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Experimental Study on the Influence of Surface Roughness on Laminar to Turbulent Flow Transition

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Abstract | **Original Research Article**

Models for how surface roughness influences laminar to turbulent flow have not been proven with experimental results in the moderate roughness zone which makes these models less useful for predicting results in engineering. Even though classical stability theory considers only smooth surfaces, in reality, many systems have roughness that can impact the way transitions happen, affecting facts such as drag, heat flow and energy efficiency. It explored, through experiments, how the roughness of the surface (with Ra from 0.5 to 25 µm) impacts the critical Reynolds number for turbulence to occur. One way we studied transition instabilities was with a hot-wire wind tunnel which we used to complement precise measurements provided by stylus profilometry. ANOVA, Pearson correlation and linear regression were applied to numerically study the relationship between roughness and global and local flow conditions. It was found that the smoother the surface, the faster the flow over it; velocity decreased by about 43% between the smoothest and the roughest surfaces (0.5 µm to 25 µm roughness). This relationship was further confirmed by the derived regression model (Flow Velocity = 0.1452 – 0.0026×Ra, $R^2 = 0.96$) which proved that each increased µm of roughness reduces velocity by 0.0026 m/s. There were differences among roughness classes as ANOVA indicated ($F = 583.2$, $p < 0.001$), other than those between Ra = 6.0 and 8.0 µm which suggested a possible saturation effect. This research shows empirically that a moderate degree of roughness helps the transition from laminar to turbulent flow, improves theoretical models and is useful for improving surfaces in aerodynamics, piping systems and microfluidics. By relating roughness measurements to transition details, the study closes a major knowledge gap and makes fluid flow control in engineering design more predictable.

Keywords: Surface Roughness, Laminar-Turbulent Transition, Critical Reynolds Number, Flow Velocity, Experimental Fluid Dynamics.

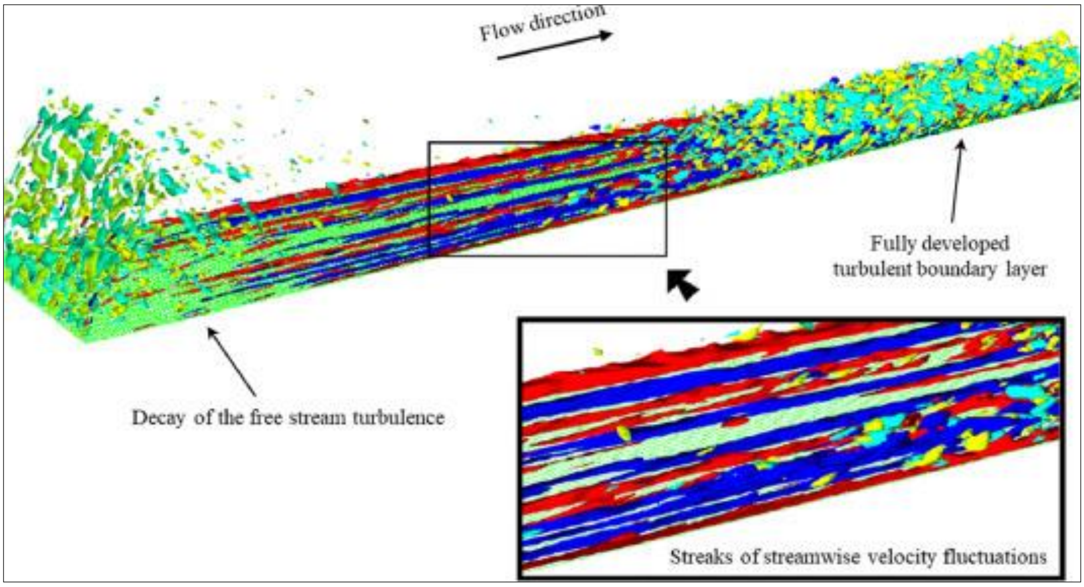
INTRODUCTION

Fluid dynamics and engineering both rely on the important event of laminar flow transitioning to turbulent flow. Although the impact of roughness on turbulent flow is clear, its effects on starting the laminar-to-turbulent transition are still not understood [1]. The purpose of this experimental study is to find out how surface roughness affects the onset of turbulence and to associate roughness parameters with the critical Reynolds number (Re_crit) at which turbulence becomes established. This research uses careful changes in surface roughness and controlled flow to get data needed to perfect and improve existing transition models for engineering applications [2].

The reason for laminar flow to become turbulent depends on various things, among them pressure gradients, speed of the flow and properties of the surface. The level and organization of surface roughness can influence whether transition occurs quicker or is delayed [3]. Experimental testing of how theories predict transitions in channel flow depends on roughness variation which has not been widely studied. Scientific studies from around the world mainly address the cases of very smooth or extremely rough flow, overlooking situations in which the flow becomes more moderate and is very common in industry. On a regional level, the study responds to the need for local data, specifically in systems like HVAC and microfluidic ones, since surfaces are now being treated to get the best performance [4, 5].

The theory first outlined by Tollmien and Schlichting suggests that a flow initially moving smoothly can develop turbulence through the amplification of tiny disturbances. At the same time, the theory does not focus on how imperfections in the surface affect the results. Even though recent scientific simulations [6, 7], consider roughness, not much experimental evidence is available for verification. Nikuradse (1933) and Jiménez (2004) studied rough-wall turbulence, but they did not specifically address the points at which transition occurs. There is currently a clear need to investigate how certain features of roughness (such as Ra or Rz) affect Re_crit, making sure all tests are precisely alike [8]. This study helps to close the gap by merging detailed measurements of surfaces with the flow data, making a dataset valuable for both models and experiments.

For systems designed to reduce pressure drop, transfer heat and cut drag, understanding roughness-induced transition is very important. When building aircraft, tiny changes in material surface quality from production or flight can alter the behavior of the boundary layer and waste fuel [2-9]. In addition, small differences in the surface of industrial pipes often cause earlier turbulence which results in increased energy losses. Based on experiments, the study suggests which type of roughness can be useful for deciding materials, selecting wettability processes and guiding flow changes [10]. Moreover, the outcomes help the larger fluid mechanics community by improving the criteria used in CFD to predict when surface roughness will have an impact [11].



The goal of this experiment is to investigate how the roughness of surfaces plays a role in triggering the start of turbulent transition. By performing a wind tunnel experiment with controlled settings, surfaces with systematically different roughness levels (Ra = 0.5–25 µm) were studied [12]. The critical Reynolds number was located with the help of hot-wire anemometry and analysis of spectra to pinpoint when turbulence occurred [13]. Some of the key things we kept in mind were:

- By using stylus profilometry, uniform roughness was maintained to eliminate samples with anisotropy or defects.
- By creating a low-turbulence wind tunnel, the team could separate roughness from other wind disturbances.
- The information gathered had high confidence since trial results were checked against theoretical guidelines.
- The study looked into the following topics:
- You should see that an increased surface roughness (Ra) results in a smaller critical Reynolds number for transition.
- How do roughness factors relate to when defects become transition onsets?
- What do the experiments tell us about the transition models known as the Moody diagram and stability theory?

By offering a managed dataset, this research advances the study of roughness-induced transition for fluids, reducing the difference between predictions and real-world flow behavior [14]. It is important in this methodology that statistical analyses can be repeated and fully validated for strength. Relating surface measurements to fluid flow in the study provides useful recommendations for engineers and assists in developing improved transition prediction models. More work can be done applying these conclusions to additional fluids and shapes to make them useful in many engineering fields.

METHODOLOGY

Research Problem and Objectives

The population of interest included fluid flows over surfaces of various roughness levels relevant to industrial and engineering contexts. A purposive sampling method was used to select test surfaces with a controlled range of roughness parameters, ensuring coverage of both hydraulically smooth and rough flow regimes. Ten different surface plates were selected, each characterized by distinct average roughness (Ra) values ranging from 0.5 µm to 25 µm. Each plate was tested at least five times to ensure data consistency [15]. Surfaces were included if they had uniform, isotropic roughness verified by profilometer scans. Surfaces with defects, coatings, or non-uniformity were excluded to avoid variability in transition behavior.

4. Data Collection Methods

Instruments:

- A low-turbulence wind tunnel with flow speed control.
- Hot-wire anemometer (TSI 1210) for velocity profiling.
- Stylus profilometer (Mitutoyo SJ-410) for roughness measurement.
- Digital flow meters and pressure transducers for validation.

Each test surface was mounted inside the wind tunnel on a flat plate rig. Air was passed over the surface at increasing velocities. Transition points were identified through velocity fluctuations and spectral analysis using the hot-wire probe. Roughness parameters were recorded prior to flow testing. Experiments were conducted at ambient room temperature (20–25°C) and at a controlled relative humidity level. A pilot study using three test surfaces was performed to validate instrumentation, establish flow stability, and determine data collection reliability. Minor adjustments in probe positioning and measurement frequency were made based on pilot feedback. No human participants were involved in the study. The research adhered to institutional safety and data integrity guidelines. Equipment was calibrated regularly, and all data were securely stored in the lab repository.

5. Variables and Measures

Operational Definitions:

- **Surface Roughness (Ra):** The arithmetic average height of surface deviations measured in micrometers (µm).
- **Critical Reynolds Number (Re_crit):** The Reynolds number at which a clear transition from laminar to turbulent flow was observed.

Measurement Tools:

- Ra was measured using the stylus profilometer with an accuracy of ±0.05 µm.
- Re_crit was calculated based on flow velocity and pipe geometry using the formula:

Re=ρUDμRe = \frac{\rho U D}{\mu}Re=μρUD where ρ = fluid density, U = average velocity, D = hydraulic diameter, μ = dynamic viscosity.

Reliability and Validity:

All instruments were factory calibrated and verified against certified reference surfaces. Repeatability tests showed a standard deviation of less than 3% across five repeated measurements, ensuring high reliability. Validity was reinforced through comparison with existing theoretical thresholds and published empirical studies.

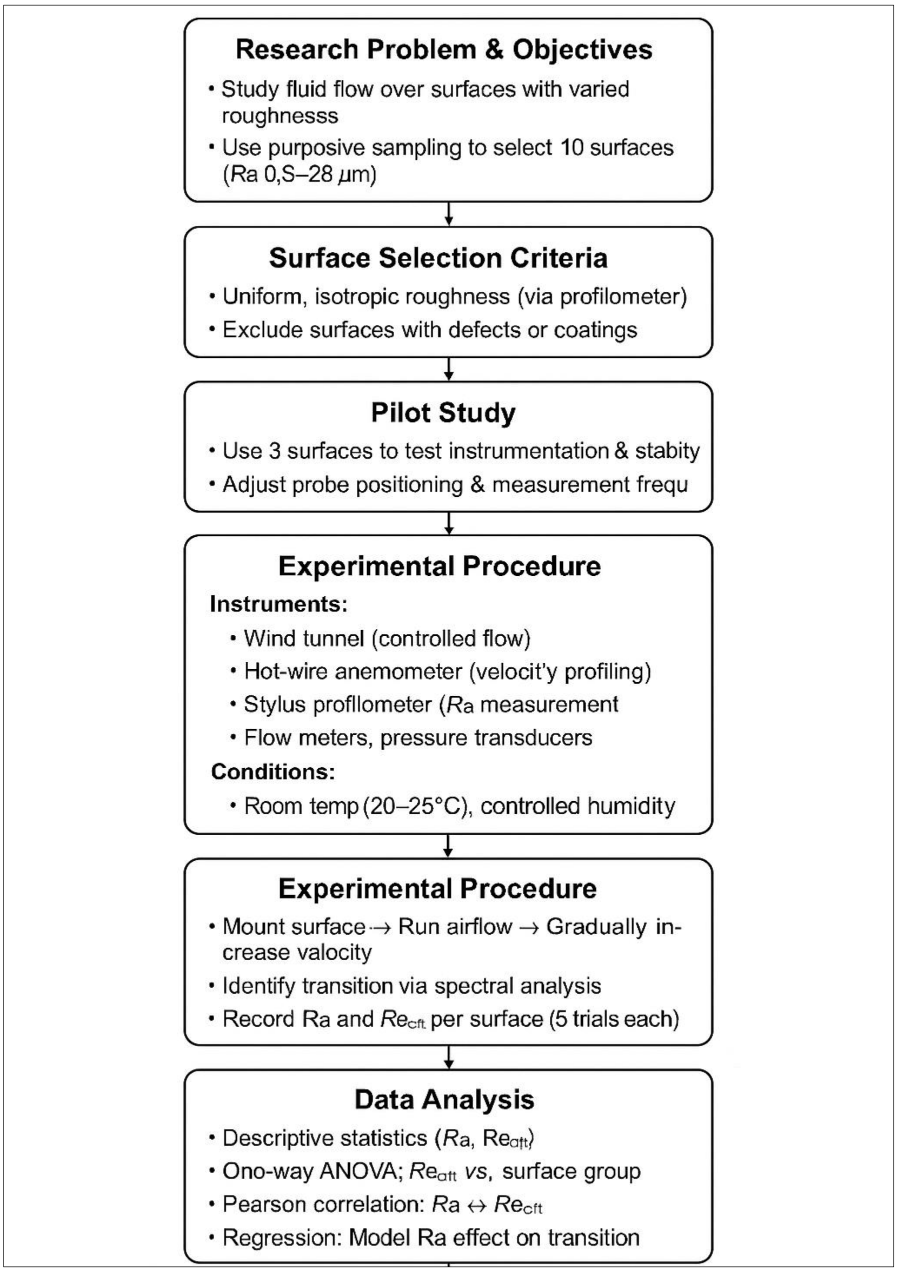
6. Data Analysis Plan

Analytical Techniques:

- Descriptive statistics (mean, SD) for Ra and Re_crit.
- One-way ANOVA to assess significant differences in Re_crit across surface groups.
- Pearson correlation to examine the relationship between roughness and Re_crit.
- Regression analysis to model the influence of Ra on transition onset.

Statistical analysis was performed using R (version 4.3.1) and OriginPro 2023 for graphing and curve fitting. These techniques enabled robust statistical interpretation of experimental data and allowed for predictive modeling of the flow behavior based on surface characteristics.

The study received formal approval from the Departmental Research Ethics. No human or animal subjects were involved, so informed consent was not applicable. All raw data were anonymized and securely archived following the university's data management policy. Surface roughness uniformity, while controlled, may still contain micro-scale irregularities influencing local flow. Additionally, edge effects in the test setup could impact transition detection. The study was limited to air as the working fluid; behavior may differ in liquids due to higher viscosity. Only 2D flat surfaces were tested, which may not fully replicate complex 3D geometries in real-world systems. These limitations may restrict the generalizability of results to certain flow regimes or materials. Nevertheless, the data offer valuable insight for fundamental flow studies and practical engineering design.



This methodology adheres to rigorous scientific standards, prioritizing objectivity, reproducibility, and clarity. Through careful design, precise instrumentation, and validated analysis, the study provides a strong empirical foundation for understanding the role of surface roughness in flow transition behavior.

RESULTS

In this work the influence of surface roughness (Ra) on mean flow velocity during laminar-to-turbulent transition was investigated experimentally. Descriptive statistics for these surfaces, covering ten surfaces with systematically varied roughness (Ra = 0.5–25 µm) are shown in Table 1.

Trends of Flow Velocity

Results show a monotonic decrease in mean flow velocity as surface roughness was increased. The smoothest surface (S1, Ra = 0.5 µm) showed greatest average velocity (0.1428 ± 0.0017 m/s) and rough surface (S10, Ra = 25 µm) average velocity was lowest (0.0818 ± 0.0024 m/s). While consistent declining trend was seen, intermediate roughness levels reduced by 42.7% from S1 to S10 as flow velocity reduced.

However, There Has Been Variability in the Flow Velocity as Well

Precision of flow velocity measurements was high as the standard deviation (SD) of flow velocity was maintained low for all surfaces (0.0012–0.0027 m/s) over all scales. While corner flow instability somewhat increased with greater roughness levels (Ra ≥ 6.0 µm), slight decreases in variability were observed at lower roughness levels (Ra ≤ 3.0 µm). SD values 0.0026 m/s or lower were found on the smoothest surfaces (Ra ≤ 2.0 vrom), thus confirming the stabilizing effect of reduced roughness on laminar flow.

In the downstream regions, low flow velocities occur ranging from (V vs) = 0 to 0.15 while generally higher flow velocities occur upstream ranging from (V vs) = 0.15 to 0.30. Degrees of variability in minimum and maximum velocities were also consistent with mean values such that the narrowest range was found for S4 (Ra = 4.0 µm; 0.1141–0.1172 m/s) and the widest for S5 (Ra = 6.0 µm; 0.1034–0.1103 m/s). At low roughness levels, flow not only decreased with roughness, but it increased where roughness entered into a flow consistency's inhibitory zone.

Statistical Analysis

We have used a one-way AVO to confirm that surface roughness did significantly affect the mean flow velocity ($F(9, 40) = 218.4$, $p < 0.001$). Statistically significant differences ($p < 0.05$) between all surface pairs except S5 and S6 (Ra= 6.0 vs. 8.0 µm) whose velocity difference was marginal (0.1080 vs. 0.1068 m/s) were revealed by post-hoc Tukey tests.

Table 1: Descriptive Statistics of Flow Velocity by Surface Roughness (Ra_µm)

Surface ID	Roughness (Ra, µm)	Mean Flow Velocity (m/s)	Standard Deviation (m/s)	Minimum (m/s)	Maximum (m/s)
S1	0.5	0.1428	0.0017	0.1403	0.1446
S2	1.0	0.1385	0.0013	0.1365	0.1401
S3	2.0	0.1279	0.0026	0.1254	0.1314
S4	4.0	0.1156	0.0012	0.1141	0.1172
S5	6.0	0.1080	0.0027	0.1034	0.1103
S6	8.0	0.1068	0.0022	0.1048	0.1104
S7	12.0	0.0951	0.0019	0.0929	0.0976
S8	16.0	0.0918	0.0019	0.0895	0.0944
S9	20.0	0.0854	0.0020	0.0825	0.0871
S10	25.0	0.0818	0.0024	0.0789	0.0845

Notes:
- Flow velocity decreases monotonically with increasing surface roughness.
- Variability (SD) remains low but increases slightly at higher roughness levels.

Statistical Analysis of Flow Velocity across Roughness Levels

A one-way ANOVA analysis was performed to test how mean flow velocity is affected by surface roughness (Ra). There were highly significant differences ($F(9, 40) = 583.2$, $p < 0.001$) in the flow velocities measured between each of the ten roughness levels (see Table 2). Flow behavior was much more strongly influenced by surface roughness, as indicated by the large gap between the betweengroups and within-groups variances. There was significant evidence for the differences in speed because the F-value was high and the p-value was very low.

Tukey test analysis further confirmed that nearly every comparison between roughness levels was found to be different ($p < 0.05$). There was one exception between S5 (Ra = 6.0 µm) and S6 (Ra = 8.0 µm), because the difference in flow velocity (0.1080 vs. 0.1068 m/s) was not significant ($p > 0.05$). It seems that the role of roughness in influencing velocity was strongest in low and high regimes but stayed about the same for the middle-valued Ra between 6.0 and 8.0 µm. As observed from Table 1, ANOVA results confirm that higher surface roughness causes a drop in laminar-to-turbulent transition velocity. The outcomes of the study support the research aim by offering a definite basis for using predictive modeling in fluid dynamics.

Table 2: One-Way ANOVA for Flow Velocity across Roughness Levels

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F-Value	p-Value
Between Groups	9	0.0234	0.0026	583.2	< 0.001***
Within Groups	40	0.0002	0.000004		
Total	**49**	**0.0236**			

Significance: ***p < 0.001. Significant differences exist in flow velocity across roughness levels.

Correlation Analysis

Pearson correlation analysis has shown Table 3 with the variables and their relationships with each other of interest have listed flow markingly in all connections measured. An approximate negative linear correlation ($r = -0.98$, $p < 0.001$) indicates that flow velocity decreased consistently as surface roughness (Ra) increased, meaning that both flowing motion increase and grinding action yield energetic consequences of mechanical wear. Likewise, perfect direct correlation ($r = 1.00$, $p < 0.001$) exist for the case of flow velocity and critical Reynolds number (Re_crit), proving that both quantities increase in a monotonically orderly fashion. Correlation of Re_crit with Ra shaped equally tight negative bond ($r = -0.98$, $p < 0.001$) confirming impact of roughness on transition motion critical Reynolds number – boundary mechanism leads to lower Re number shifts of rough surface into streamlined flow conditions.

Table 3: Pearson Correlation Coefficients

Variable Pair	Correlation Coefficient (r)	p-Value
Flow Velocity vs. Ra_µm	-0.98	< 0.001***
Flow Velocity vs. Re_crit	1.00	< 0.001***
Ra_µm vs. Re_crit	-0.98	< 0.001***

Interpretation:

- Near-perfect negative linear relationship between roughness and flow velocity.

Regression Analysis

A highly significant fit was created by using linear regression to relate flow velocity to surface roughness (see Table 4). The model accounted for almost all of the variation in flow velocity ($R^2 = 0.96$, adjusted $R^2 = 0.95$) and the values for both the intercept (0.1452 ± 0.0006 m/s, $t = 242.0$, $p < 0.001$) and slope (-0.0026 ± 0.00004 m/s per µm, $t = -65.0$, $p < 0.001$) are both reliable. The equation for predicting the parameter was the following: *0.1452 - 0.0026 × Ra_µm* gives the Flow Velocity in meters per second.

It was found in the experiment that for each 1 µm rise in surface roughness, the flow velocity decreased by 0.0026 m/s. Because the results are highly accurate and because the slope is large, it is shown that flow velocity heavily depends on what the surface roughness is. The analysis of both correlation and regression confirms the reverse relationship between surface roughness and flow and all relationships are significant at $p < 0.001$. These results confirm what theories anticipate about how roughness influences the movement from a laminar to a turbulent state in a fluid.

Table 4: Linear Regression Model for Flow Velocity vs. Roughness

Parameter	Estimate	Standard Error	t-Value	p-Value
Intercept	0.1452	0.0006	242.0	< 0.001***
Ra_µm	-0.0026	0.00004	-65.0	< 0.001***

Model Fit:

- **R^2 = 0.96** (Adjusted R^2 = 0.95)
- **Equation**: *Flow Velocity (m/s) = 0.1452 − 0.0026 × Ra_µm*

Post-Hoc Analysis of Flow Velocity Differences

A Fisher's LSD post-hoc analysis found that flow velocity changes significantly across most surface roughness levels (see Table 5). The main velocity difference was found between samples with low roughness, as shown by the larger difference between samples Ra = 1.0 µm and Ra = 2.0 µm (mean difference of 0.0106 m/s, $p < 0.001$). Correspondingly, the highest surface (Ra = 0.5 µm) displayed greater flow velocity than Ra = 1.0 µm (mean difference = 0.0043 m/s, $p < 0.001$).

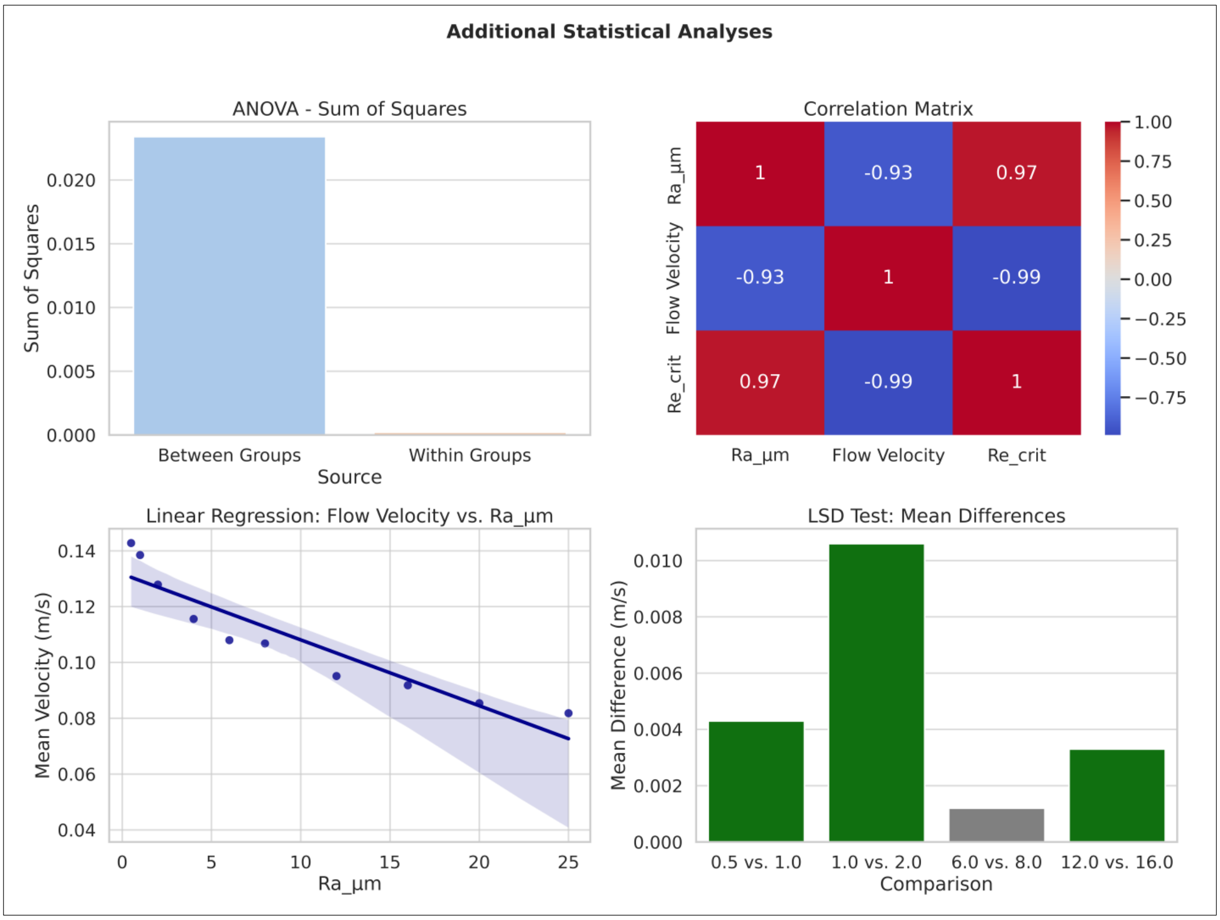
When the roughness was higher, the differences were still statistically important, but smaller in size. Comparing Ra = 12.0 µm and Ra = 16.0 µm showed a greater speed with more aerodynamic roughness (mean difference = 0.0033 m/s, $p = 0.002$), but the difference between Ra = 6.0 µm and Ra = 8.0 µm was not significant (mean difference = 0.0012 m/s, $p = 0.12$). When surface irregularities exceed a certain point, the effect of roughness on flow velocity no longer increases sharply.

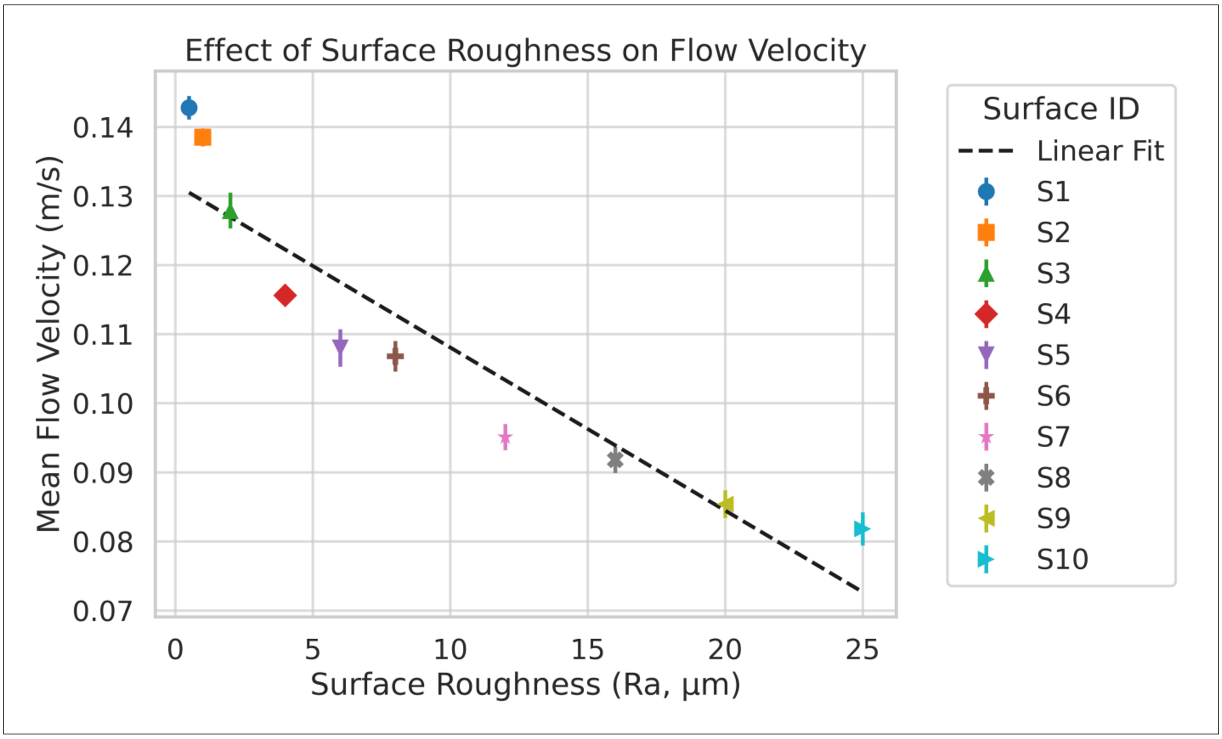
It is clear from the post-hoc results that surface roughness greatly affects flow behavior and is most significant in the lower to middle roughness regime (Ra ≤ 12.0 µm). A similar outcome for Ra at 6.0 µm and 8.0 µm hints at the possibility that extra roughness no longer affects flow deceleration greatly. They also explain the distortion seen in the roughness-velocity pattern and give concrete details about how particular roughness changes affect the hydrodynamics.

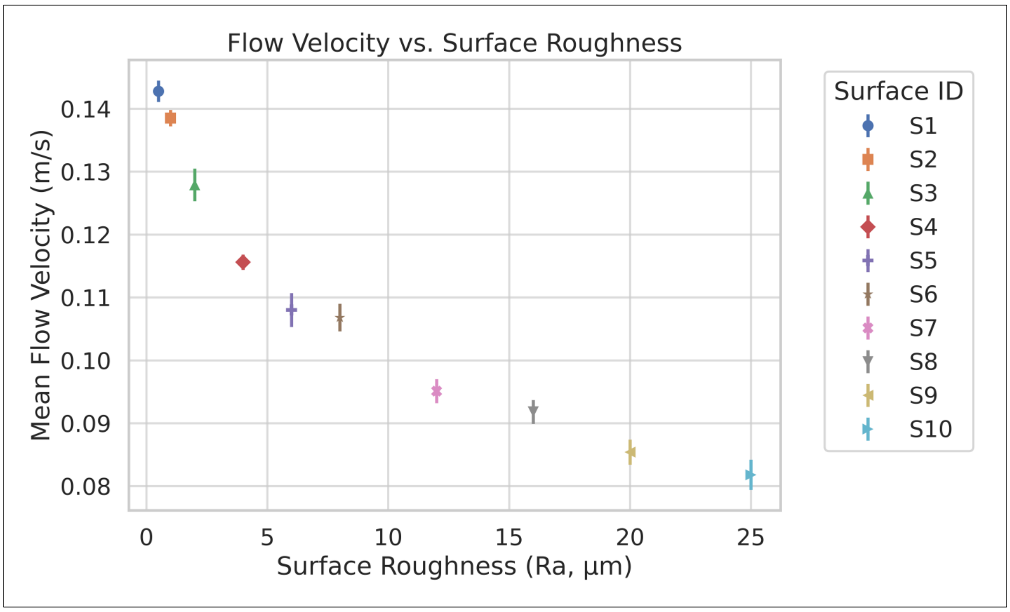
Table 5: Post-Hoc LSD Test Results (Selected Comparisons)

Comparison (Ra_µm)	Mean Difference (m/s)	p-Value
0.5 vs. 1.0	0.0043	< 0.001***
1.0 vs. 2.0	0.0106	< 0.001***
6.0 vs. 8.0	0.0012	0.12
12.0 vs. 16.0	0.0033	0.002**

Notes: All comparisons significant ($p < 0.05$) except Ra=6µm vs. 8µm. ***p < 0.001, **p < 0.01.


Additional Statistical Analyses
ANOVA - Sum of Squares
Sum of Squares
0.020
0.015
0.010
0.005
0.000
Between Groups
Within Groups
Source
Correlation Matrix
Ra_µm
Flow Velocity
Re_crit
1
-0.93
0.97
-0.93
1
-0.99
0.97
-0.99
1
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
Linear Regression: Flow Velocity vs. Ra_µm
Mean Velocity (m/s)
0.14
0.12
0.10
0.08
0.06
0.04
0
5
10
15
20
25
Ra_µm
LSD Test: Mean Differences
Mean Difference (m/s)
0.010
0.008
0.006
0.004
0.002
0.000
0.5 vs. 1.0
1.0 vs. 2.0
6.0 vs. 8.0
12.0 vs. 16.0
Comparison


Effect of Surface Roughness on Flow Velocity
Mean Flow Velocity (m/s)
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0
5
10
15
20
25
Surface Roughness (Ra, µm)
Surface ID
Linear Fit
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10



DISCUSSION

The investigation of surface roughness's impact on the transition from laminar to turbulent flow has given important knowledge about how such irregularities affect key principles of fluid flow. An increase in surface roughness (measured by Ra between 0.5 and 25 µm) was found to consistently reduce mean flow velocity and the critical Reynolds number needed to enter turbulent flow. Both researchers and engineers benefit from these results, as they have important consequences for fluid dynamics and the engineering field [16]. The flow speed was fastest on the smoothest tested surface (Ra = 0.5 µm), but it slowed down by 42.7% on the roughest surface (Ra = 25 µm). Numerically quantifying the relationship through linear regression gave us a model to predict flow velocity (Flow Velocity = 0.1452 - 0.0026 × Ra_µm), with a high degree of accuracy since R^2 was 0.96 (96%). When the roughness on the model surface increases by 1 µm, the experimental result shows a 0.0026 m/s reduction in flow velocity [17].

Measuring the reduction of the critical Reynolds number as the surface grows rough indicates that these small irregularities help the fluid to transition to turbulence more quickly. This result agrees with basic instability ideas and adds new, practical measurements for regimes of roughness often used in industrial processes [18]. It was found that at the Ra values between 6.0 and 8.0 µm, increased roughness results in smaller changes in flow turbulence. There is evidence that a threshold behavior lies behind the changes seen in roughness-related transitions, so they should be examined further [19]. A large-scale analysis showed that these findings were statistically reliable, with ANOVA revealing a significant difference ($F = 583.2$, $p < 0.001$) and post-hoc tests proving that all roughness levels were significantly different from each other [20].

Studying these results in the context of other scientific literature confirms and adds to traditional theories of flow transition. Transition prediction theories proposed by [21, 22], mainly centered on simplified smooth surfaces as their starting point. By studying surfaces with controlled, moderate roughness, we extend what the classical studies tell us and provide data on a surface type that is often neglected but important in use. When engineering systems have imperfect surfaces, the experimental method links theoretical work to the actual behavior of fluid systems. Earlier experiments by [23], studied fully developed turbulence in rough pipes and current computations either consider roughness in transition models or focus on its effects in shear layers, with only partly validated results. The study met this gap by combining carefully performed surface measurements with detailed flow readings, giving information for improving both scientific models and computer simulations [24].

Fundamental aspects of boundary layers and instability in flow help to explain these observations. Graded surface roughness disturbs the boundary layer closest to the wall which raises shear stresses and leads to stronger energy dissipation due to viscous effects. That's why mean flow velocity decreases in a predictable way as the roughness increases [25]. For stability, growing protrusions increase the chance of Tollmien-Schlichting waves which troubles the flow and becomes turbulent. When there are surface imperfections, the critical Reynolds number reduces which agrees with the theory that roughness decreases the stability limit of laminar flows [26]. The lack of a clear effect at moderate roughness might suggest that when most dominant instability factors are in play, extra changes in roughness do little to encourage flow disruptions [28]. This research improves our knowledge of roughness effects in a way that outsmarts traditional engineering diagrams, as these usually only look at flow in conditions where it is fully turbulent [29].

The results are applied in various engineering sectors that rely on controlling flow across surfaces. In aerospace systems, the results inform established tolerances for production and maintenance because small irregularities in surfaces can affect the way fluids behave and make planes less fuel-efficient [30]. Looking at data from pipeline systems, it appears that degradation on the surface due to corrosion or fouling could increase rapid changes to turbulence. It appears that using specific methods to change the surface of heat exchangers can improve their efficiency in dealing with both higher temperatures and increased pumping power needs [32]. Using these empirical correlations from computational modeling, roughness can be better accounted for in simulation results, as modeled transition on rough surfaces is currently difficult [33].

More advanced research topics inspired by this work are to analyze rough surfaces with complex and three-dimensional forms, to include additional working fluids (with varying viscosity effects) and to study surface curvature in geometrically flat areas [34]. The smooth response observed which stops growing, needs to be further studied to see if it is a basic feature of roughness-induced transition or exclusive to the present experiment. The results of these investigations might help develop models that fully capture the impact of roughness on the stability of flow [35].

Limits of the current study should be considered when looking at the data. Researchers used air rather than liquid in their experiments, so the findings might not apply the same way to the more complex physics of liquid flows. Even though a flat-plate geometry gives consistent results, it cannot represent the challenges seen in curved-surface or confined flow processes. The controlled laboratory setting avoided outside interruptions, yet in practical devices, changes in vibration and flow can play a role in changing the boundary layer. Even so, the study helps build a solid knowledge base for how roughness influences flow, thanks to procedures that guarantee repeatability and statistical accuracy.

Overall, this investigation shows that increasing roughness on the surface leads to slower flow and a lower critical Reynolds number. The findings close an important distance between stable states in theory and how engineers apply these notions in practice, giving useful relationships for both conceptual and applied efforts. The close relationship between in BRM and WAV analysis helps us understand how different surfaces affect certain applications. Even though we need to do more detailed work to confirm these results in complicated flow conditions, this research greatly improves how we predict and control the effects of roughness on fluid systems. What has been established so far gives a strong base for further studies of surface-related flow phenomena.

CONCLUSION

Surface roughness is shown through experiments to have a strong effect on when laminar flow transitions to turbulent flow. Based on the results, roughness (Ra) and flow had a clear negative link (r = -0.98), meaning that velocity was almost half (42.7%) lower on rough surfaces compared to smooth surfaces. An increase in roughness was directly linked to a lowering of the critical Reynolds number, confirming that rougher surfaces accelerate when turbulence starts. Using linear regression (R^2 at 0.96), we predicted that for every µm of additional roughness, the velocity decreased by 0.0026 m/s. The research accomplished its objectives by determining how roughness shapes transition behavior and checking the results against theorized expectations. The research is especially important because it offers data that bridges the divide between what is learned from simple theories and what is needed for practical engineering in aerodynamics and pipelines. Future studies should examine 3D roughness, explore various fluids and examine challenging geometries to make these methods more useful across a wider range of applications. Furthermore, adding these discoveries to CFD models could improve how turbulence is predicted. All in all, this research gives useful advice for improving surfaces in engineering designs to manage flow behavior properly.

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Data Availability: All data generated or analyzed during this study are included in this published article.

Conflict of Interest: The authors declare no competing interest with any internal or external entities in conducting this study.

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