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EXPERIMENTAL AND NUMERICAL ASSESSMENT OF THE INFLUENCE OF SPEED PROFILE PARAMETERS ON HYDRAULIC RESISTANCE IN SMOOTH AND ROUGH PRESSURE PIPELINES

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Annotation: The article analyzes the relationship between the logarithmic velocity profile parameters of turbulent flow in smooth and artificially rough pressure pipelines—the Karman parameter κ—and the free terms C_1 and C_2 with the hydraulic resistance coefficient λ. Empirical relationships based on the regression processing of Nikuradze's experimental profiles have been systematized, and their mathematical interdependence and application limits have been clarified. For smooth pipes, the dependence of κ and C_1 on λ and the Reynolds number, the implicit resistance equation obtained by integrating the velocity profile, and the classical Nikuradze and Blazius dependencies were compared. It is shown that the interpretation of κ and C_2 as a strictly monotonic function is limited due to the scattered nature of the experimental points along the rough pipes. To verify the results in the ANSYS Fluent environment, a numerical experimental methodology was developed, including geometry, a grid, a turbulence model, wall roughness, and evaluation criteria. Calculative analysis showed the need to evaluate the velocity profile parameters not as universal constants, but as effective parameters determined within the range of the flow under study.

Keywords: turbulent flow, pressure pipeline, Karman parameter, logarithmic velocity profile, hydraulic resistance, Reynolds number, equivalent roughness, ANSYS Fluent, numerical modeling.

Introduction

The main part of energy losses in pressure pipelines is associated with wall friction, which depends on the pipe diameter, flow velocity, Reynolds number, and internal surface roughness. In engineering calculations, this effect is expressed through the hydraulic resistance coefficient in the Darsi–Veysbax equation. Incorrect selection of the resistance coefficient leads to an overestimation of pump head, an increase in electricity consumption, or the failure to ensure the required network throughput capacity.

In the wall zone of a turbulent flow, the average velocity is often characterized by a logarithmic law. In the classical approach, κ≈0.40-0.41, and for a smooth wall, the free term is taken at a certain constant value. Nikuradze's experiments, Princeton Superpipe measurements, and modern DNS results show that the estimate of these parameters is sensitive to the measurement method, the selected profile range, the Reynolds number, and external layer

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corrections [1, 4, 8]. Therefore, applying the "universal" value of κ to any pipeline and flow regime can be a hidden source of calculation errors.

The problem becomes even more complicated on a rough wall. The height and shape of the roughness elements interact with the viscous substrate, causing a vertical shift in the velocity profile. In the transition resistance region, viscosity and surface roughness act simultaneously; in the full roughness mode, the resistance is primarily determined by relative roughness [1–3]. Modern computational packages such as ANSYS Fluent account for wall roughness using a modified wall law, but the reliability of the result depends on the wall precision of the grid, the y+ value, and the turbulence model [9, 10].

The aim of the study is to clarify the relationship between the parameters of the logarithmic velocity profile and hydraulic resistance in smooth and rough pipes, to evaluate the internal consistency and limits of existing empirical equations, and to propose a reproducible numerical methodology for their verification based on ANSYS Fluent.

Research method

The study was conducted in three stages: at the first stage, the procedure for determining the parameters κ, C_1, and C_2 from the experimental velocity profiles was formulated; at the second stage, the regression relationships between λ and Re parameters were analyzed; at the third stage, a scheme for verifying computational equations using ANSYS Fluent was developed. When matching the experimental profiles, the viscous zone directly adjacent to the wall and the points of the outer layer near the pipe axis were not automatically included in the logarithmic region. The parameters were evaluated using the least squares method only in the interval where the linearity criterion is satisfied at coordinates u^+–$\ln(y^+)$.

$$u^+=\frac{1}{K}Iny^+ +C, \quad u^+=\frac{u}{u}, \quad y^+=\frac{u^* y}{v} \qquad (1)$$

Here, u is the local average velocity; u* is the friction velocity; y is the distance from the wall; ν is the kinematic viscosity. Since κ and C are determined together along the same profile, they are statistically correlated. Therefore, the confidence interval of the parameters, residual errors, and sensitivity to the selected point range must be evaluated together.

As a result of approximating experimental data for smooth pipes, the following dependencies were adopted:

$$C_1=39.6\sqrt{\lambda}-1.33 \qquad (2)$$

$$K = 0.8\sqrt{\lambda}+0.27 \qquad (3)$$

$$C_1=49.5K-14.7 \qquad (4)$$

Equation (4) is obtained as a result of the algebraic elimination of √λ from equations (2) and (3). Thus, it is not an independent new experimental law, but rather represents the mutual compatibility of the first two regressions. This distinction is important in scientific interpretation: presenting a connection from the same data as a separate independent statement artificially increases the reliability of the result.

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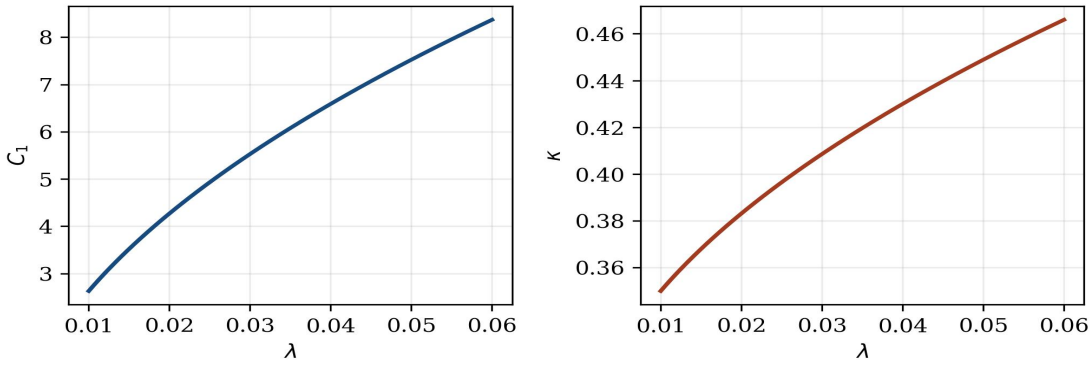


Figure 1. Calculated dependence of C_1 and κ parameters on λ for smooth pipes

Numerical model based on ANSYS Fluent

For numerical verification, a three-dimensional or axisymmetrical design area of a straight circular pipe is adopted. The design length is taken to be at least 50D for the development of the inlet profile; alternatively, a periodic boundary condition and a given pressure gradient can be used. Velocity or mass flow rate is applied at the inlet, and zero excess static pressure is applied at the outlet. Water is taken as an incompressible Newtonian fluid at a temperature of 20 °C, ρ = 998.2 kg/m^3 and ν≈1.004·10−6 m^2/s. °

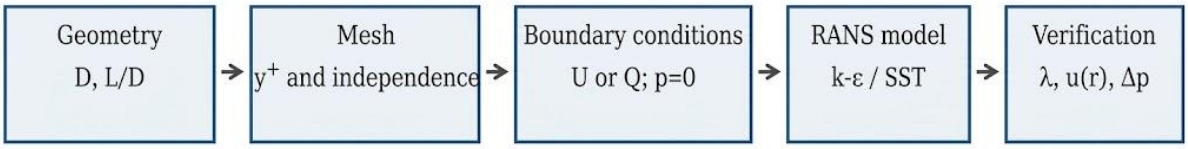


Figure 2. The sequence for constructing and verifying the ANSYS Fluent model

To compare smooth and rough modes on the same basis, the realizable *k-ε* model and scalable wall functions are selected as the initial options. The center of the first wall cell is kept within the range of y^+=30–100. When calculating additional sensitivity along a smooth pipe, it is advisable to use the SST k-ω model and the y^+≈1 grid. In a rough wall, an equivalent sand roughness k_s and a roughness constant C_s are introduced. Since ANSYS accounts for the influence of wall roughness through a modified wall law, it is not possible to automatically equate the k_s value to the height of the geometric irregularity; it must be calibrated according to the experimental resistance [9, 10].

Model element	Acceptable parameter	Control criterion
Accounting domain	D=0,2–0,6 m; L≥50D	Profile fully developed at exit
Liquid	Water, 20 °C; ρ=998,2 kg/m³	Physical properties constant
Flow interval	Re=7·10⁴–1,2·10⁶	Stable turbulent mode
Turbulence model	Realizable k–ε; additional SST k–ω	sensitivity by λ and u (r)

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Model element	Acceptable parameter	Control criterion
Wall	No-slip; k_s/D=0–0,010	Smooth, transition, and rough mode
Net	Grade 3: coarse, medium, dense	λ difference <1%
Approach	Residual <10^{-5}; mass imbalance <0.1%;	Δp and wall τ are stable. 22 / 5000

Table 1. Recommended parameters of the ANSYS Fluent computational model

Based on the calculation results, Δp, the average shear stress in the wall, the radius profile u (r), and λCFD are determined. The resistance coefficient is recalculated from the Darcy-Weisbach equation using the pressure gradient. This method allows for independent verification of the "wall shear" result within Fluent.

$$h_f=\lambda\frac{LU^2}{D2g}, \qquad \lambda_{CFD}=\frac{2D\Delta p}{pLU^2} \qquad (5)$$

Research results and analysis

For smooth pipes, equations (2) and (3) show that C_1 and κ increase together as λ increases. For example, when λ=0.01 to 0.06, κ varies approximately from 0.35 to 0.47, while C_1 varies from 2.63 to 8.37. These values indicate the need for a cautious approach to the problem of taking the constants of the classical logarithmic profile as constant for all flow modes. At the same time, such regression may reflect not only changes in the physical "universal constant," but also changes in effective parameters that combine the selected profile range, external layer effects, and experimental uncertainties.

As a result of integrating the velocity profile represented by the variable κ and C_1 across the pipe cross-section, an implicit dependence is obtained for the resistance of a smooth pipe:

$$\frac{1}{\sqrt{\lambda}}-41.5\lambda-11.8\sqrt{\lambda}=3lg(\frac{u^*\ R}{v})-5.42 \qquad (6)$$

For comparison, the Nikuradze and Blazius expressions were written as follows:

$$\frac{1}{\sqrt{\lambda}}=0.8+2lg(\frac{u^*\ R}{v}) \qquad (7)$$

$$\lambda=\frac{0.316}{Re^{0.25}}, \qquad \mathrm{Re}=\frac{UD}{v} \qquad (8)$$

Since u*R/ν itself depends on λ in equation (6), the solution is found iteratively. In the calculation, the relations u*=U√ (λ/8), R=D/2 are used, and the Blasius value is taken as the initial approximation. The calculated curves obtained in the range of 104≤Re≤106 are shown in Fig. 3.

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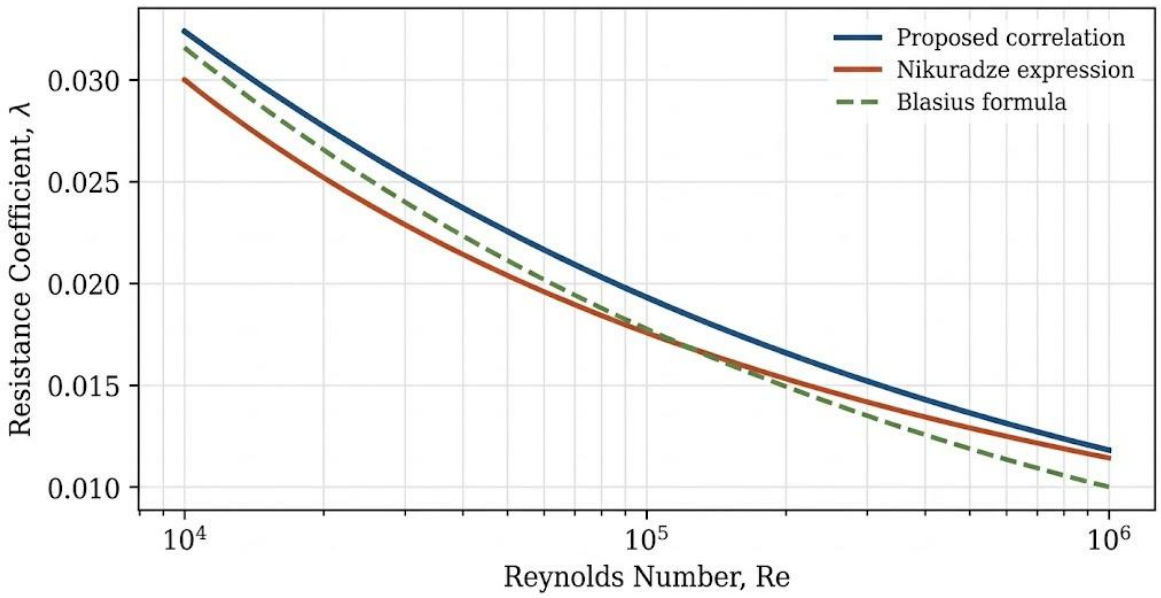


Figure 3. Comparison of calculation methods for the dependence of λ on Re in a smooth pipe

Re	Proposed equation	Nikuradze	Blazius
10 000	0.03239	0.03001	0.03160
30 000	0.02531	0.02290	0.02401
100 000	0.01932	0.01759	0.01777
300 000	0.01520	0.01417	0.01350
1 000 000	0.01181	0.01143	0.00999

Table 2. Design values of the resistance coefficient for a smooth pipe

As seen from the table, the proposed relationship is close to the Blasius result for low and medium Reynolds numbers, and with an increase in Re, it yields a higher value. The difference with Nikuradze's expression is more significant in the range of $Re \approx 10^4$–10^5, and decreases at $Re \approx 10^6$. However, which formula is "more accurate" can only be said by comparing the experimental λ values under the same conditions. In the source text, it is noted that the deviation of the proposed relationship from the experiment did not exceed 2%, while the Nikuradze values were nearly 7% lower in some selected experiments. This result applies only to that data set and does not prove universal superiority.

In smooth resistance mode, the dependence of κ and C_1 on the Reynolds number is expressed by the following approximations:

$$K = \frac{0.45}{Re^{0.125}} + 0.27, \qquad C_1 = \frac{24.67}{Re^{0.125}} - 1.83 \qquad (9)$$

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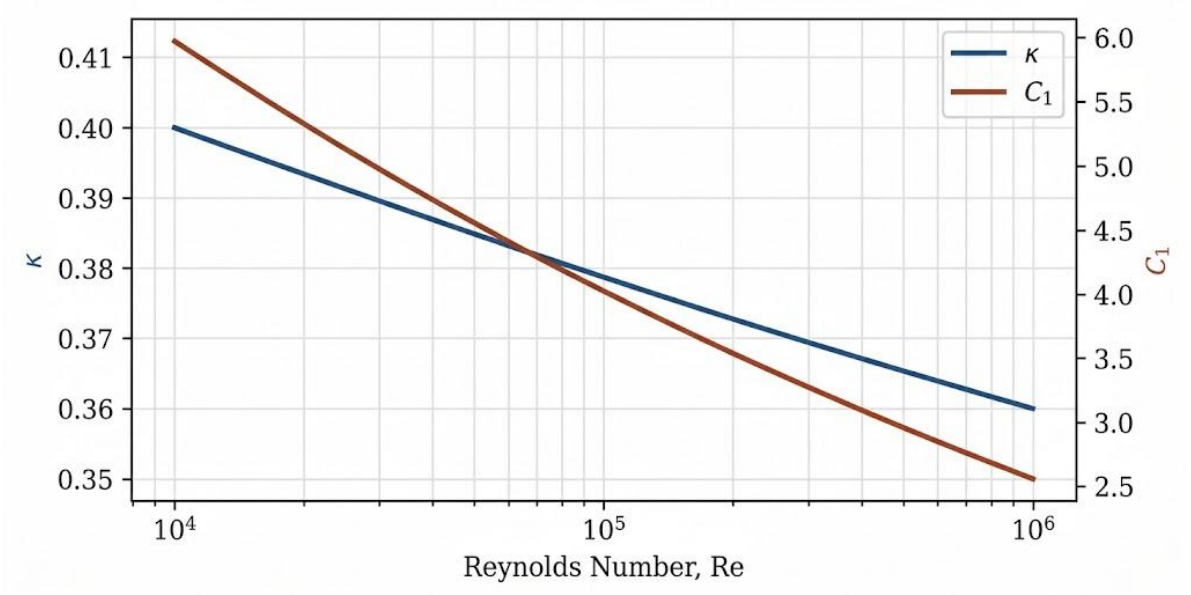


Fig. 4. Calculated dependence of κ and C_1 parameters on the Reynolds number.

It follows from the equations that as Re increases, the values of κ and C_1 decrease, and mathematical convergence occurs to the boundary values of 0.27 and -1.83, respectively. These asymptotic numbers cannot be taken as physical universal constants, as the physical meaning of the velocity profile may be distorted when the regression is extrapolated outside the investigated Re interval. In modern high-Reynolds numerical experiments, the value of κ≈0.40±0.02 [4] and in DNS results, the value of κ≈0.387 [8]. These differences confirm the importance of the profile range, external layer correction, and detection methodology.

For rough pipes, the distribution of κ and C_2 points is stronger than for smooth pipes. Existing experimental data do not confirm a strictly monotonic change in both parameters as λ increases. Therefore, initial engineering calculations may take values of κ=0.40 and C_2=8.48, but when high precision is required, they must be calibrated separately for each type of roughness. The uniform sand-grained surfaces of Nikuradze do not fully reflect corrosion, sedimentation, and irregular connections in technical pipes. Equivalent roughness is an equivalent parameter in terms of resistance, rather than a simple average value of geometric height.

During ANSYS verification, three types of compliance are verified: first, λCFD with experimental or calculated λ; second, with experimental points of the u (r) profile along the radius; and third, the values of κ and C, redefined from the logarithmic domain, are compared with regression equations. The relative error is estimated as follows:

$$\delta_\lambda = \frac{|\lambda_{his} - \lambda_{taj}|}{\lambda_{taj}} 100\% \qquad (10)$$

Good matching only for λ does not guarantee that the speed profile is correctly restored. Different turbulence models can produce different u (r) distributions in the wall and central regions, yielding the same pressure loss. Therefore, the integral indicator—pressure loss—and the local indicator—speed profile—must be verified together. The independence of the grid is also evaluated not only by residual equations but also by changes in λ, y*, and profile parameters.

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The results obtained show that there is a relationship between the parameters of the logarithmic profile and the hydraulic resistance, but this relationship does not express the cause-and-effect relationship in a simple form. κ determines the profile slope, and C determines its vertical displacement; when both parameters are adjusted to the same measurement points, their errors are also correlated. Therefore, a slight change in κ can lead to a significant compensatory change in C. For independent reliability, it is recommended to customize the profile in one part and test it in another, or to evaluate the range of parameters using the bootstrap method.

The advantage of the empirical equations in the article is their simplicity and ease of engineering calculation. The main limitations are the initial experimental range, the accuracy of the measuring instruments, and the dependence on the choice of the logarithmic interval. Before applying the formulas to water supply networks, the equivalent roughness must be determined based on the pipe material, service life, sedimentation, and corrosion state. Otherwise, the calculated accuracy is less than the uncertainty of the real object and does not give a practical advantage.

ANSYS Fluent is not a replacement for experimentation; it is a tool for testing the effects of equations, boundary conditions, and parameters under controlled conditions. It is not scientifically sufficient to assume that the model is "confirmed" only by colored velocity contours. A reliable numerical result requires quantitative comparison with geometry, grid statistics, y^+ distribution, model constants, convergence criteria, and experimentation. Especially when using the wall roughness model, it is necessary to clearly specify the values of ks and Cs.

Conclusions and practical recommendations

1. Empirical equations describing the change in κ and C_1 in smooth pipes depending on λ allow for the connection of the velocity profile and hydraulic resistance in a single design scheme.

2. The equation $C1=49.5\kappa-14.7$ follows algebraically from the first two regressions; therefore, it should be interpreted not as an independent experimental law, but as their internal consistency.

3. The proposed implicit resistance equation yields results close to classical expressions in the range of $10^4 \leq Re \leq 10^6$, but its superiority can only be confirmed by statistical criteria on the same experimental basis.

4. The scattered values of κ and C2 in rough pipes do not allow them to be taken as a strictly monotonic function of λ; the parameters must be calibrated separately by surface type and equivalent roughness.

5. The joint verification of the resistance coefficient, pressure gradient, and velocity profile in ANSYS Fluent, as well as the performance of grid independence and y^+ control, is a necessary condition for the scientific verification of the proposed dependencies.

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