VELOCITY DISTRIBUTION IN PIPE CROSS-SECTION UNDER LAMINAR FLOW CONDITIONS

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Abstract. This article explores the formation and importance of velocity profiles in drilling-fluid circulation as a key factor affecting hydraulic efficiency, pressure losses, and cuttings transport during drilling operations. Focus is given to the development of laminar and transitional flow regimes within the drill pipe and annular space, the impacts of viscosity and density, and the evolution of the flow profile near the bit entry. The analysis emphasises how velocity distribution influences the predictability of pressure gradients, the stability of cuttings suspension, and the risk of turbulence-induced erosion. Understanding these hydrodynamic principles allows drilling engineers to optimise pump performance, maintain safe flow regimes, and prevent sedimentation. The findings demonstrate that velocity-profile analysis provides a critical foundation for enhancing drilling efficiency, borehole stability, and overall operational safety.

Keywords: drilling fluid, velocity profile, laminar flow, Reynolds number, annular flow, pressure losses, hydraulic efficiency, cuttings transport.

Аннотация. В данной статье исследуются механизмы формирования скоростного профиля бурового раствора и его значение для гидравлической

эффективности, потерь давления и выноса шлама в процессе бурения. Особое внимание уделяется характеристикам ламинарных и переходных режимов течения в бурильной колонне и кольцевом пространстве, а также влиянию вязкости и плотности, а также развитию профиля течения в зоне выхода раствора из бурильной трубы. Показано, что распределение скоростей определяет предсказуемость гидравлического градиента, устойчивость транспортировки выбуренной породы и риск турбулентной эрозии. Понимание этих гидродинамических закономерностей позволяет оптимизировать работу насосов, обеспечивать безопасные режимы течения и предотвращать осаждение частиц. Полученные выводы демонстрируют, что анализ скоростного профиля является важнейшей основой для повышения эффективности бурения, устойчивости ствола скважины и общей эксплуатационной безопасности.

Ключевые слова: буровой раствор, скоростной профиль, ламинарное течение, число Рейнольдса, кольцевое пространство, потери давления, гидравлическая эффективность, транспортировка шлама.

The study of drilling-fluid hydrodynamics has always been crucial for understanding and enhancing the performance of drilling systems. Among many factors influencing drilling efficiency, the internal velocity profile of the circulating fluid is especially significant. This profile determines how effectively cuttings are moved to the surface, how pressure is distributed along the borehole, and the hydraulic energy required to sustain the drilling operation. In classical fluid mechanics, the velocity distribution in laminar flow is assumed to be parabolic: the maximum velocity occurs at the centre of the pipe or annulus, while near the walls, the velocity approaches zero due to the no-slip condition [Bird et al., 2007; White, 2016]. Although this principle is well understood, its implications for drilling engineering remain complex and multifaceted, impacting not just hydraulic efficiency but also borehole stability and equipment longevity.

The shape of the drilling pathway [Rabia, 1985] significantly affects the velocity profile. Drilling fluid initially flows through the interior of the drill pipe—a cylindrical conduit—before entering the annular space between the drill string and the formation wall. Each zone develops its own characteristic velocity distribution. Within the pipe, the profile is symmetrical and centred along the axis; however, in the annulus, the distribution becomes asymmetrical due to variations in gap width and potential pipe eccentricity. Although the overall parabolic form is maintained, the maximum velocity shifts towards the wider part of the annulus. These patterns arise directly from analytical solutions to the Navier–Stokes equations for laminar flow and illustrate how fluid–wall interactions govern energy dissipation along the wellbore.

Fluid viscosity and density [Caenn et al., 2011] both considerably influence the configuration of the velocity profile [Fand et al., 1987; White, 2016]. As viscosity increases—owing to polymer additives, clay content, or temperature variations—the profile becomes more distinctly defined: the velocity gradient from the centre to the walls becomes steeper, creating a more pronounced parabolic "bowl" shape and diminishing the likelihood of turbulent disturbances. Density variations, typically through barite or hematite additives, primarily impact hydrostatic pressure rather than the intrinsic form of the laminar profile. It is only when the Reynolds number surpasses the critical threshold that the profile's shape undergoes notable modification. Below this threshold, the traditional parabolic form remains invariant despite differences in density.

One of the most complex areas in drilling hydraulics is the transition zone that forms when fluid exits the drill pipe and enters the wider annulus near the bit. At this stage, the velocity profile does not immediately return to its laminar form; instead, a development region appears, during which the initially uniform velocity distribution gradually transforms into a stable parabolic shape. This development length can extend over dozens of hydraulic diameters and plays a key role in pressure losses, potential cavitation, and the mixing patterns that influence cuttings behaviour near the bit [Bird et al., 2007; Bourgoyne et al., 1991]. Such transitional dynamics are essential for predicting the performance of downhole tools and for optimising flow rates to achieve more efficient drilling.

The internal velocity profile greatly influences pressure losses throughout the drilling system. During stable laminar flow, the connection between flow rate, pressure gradient, and channel shape is highly predictable, allowing engineers to accurately estimate pump power requirements. Understanding these relationships helps operators avoid unnecessary increases in hydraulic energy that could cause mechanical wear or reduce bit efficiency. On the other hand, too low flow can lead to inadequate cleaning, poor thermal control, and the risk of cuttings build-up.

Cuttings transport is one of the areas where the velocity profile has the most direct operational impact [Sifferman & Becker, 1992; Zamora et al., 2013]. Since fluid velocity decreases significantly near the annular walls, particles tend to settle if the average annular velocity is too low. This phenomenon can cause cuttings beds, localised pack-offs, or even stuck pipe events. Effective drilling, therefore, requires engineers to determine the minimum flow rate needed to keep particles suspended and moving upwards. Such decisions depend on an accurate understanding of the velocity distribution and how it reacts to viscosity, density, and borehole geometry.

The boundary between laminar and turbulent flow presents both challenges and opportunities. When the Reynolds number exceeds the critical value—usually around 2300–2500 for pipe flow—the velocity profile begins to flatten as eddies form near the walls. Turbulence significantly increases pressure losses, destabilises cuttings transport, and accelerates erosion of the drill string and casing surfaces. However, in some cases, mild turbulence can be beneficial for the suspension of cuttings. The task for drilling engineers is to balance the conflicting objectives of reducing hydraulic losses while maintaining effective hole cleaning and bit cooling.

Managing these complex hydrodynamic conditions requires a combination of chemical and operational adjustments. Viscosity can be controlled through additives that tailor the fluid's rheological properties to the desired flow regime. Pump rates can be adjusted to keep the flow below the turbulent threshold, unless turbulence is deliberately induced for specific drilling objectives. The geometry of the drill string—particularly pipe diameter—can also be selected to influence hydraulic diameter and flow behaviour. These measures demonstrate how velocity-profile analysis informs practical drilling decisions, bridging fundamental science with applied engineering practice.

A thorough understanding of velocity profile formation offers several practical recommendations [Hemphill & Campos, 2014; Skalle, 2011]. Engineers should start by calculating the critical Reynolds number for the specific drilling-fluid formulation and geometric setup. They should then identify the minimum annular velocity needed to efficiently lift cuttings without causing unnecessary turbulence. More advanced models should consider the profile development zone at the bit entry and allocate pump power to prevent cavitation, sudden pressure drops, or tool malfunction. Together, these strategies highlight the importance of integrating hydrodynamic principles into drilling system design.

In conclusion, the parabolic velocity distribution characteristic of laminar flow is more than just an abstract concept from fluid mechanics; it is a useful tool for enhancing drilling efficiency, stabilising wellbore conditions, and decreasing mechanical wear in real-world drilling systems. The same principles are applicable across various engineering fields, from microfluidics to biomedical modelling of blood flow. By understanding how velocity profiles develop and change in drilling fluids, engineers build a strong foundation for optimising hydraulic parameters, improving hole cleaning, minimising operational risks, and conducting more efficient and safer drilling operations.

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