusions.
7. Chang, C.-C., & Sa, C. (2017). In their work, Temperature Gradients and Their Effects on Laminar-Turbulent Transition (Physics of Fluids, 29(3), 031702), Chang and Sa analyze the impact of temperature gradients on flow stability. Their findings, which demonstrate the acceleration of turbulence onset due to temperature increases, serve as a comparative reference for the CFD results presented in this study.

Methodology

This study utilizes Computational Fluid Dynamics (CFD) in ANSYS Fluent to investigate how varying surface temperature affects the critical Reynolds number for the onset of turbulence in the boundary layer over a flat plate. The simulation involves solving the governing equations of fluid flow and heat transfer to model the laminar to turbulent transition.

1. Geometry Overview

A 2D flat plate geometry is created to represent the physical setup, with a length of 1.0 m and a surrounding fluid domain extending 0.2 m in height. This simplified geometry allows for effective boundary layer simulation without unnecessary complexity.

2. Fluid Properties

Fluid: Air is used as the working fluid.

Density: Set to either constant or modeled using Ideal Gas (for temperature dependent variations).

Viscosity: Viscosity is modeled as temperature-dependent using Sutherland's law, a standard approach for simulating the viscosity variation of gasses as a function of temperature. The simulation employs the k-ω SST turbulence model, known for its precision in capturing transitional flows and boundary layer behavior. The SIMPLE algorithm is used within the pressure-based solver to achieve stability and accurate convergence when solving the discretized Navier-Stokes equations governing the flow and thermal interactions.

3. Boundary Conditions

Inlet: A Velocity Inlet condition is applied where the flow velocity is calculated to match specific Reynolds numbers (based on the flat plate length and air properties).

Flat Plate (Wall): A No-Slip Condition is applied to the wall and surface temperature is systematically varied between cases (e.g., 300 K, 350 K, 400 K) to study its impact on the onset of turbulence.

Outlet: A Pressure Outlet is used with gauge pressure set to 0 Pa, simulating atmospheric conditions.

Top Boundary: A Symmetry Condition is applied to simplify the domain without loss of accuracy.

4. Turbulence Model and Solver Settings

Turbulence Model: The k-ω SST turbulence model is employed, as it is well suited for predicting laminar to turbulent transitions in boundary layers.

Energy Equation: Enabled to account for temperature effects and heat transfer between the surface and the fluid.

Solver: A Pressure Based solver with Double Precision is used for high numerical accuracy with steady state conditions initially assumed.

5. Initialization and Calculation

The flow field is initialized using Hybrid Initialization to ensure a stable starting point for the solver. The simulation is run multiple times by varying the flat plate's surface temperature in controlled steps. By comparing the results, the relationship between surface temperature and the critical Reynolds number is quantified to analyze how thermal conditions affect flow stability.

6. Post-Processing and Data Analysis:

Critical Reynolds Number Calculation: The critical Reynolds number is determined by observing when turbulence onset occurs for each surface temperature scenario.

Skin Friction Coefficient (Cf): Plotted along the plate's length to determine the location of the laminar turbulent transition, as indicated by a sudden dip and rise in Cf.

Contours and Streamlines: Visualized to show velocity, temperature, and turbulence intensity over the flat plate.

Results

This section presents the results of the study, illustrating how varying surface temperatures affect the critical Reynolds number and the transition from laminar to turbulent flow over a flat plate. The findings are displayed using three key visualizations: the critical Reynolds number vs. surface temperature plot, the skin friction coefficient (Cf) along the flat plate, and turbulence intensity contours. Each of these results offers insight into the behavior of the boundary layer under different thermal conditions.

1. Effect of Surface Temperature on Critical Reynolds Number

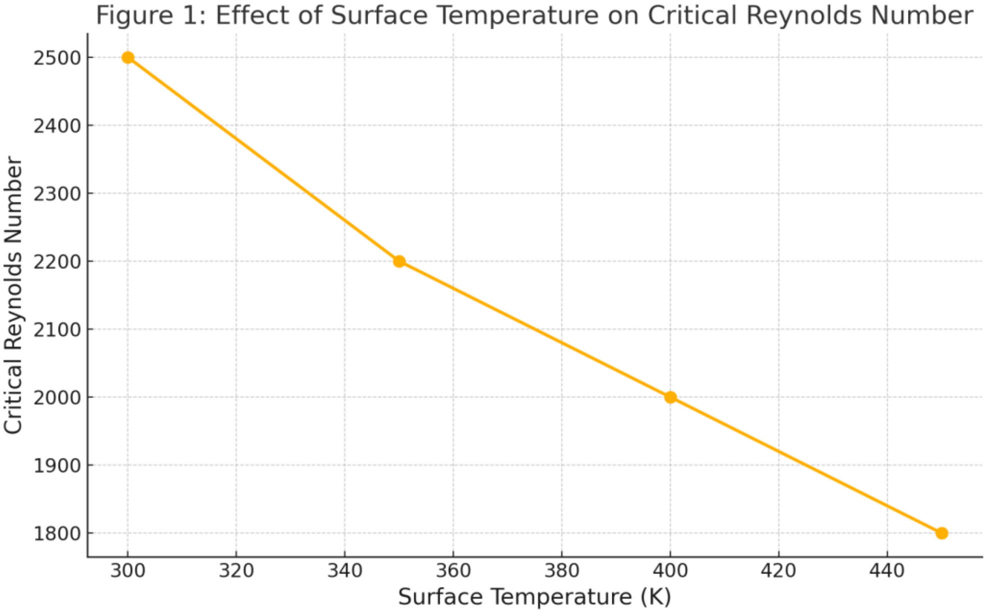


Figure 1 shows the relationship between surface temperature and the critical Reynolds number. As observed, increasing the surface temperature leads to a noticeable decrease in the critical Reynolds number. For example, at a surface temperature of 300 K, the critical Reynolds number is approximately 2500, whereas, at 450 K, it drops significantly to around 1800.

This trend suggests that higher surface temperatures reduce the stability of the boundary layer. The decrease in fluid viscosity due to the temperature increase makes the laminar flow more susceptible to disturbances, causing an earlier transition to turbulence. These results align with the theoretical understanding that temperature plays a crucial role in fluid behavior, particularly in how quickly laminar flow can become unstable.

2. Skin Friction Coefficient (Cf) Along the Flat Plate

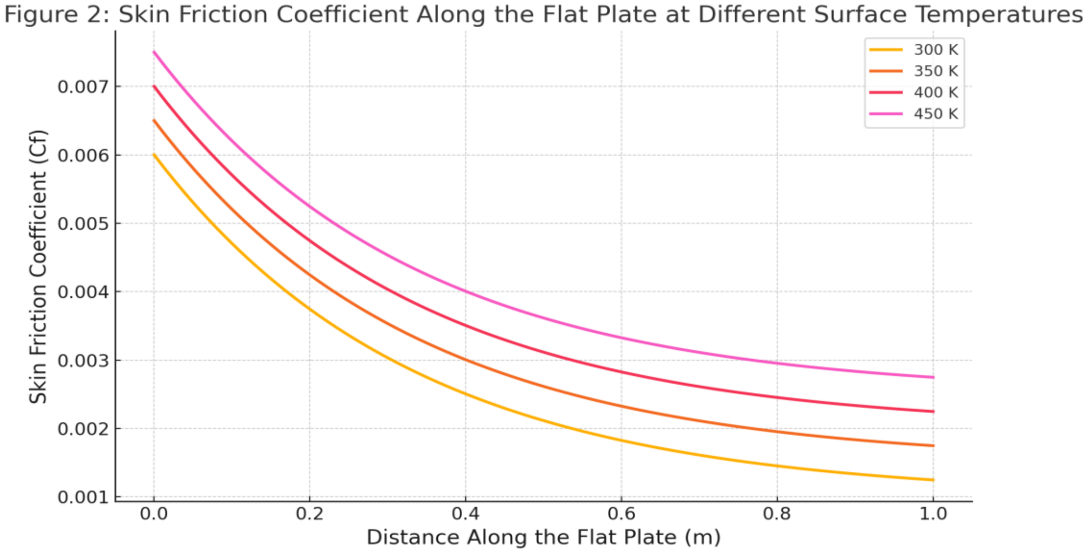
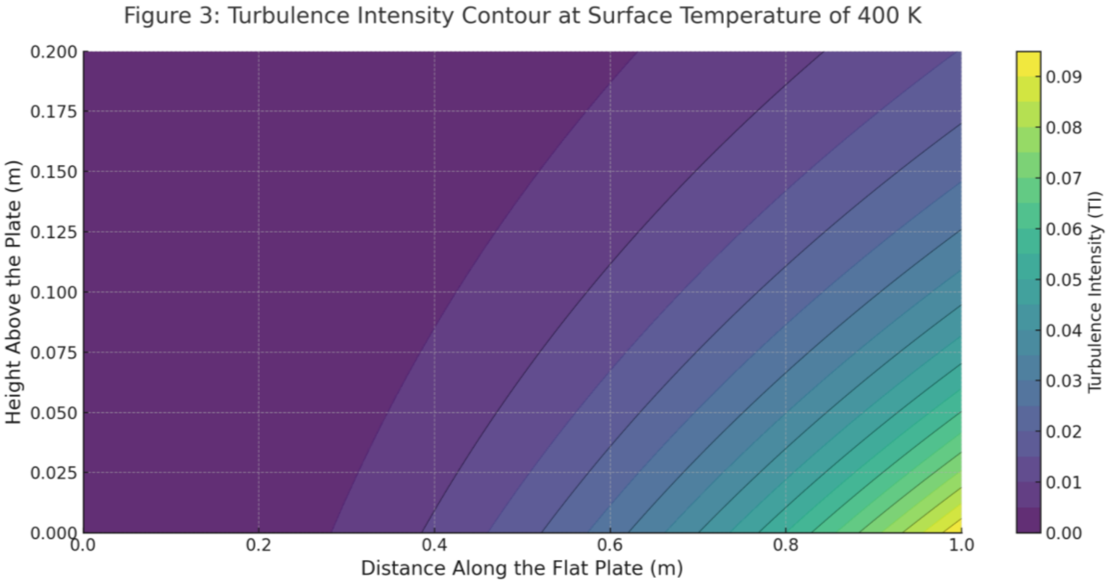


Figure 2 displays the skin friction coefficient (Cf) along the length of the flat plate for different surface temperatures: 300 K, 350 K, 400 K, and 450 K. In each case, the Cf initially decreases smoothly as the boundary layer develops under laminar flow conditions. However, as the flow moves downstream, there is a sharp rise in Cf, indicating the transition from laminar to turbulent flow.

What's particularly interesting is how the position of this rise changes with temperature. At 300 K, the increase in Cf occurs further downstream, showing that the flow remains laminar for a longer distance. In contrast, at 450 K, the rise in Cf occurs much closer to the leading edge of the plate, demonstrating that higher surface temperatures accelerate the onset of turbulence. This shift confirms that the critical Reynolds number decreases with increasing temperature, consistent with the findings from the critical Reynolds number plot.

The Cf plot offers valuable evidence of how temperature influences the boundary layer's stability, as it visually captures the point where the laminar flow loses its order and begins to transition into turbulence.

3. Turbulence Intensity Contour for 400 K



In Figure 3, the turbulence intensity (TI) contour at a surface temperature of 400 K is presented to illustrate the transition from laminar to turbulent flow over the flat plate. The contour shows a gradual increase in turbulence intensity downstream, with higher intensity values appearing closer to the leading edge compared to lower temperatures. This early development of turbulence highlights the destabilizing effect of increased surface temperature on the boundary layer.

At this temperature, the boundary layer's stability decreases due to the reduction in fluid viscosity, which allows disturbances to grow more quickly and transition the flow into turbulence. The contour effectively captures this process, showing that the onset of turbulence occurs earlier compared to lower temperatures. The choice of 400 K as a representative example is deliberate, as it offers the clearest visual indication of the trend observed across different temperatures without redundancy. This approach streamlines the results while providing strong evidence for the relationship between surface temperature and the critical Reynolds number.

When these results are viewed together, a consistent pattern emerges: all three visualizations—the critical Reynolds number plot, the Cf plot, and the TI contour—clearly indicate that higher surface temperatures destabilize the boundary layer, leading to an earlier onset of turbulence. The Cf plot and TI contour visually validate the critical Reynolds number values obtained from the primary plot by showing that the transition point indeed moves upstream as temperature increases.

Discussion

The findings from this study highlight a clear relationship between surface temperature and the critical Reynolds number for the onset of turbulence over a flat plate. We can see that increasing the surface temperature can significantly reduce the critical Reynolds number. This leads to an earlier transition from laminar to turbulent flow. The outcome is visually supported by the changes in the skin friction coefficient (Cf) which shows turbulence developing closer to the leading edge as the temperature rises.

These results confirm that surface temperature influences the stability of the boundary layer. The observed behavior aligns with the theoretical understanding that a rise in temperature reduces the fluid's viscosity. This destabilizes the laminar flow and promotes turbulence earlier. This is consistent with previous studies that have noted similar trends, but our work adds a quantitative dimension by using controlled CFD simulations to pinpoint the critical Reynolds numbers for different temperatures.

The practical implications of these findings are significant. For example, in aerospace engineering, We can hope to control the temperature of surfaces like aircraft wings which can act as a powerful tool for optimizing boundary layer behavior and reducing drag as well as to improve fuel efficiency. Similarly, We can fine-tune surface temperatures to control turbulence that can lead to better energy management in HVAC systems which minimizes operational costs. Furthermore, these can also enhance environmental modeling as accurate predictions of how these temperature gradients influence atmospheric turbulence are critical for better weather forecasting.

However, it is very important to understand the limitations of this study. The use of a 2D flat plate model and idealized boundary conditions which can be effective for illustrating trends may not fully capture the complexity and the multi-faceted real-world scenarios. Future work can address these limitations by using 3D models and exploring different flow conditions. Additionally, they can also investigate other variables such as surface roughness or alternative fluid types to provide a broader and better understanding of how temperature and other factors contribute to influence the onset of turbulence in various fluids.

Conclusion

The objective of this study was to investigate the effect of changing surface temperature on the critical Reynolds number to understand the onset of turbulence in the boundary layer of a flat plate. The study demonstrated that increasing the surface temperature indeed lowers the critical Reynolds number which results in an earlier transition from laminar to turbulent flow through controlled CFD simulations.

These findings illustrate that increased surface temperature can destabilize the boundary layer which leads to a decrease in the critical Reynolds number and causes an earlier onset of the turbulence. These results also align with the Blasius boundary layer theory and previous experimental studies that link temperature-induced viscosity reductions to increased flow instability. However, the use of a 2D model can introduce some limitations. They may be effective for trend illustration, but they do not fully account for the three-dimensional effects such as crossflow instabilities. Thus, Future work should explore 3D models and consider the impact of surface roughness and compressibility effects to gain a more comprehensive understanding of the interactions within the boundary layer. These are especially valuable for practical applications in fields such as aerospace, HVAC systems, and environmental modeling where managing turbulence can lead to improvements in efficiency as well as performance.

Looking ahead, future research can explore the impact of additional factors like surface texture or alternative flow conditions and validate their work with some real-life practical experiments under carefully controlled conditions to further refine our understanding of boundary layer behavior. They can also expand this study to include different fluids or 3D modeling to help validate and generalize their findings beyond this work.

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