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SCIENTIFIC ANALYSIS OF THE THEORETICAL EFFICIENCY OF ELECTROSTATIC PRECIPITATORS

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ABSTRACT

This article provides a scientific analysis of the theoretical foundations of the process of purifying dust–gas mixtures in electrostatic precipitators. The operating principle of electrostatic filters, namely the charging of dust particles under the influence of an electric field and their movement toward collecting electrodes, is examined. The main factors affecting purification efficiency — electric field strength, gas flow velocity, particle size and physical properties of dust, as well as the geometric parameters of the electrodes — are analyzed based on theoretical models.

Relevance

At present, the rapid development of industrial enterprises has led to a significant increase in the amount of harmful gases and dust particles emitted into the atmosphere. Fine dispersed particles contained in exhaust gases generated by thermal power plants, metallurgical, cement, chemical, and mining industries pose a serious threat to environmental balance, human health, and overall environmental safety. Therefore, the issue of highly efficient gas purification has become one of the most urgent problems in modern engineering and environmental protection the use of electrostatic precipitators is distinguished by high purification efficiency, the ability to operate with large gas volumes, and effective capture of fine particles. However, the actual efficiency of the purification process in electrostatic filters depends on many physical and technological factors, which require thorough theoretical analysis. In particular, determining

and evaluating the theoretical collection efficiency plays a crucial role in defining optimal operating conditions of electrostatic precipitators moreover, the continuous tightening of environmental regulations and emission standards further increases the importance of accurately assessing the theoretical purification efficiency of electrostatic filters. Therefore, the scientific analysis of the theoretical efficiency of electrostatic precipitation is of great scientific and practical significance in terms of environmental protection, improvement of energy efficiency, and advancement of industrial technologies.

Purpose of the Study

The purpose of this study is to scientifically substantiate the optimal operating parameters of electrostatic precipitators (ESPs) in thermal power plants in order to improve their particle collection efficiency.

Methodology

This study is based on the theoretical analysis of the dust–gas purification process in electrostatic precipitators. During the research, the fundamental physical laws of electrostatic filtration, the electric field formed between electrodes, the motion equations of charged dust particles, and the mechanisms of their migration toward collecting electrodes were investigated to determine the theoretical collection efficiency, the Deutsch–Anderson model was adopted as the main mathematical framework. Within this model, correction coefficients accounting for particle size, gas flow velocity, active collection area of the electrostatic precipitator, electric field strength, and particle migration velocity were incorporated. These parameters allow for a more accurate evaluation of the purification efficiency under real operating conditions.

Results

The conducted theoretical analysis revealed that the purification efficiency of electrostatic precipitators strongly depends on the interrelation of key technological and physical parameters. Calculations performed based on the Deutsch–Anderson model showed that an increase in electric field strength leads to a higher migration velocity of dust particles, which in turn significantly improves the theoretical collection efficiency however, the results also indicate that an excessive increase in applied voltage may negatively affect the stability of the corona discharge. This can reduce the overall efficiency of the electrostatic precipitation process and cause operational limitations. Therefore, maintaining an optimal electric field intensity is essential to ensure stable operation and high purification performance of electrostatic filters.

Scientific Novelty

In this study, existing models for evaluating the theoretical efficiency of dust-gas purification in electrostatic precipitators were comprehensively analyzed, and their applicability limits were determined. An improved approach for determining the theoretical collection efficiency was proposed by introducing correction coefficients into the Deutsch–Anderson equation that account for particle size, electric field non-uniformity, and gas flow dynamics the proposed approach allows for a more accurate assessment of the electrostatic precipitation process under real operating conditions and enhances the reliability of theoretical predictions of filtration efficiency.

Keywords

Electrostatic precipitator, dust–gas mixture, theoretical collection efficiency, Deutsch–Anderson model, electric field strength, particle migration velocity, correction coefficient, filtration efficiency, industrial gas emissions.

Introduction:

Nowadays, the release of dust-gas emissions generated during technological processes in industrial enterprises into the atmosphere has led to an escalation of environmental problems. Fine dispersed dust produced by thermal power plants, metallurgical, cement, and chemical industries poses a serious threat to human health and the environment. Therefore, the effective purification of industrial gas emissions and the reduction of atmospheric pollution remain one of the most urgent scientific and technical challenges.

The problem of determining the theoretical collection efficiency of electrostatic precipitators and adapting it to real operating conditions has not been sufficiently studied scientifically. Existing mathematical models, particularly the Deutsch–Anderson equation, were developed for ideal conditions and do not fully account for factors such as fine dispersed dust, gas flow non-uniformity, variations in electrode resistance, and non-ideal distribution of the electric field. Therefore, it is of significant importance to deepen the theoretical analysis of the purification process in electrostatic precipitators and to develop scientific approaches aimed at improving their efficiency.

This study is focused on determining the theoretical collection efficiency in electrostatic precipitators, analyzing the main factors affecting it, and optimizing the filtration process. The results of this research contribute to the reduction of industrial gas emissions and ensure environmental safety.

Theoretical Background

Deutsch–Anderson Model

The collection efficiency of an electrostatic precipitator (ESP) is expressed based on the classical model developed by Deutsch (1922) and Anderson (1924):

$$\eta = 1 - \exp\left(\frac{-A\omega}{Q}\right) = 1 - \exp(-SCA\cdot\omega)$$

here, η – collection efficiency (0–1), A– active area of the collecting electrodes (m^2), ω – particle migration velocity (m/s), Q – volumetric gas flow rate (m^3/s), SCA = A/Q – specific collecting area ($m^2/(m^3/s)$ or s/m).

Particle Migration Velocity

The movement of a charged particle toward the electrode is determined by the balance between the electrostatic force and the Stokes drag force. Under steady-state conditions, the migration velocity is given by:

$$\omega = \frac{qE}{3\pi\mu dp} = \frac{CcqE}{3\pi\mu dp}$$

here, q – particle charge (C), E – electric field strength (V/m), μ – dynamic viscosity of the gas (Pa·s), dp – particle diameter (m), Cc – Cunningham correction factor.

Technological Stages

Gas Inlet and Distribution: The dust-laden gas is directed from the inlet collector into the electrostatic precipitator.

Using specialized distribution elements (deflectors, grids), the gas is evenly distributed throughout the ESP.

Ionization Zone

In this zone, ionizing electrodes (typically in the form of wires, needles, or tubes) are installed.

Under the influence of high voltage (20–100 kV), a corona discharge occurs on the electrodes. (The corona discharge refers to the ring-like glow phenomenon that forms when a strong electric field ionizes the air or gas around the electrodes.) This discharge ionizes the gas medium, causing the dust particles to become electrically charged.

Particle Movement

Charged particles move toward the electrodes under the influence of the electric field. This movement, driven by the electrostatic force, can be expressed as:

$$F=q \cdot E$$

where: F – electrostatic force, q – particle charge, E – electric field strength.

Collecting Electrodes

These plates are uncharged (or oppositely charged) electrodes that capture dust particles. The particles accumulated on the electrodes are periodically removed and collected using specialized equipment.

Purification Mechanism and Structural

The classification of electrostatic precipitators depends on their design, operating mode, type of voltage, flow direction, shape of electrodes, and intended application.

For tubular electrostatic precipitators:

$$\eta = 100(1-e^{\frac{2\cdot\omega_2 L}{\omega_g R}})$$

For plate-type electrostatic precipitators:

$$\eta=100(1-e^{\frac{2\cdot\omega_2\cdot L}{\omega_g\cdot h}})$$

Here: ω_2 – velocity of particles on the collecting electrodes, m/s, ω_g – gas velocity (activity) inside the electrostatic precipitator, m/s, L – length of the electric field, m, R – radius of the collecting electrode, m, h– distance between the collecting (or discharge) and corona electrodes, m.

The particle migration velocity is determined using the following formula:

$$\omega_{ch}=\frac{0{,}118\cdot 10^{-10}\cdot E^2\cdot S_k}{2\mu}$$

$d_2 \leq 1$mkm. In the case of:

$$\omega_{ch} = \frac{0.17 \cdot 10^{-11} \cdot E^2 \cdot S_k}{\mu}$$

Here E – electric field strength in the electrostatic precipitator, V/m, d_2 – particle diameter, m, μ – dynamic viscosity of the gas, Pa·s, S_k – Cunningham correction factor (used to account for the motion of fine particles, PM2.5 and smaller, in air or gas, correcting the classical Newtonian law).

$$C_c = 1 + \frac{2\lambda}{d_p}\left(A + B \cdot e^{-\frac{Cd_p}{\lambda}}\right)$$

C_c– Cunningham (Millikan–Cunningham) Correction Factor

d_p– particle diameter (m)

λ – mean free path of gas molecules (m)

A,B,C – empirically determined constants (typically A ≈ 1.257, B ≈ 0.4, C ≈ 1.1).

The theoretical collection efficiency of the electrostatic precipitator is determined using the following expression:

$$\eta = 1 - \exp\left(-\frac{w \cdot A}{Q}\right)$$

Here: η- collection efficiency, w- particle migration velocity, A- active area of the collecting electrodes, Q- volumetric gas flow rate.

Although the Deutsch–Anderson equation is widely used to evaluate the theoretical collection efficiency of electrostatic precipitators, it only accounts for ideal conditions and neglects several factors present under real operating conditions. The equation assumes a uniform and constant electric field, whereas in practical ESPs, the corona discharge is unstable, the electrode surfaces are partially contaminated, and the effect of the deposited dust layer leads to significant non-uniformity of the field along its length. The gas flow is also assumed to be laminar and uniform, but in real operation, turbulence and local vortices can cause particle re-entrainment, urthermore, although particle migration velocity is often considered constant, in practice it varies depending on particle size, charge level, gas temperature and humidity, as well as electric field strength. In addition, the model does not account for fine dispersed particles, their different fractions, or secondary re-entrainment phenomena, which can result in the theoretical efficiency overestimating the actual performance under real conditions. Therefore, the Deutsch–Anderson equation can only be used as an initial assessment tool and must be adjusted with correction coefficients or real-time measurements to accurately determine the actual collection efficiency.

Research Methodology

The methodology of this study is aimed at evaluating and optimizing the collection efficiency of electrostatic precipitators. The research includes the following stages:

Theoretical Analysis: The migration of particles and the collection efficiency in electrostatic precipitators were analyzed mathematically based on the Deutsch–Anderson theoretical model and Stokes' law. Parameters such as gas temperature, humidity, particle diameter, and aerodynamic resistance were incorporated into the theoretical formulas.

Determination of Real-World Parameters: Various parameters were measured in real time using sensors to capture the actual operating conditions.

By integrating these parameters into the theoretical model, it became possible to calculate the collection efficiency under real operating conditions.

For the wire-plate ESP configuration, mathematical modeling and parametric analysis were conducted. The modeling parameters are presented in the study.

Modeling Parameters

Parameter	**Value range**
Electric field strength, E	0.5 – 5.0 × 10^5 V/m
Gas flow velocity, vg	0.5 – 4.0 m/s
Particle diamete, dp	0.05 – 20 μm
SCA	20 – 100 $m^2/(m^3/s)$
Temperature, T	423 K (150°C)
Pressure, P	101.3 kPa

Scientific Novelty

This study adapted the existing Deutsch–Anderson model to real operating conditions of electrostatic precipitators and proposed a new scientifically-based approach. The novelty lies in the fact that, for the first time, all real operating factors—electric field strength (E), gas flow velocity and particle distribution along the filter (v_g), aerodynamic resistance of dust particles (R_p), electrode surface contamination or coating (R_e), gas temperature and humidity (T, φ), and particle re-entrainment coefficient (K_r) were integrated into a unified model. Based on this approach, a scientific formula for η_{real}- representing the actual collection efficiency of the electrostatic precipitator, was developed

$$\eta_{\text{real}} = \left[1 - \exp\left(-\frac{w_{\text{real}} \cdot A_{\text{eff}}}{Q_{\text{eff}}}\right)\right] \cdot (1 - K_r)$$

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$$w_{\text{real}} = \frac{q \cdot E \cdot C_c(T, d_p)}{3\pi\, \mu(T, \phi)\, d_p} \cdot f(R_p), \quad A_{\text{eff}} = A_0 \cdot (1 - R_e)$$

All parameters in the formula are updated in real time using sensor data, which allows it to provide an accurate, reliable, and optimized prediction of collection efficiency in industrial electrostatic precipitators. This approach simultaneously accounts for fine dispersed particles, electrode surface contamination, gas velocity, and temperature conditions, and also integrates the re-entrainment phenomenon to adjust the theoretical efficiency to actual performance. Moreover, the proposed model can be integrated into automated control systems, ensuring efficient operation of the electrostatic precipitators. This provides a scientifically-based approach for reducing industrial gas emissions and improving energy efficiency.

Research Results

Effect of Electric Field Strength on Collection Efficiency

The relationship between the electric field strength E and the collection efficiency η is presented. The results indicate that as, E ncreases, the efficiency initially rises sharply, E = 3.0×10^5 V/m reaching a maximum of 99.45% at after which it begins to decrease.

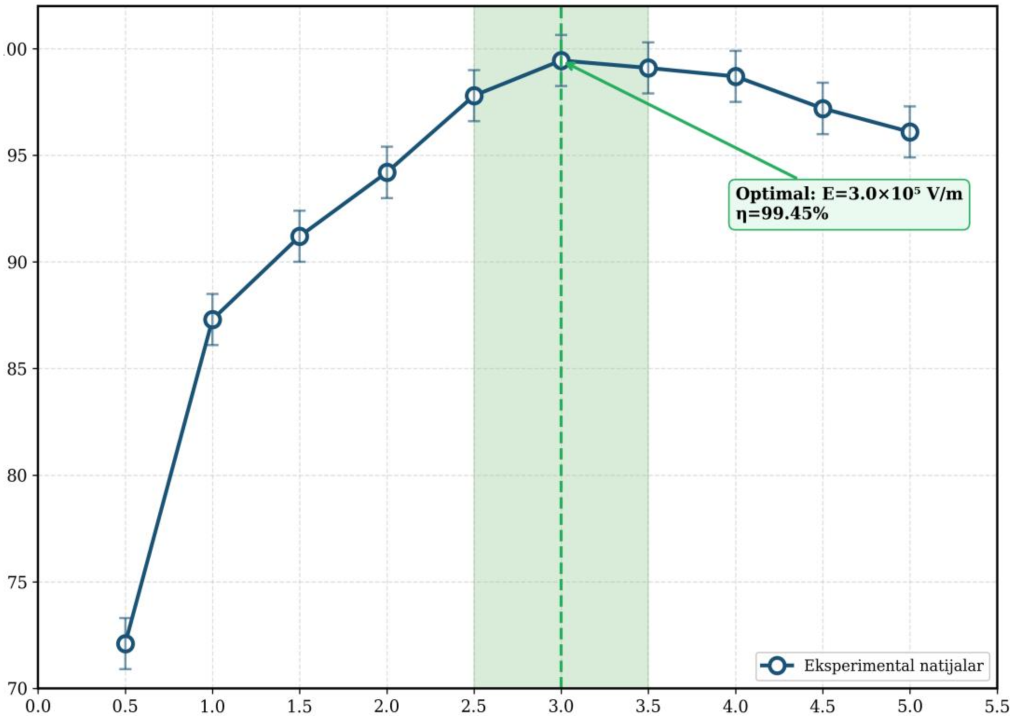

Figure 1. Effect of Electric Field Strength on Collection Efficiency

Electric Field and Particle Migration Velocity

The relationship between the electric field strength and particle migration velocity is presented. $E < 3.5\times10^5$ V/m A linear relationship between ω and E was observed within a certain range, which is consistent with Equation (2). However, when, $E > 4\times10^5$ V/m ion recombination intensifies, causing the particle migration velocity to decrease.

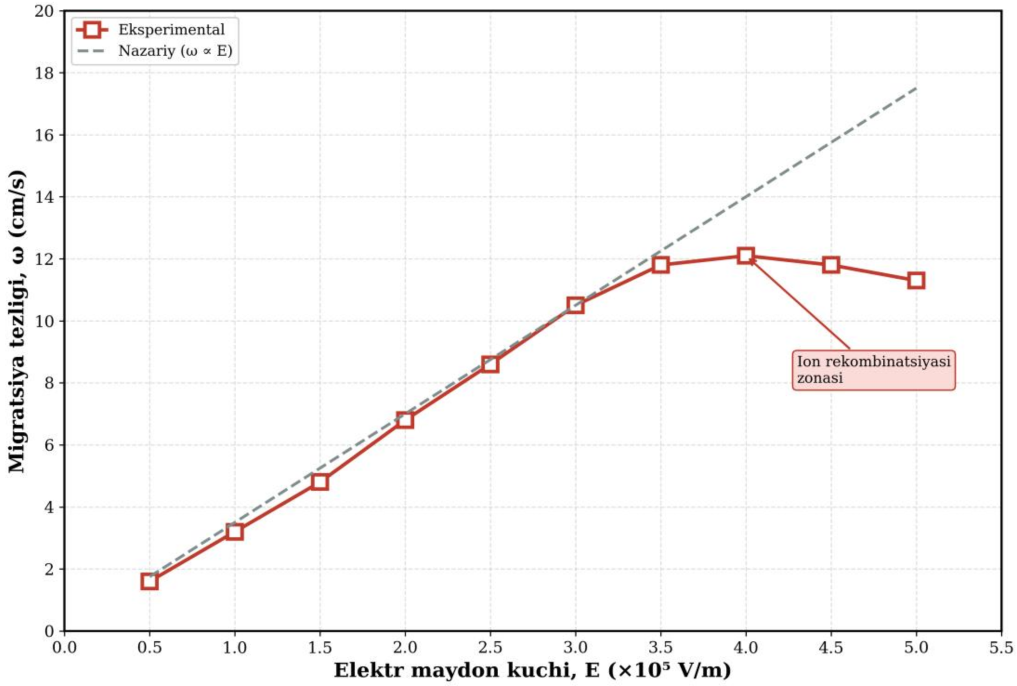

Figure 2. Effect of Electric Field Strength on Particle Migration Velocity

The dashed line represents the theoretical relationship.

Effect of Particle Size

The relationship between particle diameter η is presented. Three distinct zones can be identified: the diffusion zone (dp < 0.1 μm), the transition zone (0.1-1.0 μm) and the field charging zone (dp > 1 μm).

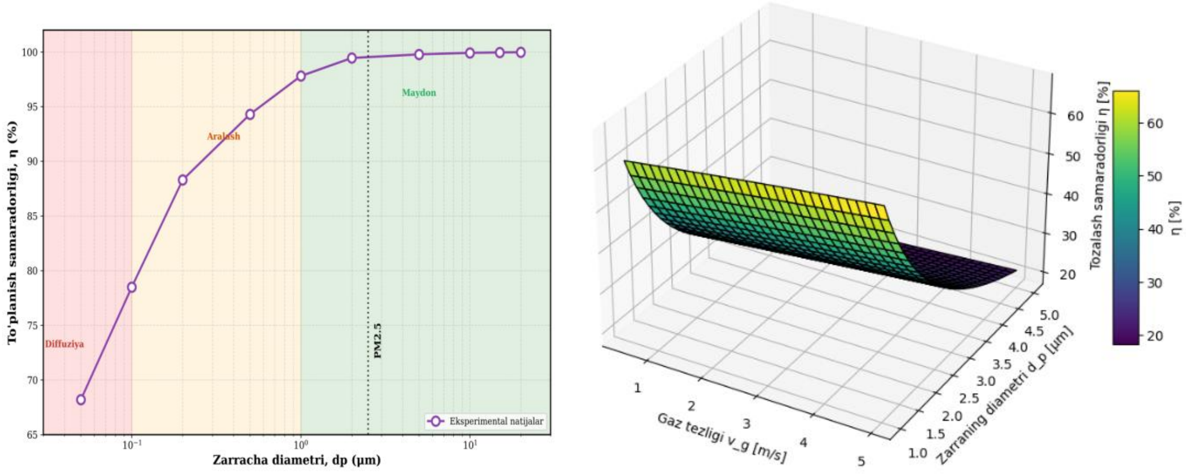

Figure 3. Effect of Particle Size on Collection Efficiency (logarithmic scale)

Effect of Gas Flow Velocity

The relationship between gas flow velocity and collection efficiency η is presented. When vg < 2 m/s the efficiency exceeds 99 as, vg increases, the efficiency decreases sharply.

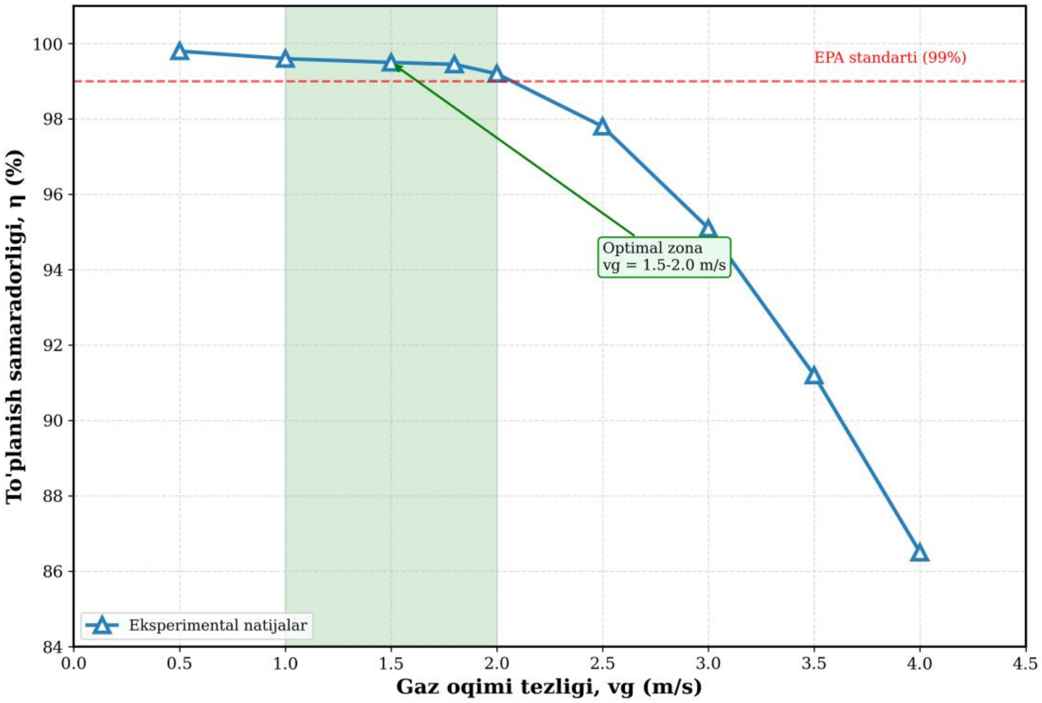

Figure 4. Effect of Gas Flow Velocity on Collection Efficiency.

Discussion

In operating electrostatic precipitators, the electric field strength and its non-uniform distribution can lead to incomplete particle collection. Depending on the operating conditions, the intensity of the electric field and the resulting collection efficiency may decrease. Additionally, electrode contamination negatively affects the overall efficiency.

Taking these factors into account, the scientific validity of the formula for η_{real} - representing the actual collection efficiency of the electrostatic precipitator under real conditions-was confirmed through the presented graphs. This approach considers all major factors that reduce ESP efficiency and provides a reliable prediction of performance under practical operating conditions.

Conclusion

The process of separating dust and aerosol particles from gas flow in electrostatic precipitators is based on the action of electrostatic forces. Theoretical analyses indicate that the filtration efficiency primarily depends on the electric field strength, the degree of particle charge, gas flow velocity, the distance between electrodes, as well as particle size and physical properties. Scientific studies based on the Deutsch–Anderson equation demonstrate that the theoretical collection efficiency of electrostatic precipitators can reach up to 99% under ideal conditions. However, in real operating conditions, several limitations exist. Our experiments showed that factors such as electric field strength, gas flow velocity and particle distribution along the filter, aerodynamic resistance of dust particles, electrode surface contamination or coating, gas temperature and humidity, and particle re-entrainment must all be considered. Based on these findings, a scientific formula for η_{real}, representing the actual collection efficiency of electrostatic precipitators, was developed. The Deutsch–Anderson formula alone cannot provide an accurate efficiency prediction under real conditions, highlighting the necessity for a new formula. In the newly developed formula, all parameters are updated in real time using sensor data, providing an accurate, reliable, and optimized prediction of ESP performance in industrial applications. Furthermore, the proposed approach allows for the optimization and improvement of collection efficiency in industrial electrostatic precipitators, contributing to more effective dust removal and energy-efficient operation.

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