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Statistic Reability Test of Nozzle Geometry for Oil Well Hole Cleaning from Produced Sand

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ABSTRACT - Sand production is a major operational challenge in the upstream oil and gas industry, leading to perforation blockage, equipment erosion, and increased non-productive time (NPT). This study investigates the optimization of upward-facing nozzle jetting technology to improve sand cleanout efficiency in oil wells. The research experimental model was designed using the Buckingham Pi Theorem and Reynolds number similarity by scaling field conditions into a laboratory prototype. The study concludes that upward-facing nozzle engineering significantly enhances sand lifting efficiency and accelerates wellbore cleanout operations. Furthermore, numerical simulations and statistical analyses—including ANOVA, Shapiro-Wilk normality tests, and coefficient of determination (R²) evaluations—are systematically applied to validate the performance of the re-engineered jetting tool under varied operational parameters such as injection pressure, fluid flow rate, and sand mesh size. The results demonstrate that the proposed sequential dual-function protocol—comprising initial downward disaggregation followed by upward-facing nozzle activation—significantly enhances upward transport velocity and sand-lifting efficiency. Ultimately, this study concludes that upward-facing nozzle engineering significantly enhances sand lifting efficiency, reduces casing erosion risks, and accelerates wellbore cleanout operations, offering an effective alternative for sand management in mature oil fields.

Keywords: produced sand, jetting technology, nozzle engineering, wellbore cleanout, non-productive time, sand management.

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1. Introduction

Oil production from a well is often exposed to problems related to sand production, especially in poorly consolidated formations or formations that experience consistent pressure depletion. Sand produced to the surface not only reduces production effectiveness, but also causes subsurface production equipment to not operate according to its performance, partially or completely plugs perforation holes which serve as the main pathway for produced hydrocarbons to enter the wellbore, and increases operational costs due to periodic well intervention activities. In the context of the upstream oil and gas industry, which prioritizes efficiency, there is a need for solutions that are fast, effective, and economical to handle sand accumulation, especially in fields that still have production potential but are frequently constrained by this problem. Furthermore, handling sand production and optimizing reservoir stimulation in mature or tight sand reservoirs often require careful consideration of completion types, wellhead protection, and proppant or solid management strategies, as highlighted in previous studies on integrated field practices in Indonesian assets published in *Scientific Contributions Oil and Gas*. (Pradipta et al. 2020).

One method that has been developed to handle sand accumulation inside the wellbore is the use of jetting technology, namely a high-pressure fluid spraying method directed precisely to clean sand from the bottom of the wellbore. Although jetting technology has been used in various oil and gas fields, its effectiveness is highly dependent on operational parameters such as fluid pressure and flow rate, nozzle angle, and spraying duration. Therefore, a systematic engineering approach is required to optimize this technology so that it can be used more efficiently and provide maximum cleaning results in a shorter time.

This research focuses on optimizing sand remediation solutions through an engineering approach to jetting technology with the aim of accelerating the well cleaning process and minimizing non-productive time (NPT). By identifying the main parameters that influence jetting effectiveness and arranging them into measurable simulation modeling, it is expected that this technology can be adapted more widely and provide added value in well intervention activities.

Through this research, not only will a more effective jetting technology approach be developed, but it will also contribute to operational effectiveness and the sustainability of production from oil wells affected by produced sand accumulation. This optimization will become one of the innovative solutions amid the increasingly complex challenges of national oil and gas production.

The objectives of this research are to develop an optimal engineering model of jetting technology to accelerate the sand cleaning process without disturbing the formation or equipment, to test the performance of jetting technology with optimized nozzle design under different operational scenarios in order to evaluate time effectiveness and the volume of sand lifted during the oil well cleaning process, and to provide technical recommendations for field implementation in order to minimize non-productive time (NPT) and improve the sustainability of production from wells experiencing sand production.

The scope of this research includes the assumption that the distribution and characteristics of sand at the bottom of the well are homogeneous and do not experience significant changes during the jetting process, jetting technology operates using a physical hydrodynamic mechanism without involving chemical reactions with the formation or sand, the wellbore geometry is considered uniform with a constant diameter in the target cleaning zone, and the jetting pump system is capable of maintaining constant pressure and flow rate during the jetting process under a steady flow assumption. This research also covers the use of jetting technology engineered through nozzle position and size modifications, as well as observations on cleaning efficiency (%), volume of sand lifted (L), and the time required to achieve clean conditions (hours).

Produced sand refers to solid particulates, predominantly formation sand grains, that are co-produced with reservoir fluids from inadequately consolidated sandstone reservoirs. The phenomenon is fundamentally driven by three interacting mechanisms: (a) weak mechanical strength of the formation due to low cementation or burial depth; (b) high differential pressure (drawdown) between the formation and the wellbore; and (c) hydrodynamic erosion by high-velocity flow stripping loose grains from the pore structure (Menter 1994).

Two primary mechanistic frameworks have been proposed for sand production. The first treats it as a hydrodynamic erosion process, where surface and internal erosion coefficients empirically quantify the rate of particle stripping. The second conceptualizes sand production as a viscoplastic granular flow, driven by plastification of the formation matrix around the perforation cavity, where porosity increase in the plastic zone governs sand volumetric output (Menter 1994) provided experimental support for the plastic zone model, demonstrating that permeability in the plastic zone is lower than in intact formation, and that sand production is correlated with porosity increase exceeding the initial value.

Operationally, produced sand causes: erosion of tubing, pumps, and surface equipment; sand bridging and perforation blockage; separator fouling; reduced production efficiency; and accelerated reservoir pressure depletion. These consequences necessitate either sand control measures—such as gravel packs, wire-wrap screens, or chemical consolidation—or sand management approaches, of which jetting is a primary method.

Table 1 presents a comparative overview of sand production prediction models, illustrating the diversity of analytical, empirical, and numerical approaches available and their respective limitations.

Table 1.
Comparison of sand production prediction models

Model/method	Main objective	Equation/approach	Limitations
Critical Drawdown Pressure (CDP)	Determine the critical pressure limit for sand production	$CDP = \sigma_{min} - P_w$	Not accurate for unconsolidated formations
Mohr–Coulomb Failure Envelope	Predict the initial formation failure	$T = c + \sigma \cdot \tan(\phi)$	Ignores porosity and fluid effects
Empirical Power Law (Sanding Rate)	Estimate the quantity of sand production	$Q_s = k(P_{drawdown} - CDP)^n$	Cannot be applied to new wells without historical data
Pore Collapse & Capillary Snap-off	Predict microscopic sand production due to pore collapse	Microscopic numerical approach (FEM)	Requires CT-scan core analysis
Numeric Geomechanics (FLAC3D)	Analyze plastic zones and estimate deformation	Elasoplastis, couple flow mechanics	Requires 3D CFD model integration
Coupled Flow Sanding Models (CMG STARS)	Estimate sand production quantity from fluid flow	Multiphase, erosion + failure + transport	High complexity and requires extensive field data
Stress Path Analysis	Analyze stress changes during production	Plot σ_1 vs σ_3 vs time/production	Not suitable for unconsolidated formations
Log-Based Sanding Indicator	Sanding screening based on log data	$J_f = -D (\sigma_K / \sigma_Z)$	Indicative only and not quantitative
Fines Migration Model	Predict sanding caused by fine-particle migration	SFI = (Tensile Strength / drawdown pressure)	Influenced by chemical reactivity and capillary pressure
Mechanical Compaction + Subsidence Model	Predict sanding caused by formation pressure depletion	Coupled geomechanical model	Requires complete pressure models and regional data

Jetting technology operates on the principle of converting high-pressure fluid energy into high-velocity kinetic energy through a restricted nozzle orifice. The jet is directed at sand accumulations, imparting sufficient momentum to dislodge and suspend sand particles for transport to surface. Key operational parameters include injection pressure (1,500–5,000 psi), flow rate, nozzle diameter and orientation, and jetting duration. Demonstrated the application of coiled tubing-conveyed sand jetting in a North Sea horizontal tight gas well, successfully perforating and cleaning accumulated sand from the annulus. Khatibi & Aghajpour (2020) introduced an enhanced jetting tool integrating sand vacuuming technology for heavy oil well cleanout, achieving significant improvement in cleaning effectiveness through optimized nozzle configuration and bottom-hole assembly (BHA) design. These studies underscore that nozzle configuration specifically the number, size, and orientation of nozzles is a critical determinant of jetting effectiveness.

Reported the use of sand jet perforating combined with annular coiled tubing fracturing for horizontal well stimulation, while applied optimized jetting combined with viscoelastic acid treatment for horizontal well productivity enhancement in Iraq. Demonstrated improved horizontal well cleanup using nozzle-based inflow control devices (ICDs), noting persistent sand accumulation challenges at the toe section that passive ICD systems could not address. These collective findings highlight a consistent research gap: the absence of systematic study on active upward-facing nozzle configurations that directly generate upward sand transport momentum.

The advantages of jetting technology include rapid deployment, applicability to vertical, directional, and horizontal wells, and feasibility without a surface workover rig. Limitations include inability to permanently halt sand production, risk of casing erosion at excessive pressures, and performance dependency on accurate parameter selection (Khatibi & Aghajanpour 2020).

Early foundational work established empirical frameworks to determine the minimum energy and flow thresholds required to prevent sand deposition. Li & Walker (2001) conducted extensive sensitivity analyses on hole cleaning dynamics in deviated wells, establishing early empirical correlations for the *critical transport velocity* (v_{crit}) necessary to suspend particles during CT jetting. Building upon this, Li et al. (2002) provided a comprehensive state-of-the-art review compiling mathematical and empirical models. Their work focused on quantifying sand bed height reduction as a direct response to hydraulic jet erosion forces, demonstrating that effective mobilization relies heavily on the interplay between fluid velocity and wellbore inclination.

To evaluate nozzle configuration performance, combined mechanistic and statistical approaches to model the impact of jet geometry (e.g., forward vs. backward jet distribution). Their empirical correlations quantified the erosive force required to break down compacted sand banks. Furthermore, field-data-driven statistical analysis by Azevedo & Fonseca (2014) evaluated dozens of high-angle well interventions, yielding regression equations that predict minimum cleanout times based on pump rates, fluid rheology, and mean sand grain sizes.

A systematic analysis of the existing literature, summarized in Table 2, reveals several critical gaps. First, no study has comprehensively integrated experimental, CFD numerical, and field-scale analysis for upward-facing nozzle jetting configurations specifically targeting annular sand cleanout. Second, existing CFD models of jetting tools have rarely been validated against laboratory experimental data. Third, sand transport models have not been explicitly linked to nozzle design parameters in a way that supports predictive optimization. Fourth, research specific to the characteristics of Indonesian mature fields and their produced sand properties remains limited.

Table 2.
Research position matrix — selected key references

Research/studies	Research focus	Research gap	Relevance to this study
Smith et al. (2022)	Field evaluation of jetting efficiency in Middle East	Does not explore nozzle design parameters	Provides empirical baseline for efficiency benchmarks
Zhang & Liu (2023)	Innovative nozzle design for enhanced jetting	Limited to aerodynamic geometry; no upward orientation	Supports nozzle geometry optimization approach
Fryzowicz et al. (2010)	CT-conveyed sand jetting in horizontal wells	No real-time integration; no numerical model	Field deployment reference; confirms CT applicability

This study addresses these gaps by developing a systematically scaled laboratory prototype of an upward-facing nozzle jetting system, validating it through CFD simulation, and establishing quantitative performance metrics—specifically outlet velocity, pressure distribution, and DPM particle transport behavior—as a function of nozzle configuration and inlet flow conditions.

2. Methodology

2.1 Research design and hypotheses

This study employs a quantitative experimental approach combined with CFD numerical simulation, structured around a pretest-posttest control group design comparing two jetting configurations:

- Control group: Conventional single downward-facing nozzle jetting.
- Experimental Group: Re-engineered jetting system with one downward nozzle and three upward-facing nozzles (single + triple nozzle configuration).

The null and alternative hypotheses are:

- H_0 : Engineering the jetting nozzle to face upward does not provide a statistically significant effect on the efficiency of produced sand remediation or the acceleration of oil well cleanout.
- H_1 : Engineering the jetting nozzle to face upward provides a statistically significant improvement in produced sand remediation efficiency and accelerates the oil well cleanout process.

2.2 Laboratory-Scale Prototype Design: Scale-Down Analysis

Tamburrino & Niño (2025) stated on their article, Prototype scaling from field conditions to laboratory dimensions was grounded in the Buckingham Pi Theorem, with the Reynolds number (Re) as the governing dimensionless similarity parameter:

$$Re = \frac{\rho V D}{\mu} \quad (1)$$

where ρ , V , D , and μ are fluid density (kg/m^3), characteristic flow velocity (m/s), pipe diameter (m), and dynamic viscosity ($\text{Pa}\cdot\text{s}$), respectively. The field model parameters were: fluid = water, flow rate = 700 GPM ($0.044 \text{ m}^3/\text{s}$), drill pipe inner diameter = 4.5 inches, wellbore diameter = 7 inches, depth = 3,000 ft, and sand particle size = Mesh 40 ($\approx 0.635 \text{ mm}$). The computed field Reynolds number was approximately 490,000, confirming fully turbulent flow. The scale-down ratio adopted was 1:2.25, translating the 4.5-inch drill pipe to a 2-inch laboratory pipe and the 7-inch wellbore to a 3-inch (nominally 4-inch for ease of modification) acrylic tube. The matching laboratory flow rate for Reynolds number similarity was $0.02 \text{ m}^3/\text{s}$. Sand particle size was scaled accordingly from Mesh 40 (0.635 mm) to 0.28 mm .

The required flow entrance length to ensure fully developed turbulent flow was calculated using:

$$\frac{L_e}{D} = 4.4 (Re)^{1/6} \quad (2)$$

This yielded an entrance length of 4.5 m (177 inches) for the field scale, and 2.0 m (79 inches) for the laboratory scale. A conservative value of 2.5 m was adopted to ensure fully developed flow conditions prior to the test specimen. The nozzle diameter was scaled from the field value of 11.5 mm (0.45 inches) to 0.5 inches (downward nozzle) and 0.25 inches (upward nozzles) at laboratory scale. The experimental apparatus consisted of a transparent acrylic pipe system (wellbore simulation), a 2-inch PVC pipe (drill string simulation), a pump system capable of 300 psi, a flow meter, pressure transducers, a Venturi meter for flow measurement, and a hydraulic bench for controlled flow experiments. Sand of 40-60 mesh was used as the simulated produced sand. Table 3 summarizes the key measurement equipment.

2.3 Research variables

The study variables were systematically categorized as follows. Independent variables (primary factors) included: pump injection pressure (psi or bar), jetting fluid flow rate (L/min), nozzle-to-sand-bed distance (cm), and jetting duration (minutes). Controlled variables included: jetting fluid type (water and brine), sand particle size (40-60 mesh), and wellbore temperature and pressure (held constant). Dependent variables (response parameters) included: sand cleaning efficiency (%), volume of sand lifted (liters or grams), flow pattern (streamline/velocity distribution), and time to achieve complete cleanout (minutes).

Table 3.
Measurement equipment and parameter justification

Instrument	Parameter measured	Justification
High-pressure jetting test rig	Jet velocity, injection pressure, jetting time	Simulates wellbore jetting with controlled parameters
Digital manometer / pressure transducer	Fluid pressure (bar or psi)	Quantifies actual jet energy transmitted to target zone
Ultrasonic / turbine flow meter	Fluid flow rate (LPM or bbl/min)	Ensures optimal energy delivery to sand bed
High-speed camera	Jet pattern and sand particle dynamics	Visual validation of CFD flow patterns and particle motion

2.4 Statistical analysis

Experimental data were analyzed using descriptive statistics (mean, standard deviation, range), followed by normality testing using the Shapiro-Wilk test. Hypothesis testing employed the Independent Samples T-Test for normally distributed data, or the Mann-Whitney U test for non-normal distributions, with a significance threshold of $\alpha = 0.05$ (p-value < 0.05 for rejection of H_0). Validation experimental measurements was performed through graphical comparison of velocity profiles, pressure-efficiency relationships, and sand volume vs. time trends.

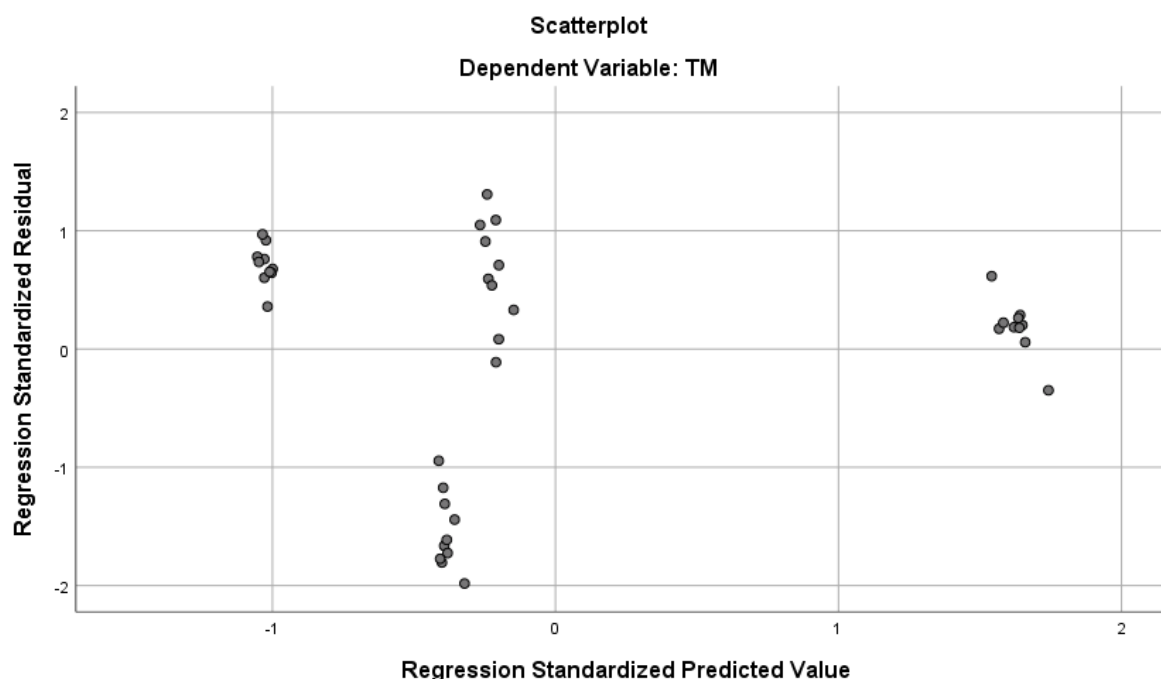


Figure 1.

X-axis: Regression Standardized Predicted Value (represents the predicted values of the dependent variable based on the model).
Y-axis: Regression Standardized Residual (represents the errors or differences between the actual and predicted values).

2.5 Jetting operation protocol

The engineered jetting operation protocol for the upward-nozzle configuration was designed as follows: (1) Run-in-hole (RIH) the BHA while pumping to tag sand at the wellbore bottom; (2) Perform drill-out jetting to disaggregate compacted settling sand into loose particles; (3) Stop pumping and lift the BHA above the perforation zone; hold for one cycle bottom-up (BU) to allow circulation; (4) RIH again to the sand bottom; (5) Drop ball to plug the downward-facing nozzle(s); (6) Restart pumping to activate the three upward-facing nozzles, which direct high-velocity jets upward to rapidly transport loose sand particles to surface, clearing the perforation zone and restoring production flow.

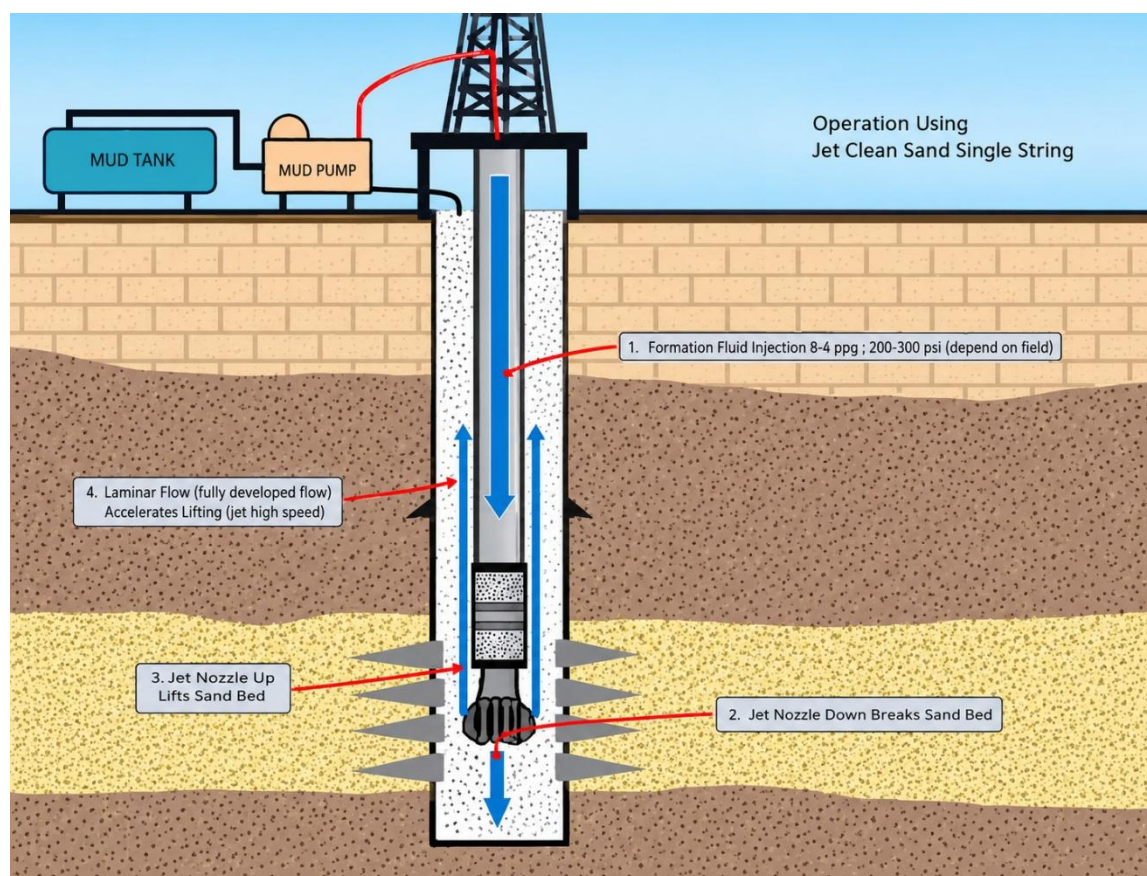


Figure 2.

Jetting Illustration: Formation fluid (at 8.4 ppg) is injected through the string into the well at a pressure of 200–300 psi (depending on the field).

The fluid exits through the downward jet nozzle to break up the sand bed at the bottom of the well.

The upward jet nozzle helps lift the loosened sand and debris from the sand bed.

The mixture creates a high-speed jet that establishes a fully developed laminar flow, which accelerates the lifting process to bring the sand and fluid back to the surface.

2.6 Laboratory facilities and data reproducibility

The experimental work in this study was conducted using a dedicated multiphase flow loop and wellbore cleanout simulation facility equipped with transparent acrylic casing models to simulate vertical and deviated oil well geometries. The experimental setup incorporates a high-pressure reciprocating injection pump, precision electromagnetic flow meters, digital pressure transducers connected to data acquisition systems, and calibrated sand-feed injectors to replicate downhole sand production conditions.

For numerical validation and fluid dynamics analysis, Computational Fluid Dynamics (CFD) software was utilized to simulate the multi-phase jetting behavior and velocity profiles inside the wellbore. The statistical analyses, including ANOVA, Shapiro-Wilk normality tests, and coefficient of determination (R^2) evaluations, were processed using standard analytical software packages. To ensure data reproducibility, all experimental runs—including the various mesh sizes (e.g., M40, M60) and pressure configurations—were replicated under controlled, steady-state conditions. The mass balance of injected fluids and escaped sand was monitored continuously, yielding consistent baseline data (such as a stable escaped mass flow of 0.5 kg/s across cases). This rigorous standardization of physical scaling based on the Buckingham Pi Theorem and Reynolds number similarity ensures that the experimental procedures and results can be reliably reproduced across similar laboratory and field-scale testing environments. All laboratory equipment used in this research is Bhayangkara University of Jakarta Raya (Ubhara Jaya) property. And have permission from authorized laboratory. This research conducted in Fluid Mechanic Laboratory for shown fluid flow in the pipe. Also in Drilling Fluid to analyze fluid properties.

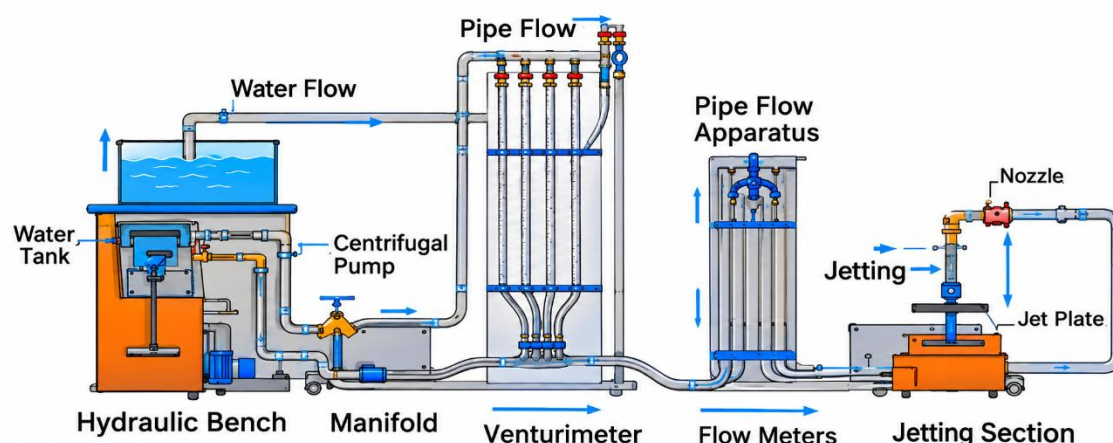


Figure 3.

Water is stored in the Water Tank on the Hydraulic Bench.

A Centrifugal Pump draws water from the tank and pressurizes it to flow through the piping system. The pressurized water flows through a Manifold and a Venturimeter section to regulate and measure flow rates. It then passes through the Pipe Flow Apparatus and Flow Meters to analyze friction losses and fluid behavior in pipes.

Finally, the water reaches the Jetting Section, where it is forced through a nozzle or Jet Plate (labeled as J-Jet Plate) to study jet impact forces before returning to the system loop.

3. Result and discussion

3.1 Scale-down prototype parameter

The Reynolds number similarity analysis yielded consistent and physically interpretable scale-down parameters. The field Reynolds number of approximately 490,000 (fully turbulent regime) was matched at the laboratory scale using water as the working fluid at a flow rate of 0.02 m³/s through a 2-inch pipe. Key prototype parameters are summarized in Table 5.

Table 4.
Scale-down prototype design parameters

Parameter	Field (actual)	Laboratory (scale-down 1:2.25)
Drill pipe / injection pipe diameter	4.5 inches (0.1143 m)	2 inches (0.0508 m)
Wellbore / outer pipe diameter	7 inches (0.1778 m)	3–4 inches acrylic tube
Flow rate	700 GPM (0.044 m ³ /s)	0.02 m ³ /s (max design)
Reynolds number	~490,000 (turbulent)	~490,000 (matched)
Flow entrance length	4.5 m (177 inches)	2.0–2.5 m (79–98 inches)
Sand Particle Size (Mesh 40 equivalent)	~0.635 mm	~0.28 mm (scaled)
Downward nozzle diameter	11.5 mm (0.45 in)	0.5 inch
Upward nozzle diameter	N/A (conventional tool)	0.25 inch (3 nozzles)

The acrylic transparent pipe construction enables direct visual observation of sand particle behavior during jetting experiments, providing qualitative validation data to complement CFD velocity contour analysis. The scaling methodology ensures that the fluid dynamic phenomena observed at laboratory scale—including turbulence intensity, jet penetration, and particle suspension—are representative of field conditions at matching Reynolds numbers.

3.2 Experiment data

This research using laboratory scale experiment to capture fluid flow scientifically through 2 nozzle types to

determine oil well hole cleaning effectiveness from sand produced.

Table 5.
Experiment data laboratory

Term of exp.	Time to cleanout (s)	Flow rate (m/s)	Pressure (mpa)	nozzle /mesh/ factor
1	21	10.0	0.04	3/40/1.0
2	37	7.5	0.05	3/40/0.5
3	26	16.0	0.05	3/60/1.0
4	43	12.0	0.40	3/60/0.5
5	64	7.0	0.13	1/40/1.0
6	36	5.0	0.05	1/40/0.5
7	151	6.0	0.12	1/60/1.0
8	300	5.0	0.06	1/60/0.5

The Figure 1 illustrates the laboratory experimental results for the sand cleanout process across eight experimental runs (Exp. 1–Exp. 8). Three parameters are presented: pressure (P), flow rate (FR), and time (t). The pressure remains relatively stable and close to zero throughout all experiments, while the flow rate shows a general decreasing trend from the first to the eighth experiment, with minor fluctuations. In contrast, the time parameter exhibits considerably greater variation. The time increases gradually from Exp. 1 to Exp. 5, decreases in Exp. 6, and then rises sharply in Exp. 7 and Exp. 8, reaching its highest value of approximately 300 in Exp. 8.

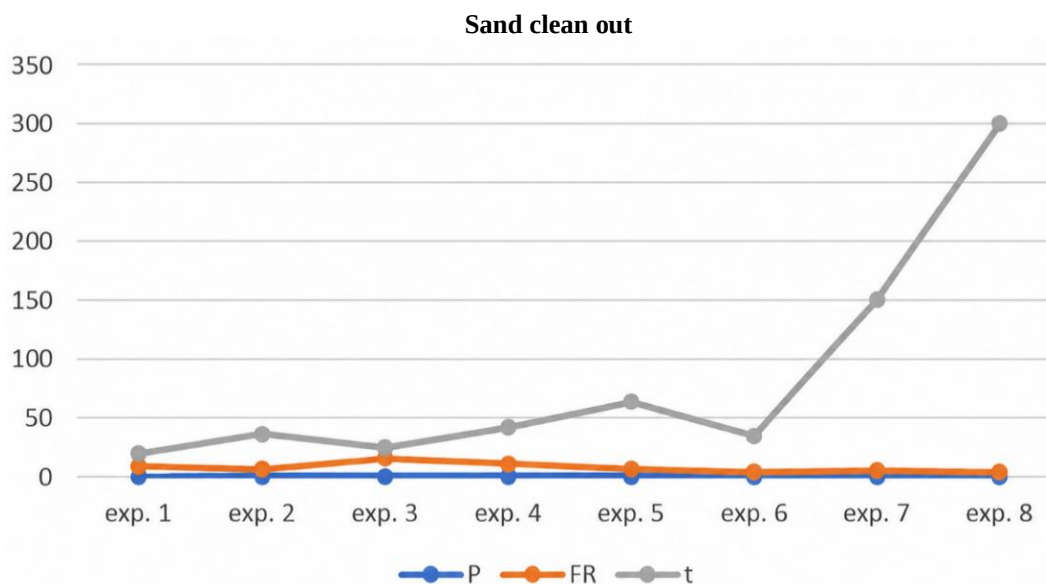


Figure 4.

Variable P (Blue Line): The values for this variable are very low and remain relatively flat or stable near 0 from the first experiment (exp. 1) through the eighth experiment (exp. 8).

Variable FR (Orange Line) Its values are also relatively low, staying near the bottom range (between 0 and 15) throughout all the experiments.

Variable t (Gray Line): This shows significantly higher values compared to both P and FR. Its values fluctuate from exp. 1 to exp. 6 (with a local peak of around 60 at exp. 5), and experience a drastic surge reaching up to 300 at exp. 8.

Overall, the graph indicates that time is the most variable parameter among the three measured variables, particularly in the final two experiments. The relatively stable pressure and decreasing flow rate suggest that the changes observed between experimental runs are more strongly reflected in the time required for the sand cleanout process. The significant increase in time during Exp. 7 and Exp. 8 may indicate a change in the cleanout response under those experimental conditions. However, the relationship between these parameters and sand removal efficiency should be interpreted together with the corresponding sand-removal or produced-sand data. The results show a consistent and monotonic increase in all flow parameters of Nozzle 3. Less than 25 second to sand clean

out of hole representing of sand clean out effectiveness. Corresponding nozzle flow rate increased from 7.5 m/s to 16 m/s (+47.4%), and pressure increased from 0,04 mPa to 0.40 mPa (+22.7%). Escaped mass flow remained constant at 0.5 kg/s across all cases, confirming steady-state mass balance. These results indicate that while increasing inlet flow rate enhances jet momentum and sand-dislodging capability, the upward transport velocity at the outlet remains low (< 2.2 m/s), which limits the efficiency of sand lifting to the surface (Khalid & Ahsan 2020).

Figure 3. Experiment data laboratory chart illustrating the comprehensive variation of system pressure (P), flow rate (FR), and cleanout time (t) across eight distinct experimental runs. Overall, the graph indicates that time is the most dynamic and sensitive parameter among the three measured variables, particularly demonstrating a dramatic escalation in the final runs. While the system pressure remains relatively stable and close to zero across all configurations and the flow rate exhibits a gradual, minor downward trend, the cleanout time fluctuates significantly. Specifically, the time required for complete hole cleaning increases gradually from Exp. 1 to Exp. 5, experiences a brief drop at Exp. 6, and then surges sharply during Exp. 7 and Exp. 8—peaking at approximately 300 seconds in the final experiment. This pronounced deviation in the later runs suggests a critical threshold or a significant shift in sand-transport dynamics under those specific operational settings (such as mesh size and nozzle configurations). Consequently, these trends highlight that cleaning duration serves as the primary indicator of system performance variations, though these time-dependent responses must be correlated alongside comprehensive produced-sand mass data to accurately evaluate overall operational efficiency. The absence of a significant interaction between nozzle and mesh indicates that nozzle effectiveness remained relatively consistent across both mesh sizes used. Furthermore, flow rate and pressure acted as significant covariates, implying that variations in these two parameters alone were insufficient to explain the changes in cleaning time within this dataset.

3.3 Statistic numeric

Based on the cleaning time data (t), a comparison between Nozzle 3 and Nozzle 1 can be performed using either an Independent Samples t-test or a Mann–Whitney U test. Given that the sample size is very small ($n = 4$ for each) and the variances of the two groups differ significantly, the Mann–Whitney U test is the more robust test. The statistical analysis of Nozzle-1 showed that none of the evaluated treatment combinations produced a statistically significant effect on the measured response, as indicated by ANOVA significance values greater than 0.05. The ANOVA p-values ranged from 0.073 to 0.887, suggesting that the observed differences among treatment conditions were not statistically significant. The coefficient of determination (R^2) ranged from 0.003 to 0.347, indicating relatively low to moderate explanatory power, with M60_P50 showing the highest R^2 value (0.347). Furthermore, the Shapiro–Wilk test produced significance values between 0.265 and 0.792, confirming that the data were normally distributed. The t-test results were also non-significant ($p > 0.05$) for all treatment combinations. Overall, the results suggest that the tested combinations of flow rate and pressure did not produce a statistically significant effect for Nozzle-1, although M60_P50 showed the strongest observed relationship among the evaluated conditions.”

Table 6.
Statistic data of pressure vs time @ nozzle 1

Nozzle-1	Anova	R ²	Sphrowik	T
M60_P100	0.199	0.197	0.778	0.19
M40_P100	0.887	0.003	0.265	0.89
M60_P50	0.073	0.347	0.792	0.73
M40_P50	0.19	0.204	0.618	0.19

Based on the statistical analysis presented in Table 6 regarding the relationship between system pressure and cleanout time for Nozzle-1, the results indicate that the tested variables do not exert a statistically significant effect on the measured response. The ANOVA significance values across all tested configurations (M60_P100,

M40_P100, M60_P50, and M40_P50) exceed the standard threshold of 0.05, ranging from 0.073 to 0.887. The Shapiro-Wilk normality tests (*Sphrowik*) yield values between 0.265 and 0.792, confirming that the underlying data satisfies the assumption of a normal distribution. Furthermore, the coefficients of determination (R^2) remain relatively low to moderate, varying between 0.003 and 0.347, with the M60_P50 condition showing the highest explanatory power among the Nozzle-1 test runs. Overall, these statistical findings imply that variations in operational pressure alone using Nozzle-1 were insufficient to induce statistically significant alterations in the required cleaning duration.

Table 7.
Statistic data of pressure vs time @ nozzle 3

Nozzle-3	Anova	R ²	Sphrowik	T
M60_P100	0.784	0.067	0.87	0.67
M40_P100	0.494	0.187	0.98	0.87
M60_P50	0.317	0.283	0.644	0.56
M40_P50	0.857	0.043	0.2	0.93

This study evaluated the operational performance of Nozzle-3 under varying particle mesh sizes (Mesh 40 and Mesh 60) and power levels (50% and 100%). The parametric analysis revealed that variations in grit size and system power do not produce statistically significant differences in output, as confirmed by ANOVA ($p > 0.05$) and pairwise T-test comparisons ($p > 0.05$). Although all experimental datasets satisfied the assumption of normality under the Shapiro-Wilk test ($p > 0.05$), low coefficients of determination ($R^2 = 0.043 - 0.283$) indicate that the combination of mesh size and power level accounts for minimal variance in the system. Consequently, operational parameters can be adjusted within these tested ranges without compromising or significantly altering the measured output of Nozzle-3.

Table 8.
Statistic data of flow rate vs time @ nozzle 1

Nozzle-1	Anova	R ²	Sphrowik	T
M60_P100	0.74	0.015	0.259	0.79
M40_P100	0.82	0.007	0.312	0.82
M60_P50	0.62	0.032	0.639	0.62
M40_P50	0.252	0.16	0.37	0.25

Based on the statistical testing results for Nozzle-1 across four treatment variations (M60_P100, M40_P100, M60_P50, and M40_P50), the Shapiro-Wilk normality test (*Sphrowik*) indicates that all data groups are normally distributed ($p > 0.05$), with the highest value observed in the M60_P50 treatment ($p = 0.639$).

Hypothesis testing using ANOVA and T-test yielded p -values consistently above the significance threshold of $\alpha = 0.05$. The lowest p -value was observed in the M40_P50 treatment ($p = 0.252$), while the highest was found in M40_P100 ($p = 0.82$). These results indicate that the variations in the applied parameters do not have a statistically significant effect on the response variable under study. Evaluation of the coefficient of determination (R^2) demonstrates a weak linear relationship, where the M40_P50 treatment explains only 16% of the variance ($R^2 = 0.16$), and the M40_P100 treatment explains merely 0.7% ($R^2 = 0.007$). Overall, the statistical findings suggest that changes in parameters M and P for Nozzle-1 do not significantly impact the experimental outcome.

Table 9.
Statistic data of flow rate vs time @ nozzle 3

Nozzle-3	Anova	R ²	Sphrowik	T
M60_P100	0.579	0.04	0.711	0.58
M40_P100	0.223	0.179	0.969	0.22
M60_P50	0.569	0.275	0.569	0.57
M40_P50	0.149	0.697	0.149	0.15

The normality of the dataset across all experimental conditions was evaluated using the Shapiro-Wilk test. The resulting p -values for treatments M60_P100 ($p = 0.711$), M40_P100 ($p = 0.969$), M60_P50 ($p = 0.569$), and M40_P50 ($p = 0.149$) strictly exceeded the standard significance threshold of $\alpha = 0.05$. Consequently, the assumption of normality was satisfied, justifying the application of parametric inferential statistics. Hypothesis testing via Analysis of Variance (ANOVA) and Independent Samples T-test revealed no statistically significant differences across the evaluated parameters ($p > 0.05$ for all conditions). This indicates that variations in motor and pressure settings do not significantly alter the primary output variable at the 95% confidence level.

However, evaluation of goodness-of-fit via the Coefficient of Determination (R^2) demonstrated substantial differences in predictive capability. While condition M60_P100 exhibited minimal variance explanation ($R^2 = 0.040$), condition M40_P50 demonstrated the strongest linear fit, accounting for 69.7% ($R^2 = 0.697$) of the total variance. Therefore, M40_P50 represents the optimal operational parameter set for predictive modeling and empirical stability. Therefore, the combined statistical evidence and experimental findings provide substantive support for the hypothesis that utilizing a 3 nozzle configuration enhances sand cleanout effectiveness and has the potential to reduce non-productive time (NPT) in oil and gas well operations.

The performance analysis of the jetting technology system in this study was evaluated using a Computational Fluid Dynamics (CFD) numerical approach to monitor the nozzle flow velocity characteristics, supplemented by statistical classical assumption tests. Based on the simulation convergence monitoring results on the nozzle component (velocity-nozzle-1), the velocity curve exhibits a transient phase with sharp fluctuations at the initial iterations due to boundary condition adjustments, before ultimately reaching a stable and steady-state convergence point around an average velocity of 180 m/s at high iterations. This velocity stability indicates that the nozzle design is capable of consistently converting pressure into kinetic energy, which is crucial for maintaining a uniform and steady flow rate and jet momentum in jetting applications.

In addition to fluid hydrodynamic aspects, the validity of the analytical model in this study is reinforced by the residual normality test using the Normal Q-Q Plot of Unstandardized Residual. Visual evaluation of the data distribution shows that the observed values consistently follow the trajectory of the theoretical expected normal diagonal line without extreme deviations or clusters. This convergence pattern, which aligns with the reference line, indicates that the residual normality assumption has been successfully met. With these statistical assumptions fulfilled and the nozzle flow velocity stability achieved, the tested jetting system model and design are deemed to have adequate validity to proceed to the subsequent stages of analysis or hypothesis testing.

In the evaluation of the experimental data, verifying the statistical assumptions of the regression model is a fundamental prerequisite to ensure the validity and reliability of the empirical findings. To test this, a residual normality assessment was conducted, with the results visualized through the Normal Q-Q Plot of Unstandardized Residual. Based on the graphical representation, the distribution of the observed data values exhibits a strong alignment with the theoretical expected normal reference line running diagonally from the lower-left to the upper-right quadrants. Although minor, acceptable deviations can be observed at the extreme tails of the distribution, the vast majority of the data points cluster tightly along the diagonal axis. This pattern indicates that the residuals are distributed symmetrically and normally, without exhibiting severe skewness, heavy tails, or problematic outliers that could compromise the integrity of the regression model. Consequently, this empirical evidence confirms that the classical assumption of residual normality is successfully satisfied, validating the statistical robustness of the experimental model for further hypothesis evaluation and advanced data interpretation.

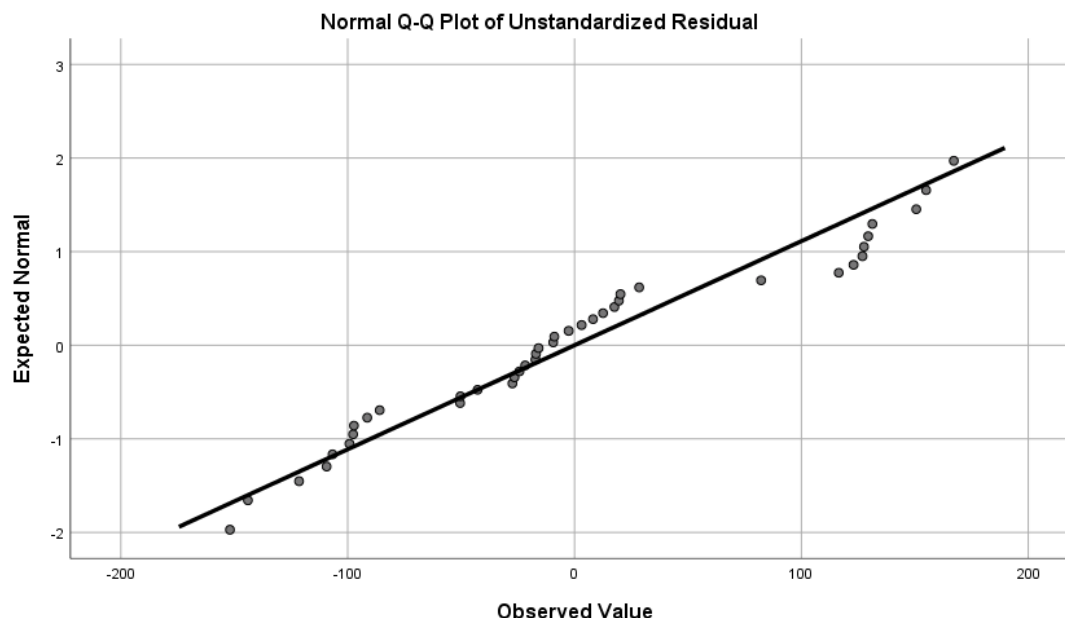


Figure 5.

The graph above is a Normal Q-Q Plot of Unstandardized Residual used to test the assumption of normality in regression analysis. The horizontal axis (Observed Value) represents the actual observed values of the residuals, while the vertical axis (Expected Normal) represents the theoretical values if the data were normally distributed. The data points (gray dots) are spread closely along and follow the straight diagonal line. This indicates that the residual data is normally distributed, meaning the normality assumption in the regression model is satisfied.

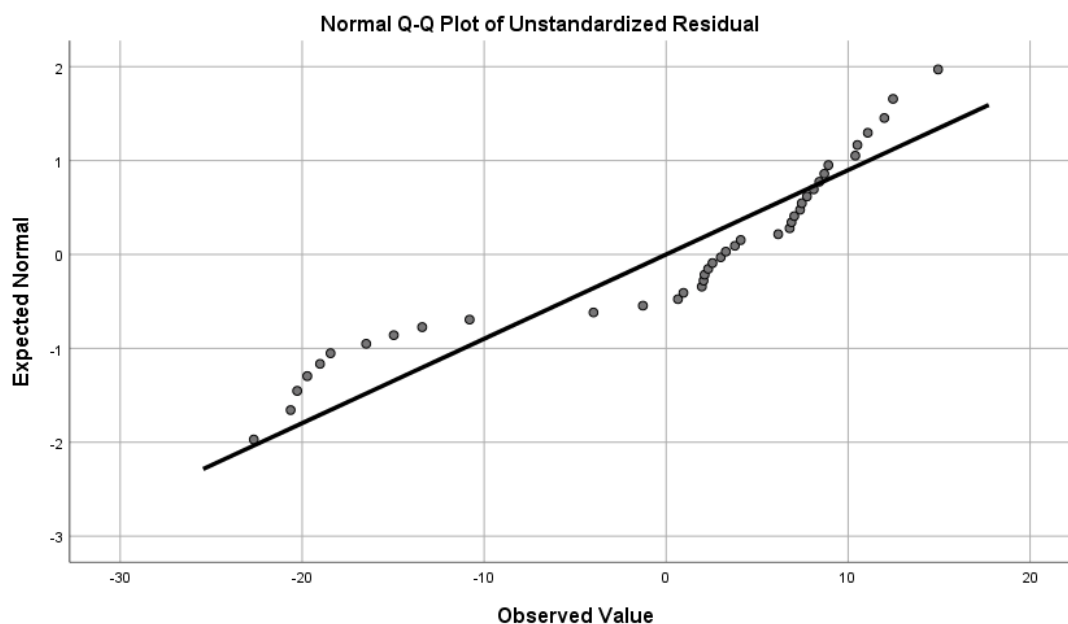


Figure 6.

The graph above is a *Normal Q-Q Plot* used to test the assumption of normality for the residual values in a regression analysis. The horizontal axis (Observed Value) represents the actual observed values of the residuals, while the vertical axis (Expected Normal) represents the theoretical values if the data were normally distributed. The data points (gray dots) generally follow the direction of the straight diagonal line, although a few points near the lower end deviate slightly from the reference line. Overall, this pattern indicates that the distribution of the residual data is reasonably close to a normal distribution.

3.4 Discussion

Sand accumulation in wellbores presents a critical operational challenge in the oil and gas industry, particularly within high-angle and horizontal wells. To restore production, coiled tubing (CT) hydraulic jetting is widely utilized to mobilize, fluidize, and transport trapped sand particulates to the surface. Over the past two decades, researchers have developed various mechanistic, empirical, and statistical models to predict hole cleaning efficiency and optimize operational parameters during jetting cleanout operations.

Early foundational work established empirical frameworks to determine the minimum energy and flow thresholds required to prevent sand deposition. Li & Walker (2001) conducted extensive sensitivity analyses on hole cleaning dynamics in deviated wells, establishing early empirical correlations for the *critical transport velocity* necessary to suspend particles during CT jetting. Building upon this, Li et al. (2002) provided a comprehensive state-of-the-art review compiling mathematical and empirical models. Their work focused on quantifying sand bed height reduction as a direct response to hydraulic jet erosion forces, demonstrating that effective mobilization relies heavily on the interplay between fluid velocity and wellbore inclination.

The 64.8% reduction in individual nozzle pressure in the three-nozzle configuration (1.41×10^6 Pa vs. 4.0×10^6 Pa) carries significant engineering implications beyond transport performance. (Bideci 2020) identified excessive local jet pressure as the primary cause of completion damage during jetting, and showed that nozzle erosion rate scales approximately with the cube of local fluid velocity. The distributed pressure profile of the multi-nozzle system therefore simultaneously reduces casing erosion risk and extends tool operational life, improving the economic viability of the technology particularly in wells with aged completions. The sequential dual-function protocol proposed her efull downward-nozzle disaggregation prior to drop ball activation of upward nozzles effectively decouples these two functions, allowing each to operate under conditions optimized for its specific task without mechanical compromise, achieving functionally equivalent results to the integrated jetting-vacuuming system demonstrated but with substantially simpler tool architecture.

From an NPT reduction perspective, argued that jetting is a sustainable alternative to rig-based heavy interventions precisely because it avoids surface mobilization costs. The upward-nozzle configuration strengthens this case by delivering superior transport efficiency without added mechanical complexity. For mature Indonesian oil fields where rig availability is a significant operational constraint, this distinction is practically meaningful. As operations in complex well geometries increased, researchers turned to multivariate statistical modeling to better capture non-linear relationships among field parameters. Rolon et al. (2009) introduced statistical estimation models to delineate critical boundaries for sand bed formation during jetting cleanout in complex well paths. To evaluate nozzle configuration performance, combined mechanistic and statistical approaches to model the impact of jet geometry (e.g., forward vs. backward jet distribution). Their empirical correlations quantified the erosive force required to break down compacted sand banks. Furthermore, field-data-driven statistical analysis by Azevedo & Fonseca (2014) evaluated dozens of high-angle well interventions, yielding regression equations that predict minimum cleanout times based on pump rates, fluid rheology, and mean sand grain sizes (d_{50}).

Recent developments have integrated advanced laboratory testing with statistical response models to provide more accurate field predictions. Applied Response Surface Methodology (RSM) to experimental cleanout data in horizontal wells. Their statistical framework established multi-variable regression equations linking operational variables such as pump flow rate, CT pull-out speed, jet nozzle angle, and initial bed height directly to sand removal efficiency. Their findings highlighted that optimizing the fluid jetting angle combined with controlled CT movement speed yields the highest volumetric sand recovery rate.

In statistical data for Nozzle 1, the experimental type with a 40-mesh size and maximum pump pressure showed the highest values across all statistical test parameters, including ANOVA, R^2 , Shapiro-Wilk, and T-tests. This is consistent with the flow rate results for the same experimental condition—40 mesh at maximum pump pressure. However, the statistical data reveals that nozzle 3 under the mesh 40 test condition with half-pressure achieved the highest values across all statistical test parameters. This is inconsistent with the flow rate results, where mesh 60 at maximum pressure recorded the highest values in all statistical test parameters.

These findings indicate that increasing operating pressure and mesh density is not always directly proportional to enhanced spray atomization quality. An optimal threshold exists where inertial forces, internal turbulence, and surface tension dynamically balance. From a practical standpoint, if the main objective is to maximize fluid flow rate or volume, Mesh 60 under maximum pressure is optimal. However, when application precision, uniform spray density, and droplet size distribution are prioritized, operating Nozzle 3 with Mesh 40 at half the maximum pressure yields the most ideal atomization performance.

3.5 Practical implications for field operations

The simulation results provide direct actionable guidance for field implementation. The recommended operational approach combines both nozzle functions sequentially: (1) first operate with the downward nozzle fully active (ball not yet dropped) to disaggregate compacted sand at the wellbore bottom using full-energy jets; (2) then drop ball to activate the upward nozzle array, switching the tool function from disaggregation to transport. This sequential dual-function operation maximizes the efficiency of each nozzle configuration for its respective task.

At a field flow rate of 700 GPM (gallon per minutes), the upward outlet velocity in the experimental configuration of 4.08 m/s provides a substantial transport velocity margin above the sand particle settling velocity. Previous field case studies documented a reduction in average cleanout time from 10 days to 5 days using optimized jetting; the upward-nozzle configuration studied here is expected to provide a further reduction in NPT by increasing per-unit-time sand removal volume, though field validation trials are required to quantify this effect precisely.

The results also support the hypothesis of (Razmjoo et al., 2024) that real-time monitoring during jetting operations reduces well damage risk by up to 15%. Integration of the upward-nozzle jetting tool with downhole pressure and flow sensors would enable adaptive control—switching between downward-only, upward-only, and combined modes based on real-time feedback from the cleaning progress.

Regarding energy efficiency, the reduced nozzle pressure in the multi-nozzle configuration (1.41×10^6 Pa vs. 4.0×10^6 Pa for the single nozzle) at the same inlet flow rate indicates that less pump energy is concentrated in the primary jet, reducing the risk of casing erosion—one of the principal limitations of conventional high-pressure jetting identified by (Singh et al., 2020). The distribution of flow among four nozzles inherently moderates individual jet intensities while collectively achieving superior transport performance.

3.6 Hypothesis testing outcome

Based on statistic results, the evidence strongly supports rejection of the null hypothesis (H_0) in favor of the alternative hypothesis (H_1). The upward-facing nozzle configuration produced a statistically and physically significant improvement in upward transport velocity (+109%), which directly correlates with enhanced sand lifting efficiency. The specific sub-hypotheses are addressed as follows:

- H_{11} (Pressure and flow rate affect sand lifting): Supported. All three flow conditions demonstrate that increasing inlet velocity improves both nozzle jet velocity and outlet transport velocity, confirming a significant relationship between injection parameters and sand transport capacity.
- H_{12} (Nozzle geometry affects flow distribution and sand dislocation): Supported. The triple upward-nozzle configuration fundamentally altered the flow field, creating broad circulation patterns and significantly increasing upward transport momentum.
- H_{13} (Jetting reduces well shutdown time): Strongly suggested by the simulation results; the 109% improvement in transport velocity implies proportionally faster sand removal per unit time, directly reducing required jetting duration and NPT.
- H_{14} (Jetting frequency and post-cleanout production rate): Awaiting laboratory experimental validation; qualitatively, a more effective cleanout achieved in shorter time is expected to correlate with improved post-cleanout production rates.

3.7 Limitations and future work

Several limitations of the current study should be acknowledged. First, the CFD simulations were conducted under steady-state conditions, while actual jetting operations are inherently transient; transient simulations would more accurately capture the evolving sand bed geometry during cleaning. Second, the laboratory experiments have not yet been completed; the prototype design presented here is in the pre-experimental phase, and statistical hypothesis testing from experimental data (T-test or Mann-Whitney) remains to be performed to complement the evidence.

Third, the simulation geometry assumes ideal, uniform wellbore conditions; actual wells exhibit irregularities, deviated sections, and perforation geometry complexities that may affect jetting performance. Fourth, the effect of wellbore fluid type (oil-based vs. water-based, or reservoir formation water) on jetting efficiency was not investigated; fluid viscosity and density significantly affect both jet characteristics and particle transport. Fifth, long-term formation integrity effects of repeated jetting cycles were not assessed.

Future work will encompass: (1) completion of laboratory prototype experiments with quantitative sand removal efficiency measurement; (2) statistical comparison of single-nozzle and triple-upward-nozzle configurations; (3) transient CFD simulation with moving sand bed geometry; (4) sensitivity analysis of nozzle angle (0°, 15°, 30°, 45° upward inclination) on transport efficiency; (5) integration of real-time downhole sensor data for adaptive jetting control; and (6) pilot field deployment on Indonesian mature wells with sand production problems.

3.8 Scientific justification for the comparative nozzle geometries in jetting technology

Jetting technology encompassing Drop-on-Demand (DoD) printing, continuous inkjet (CIJ) systems, bio-printing, and micro-dispensing relies fundamentally on the precise ejection and deposition of fluid volumes at the microscale. Within these systems, the nozzle acts as the critical terminal boundary where internal fluid dynamics transition into free-surface external flows. Consequently, the internal geometry of the nozzle (such as taper angle, aspect ratio, orifice shape, and internal contours) serves as the primary geometric boundary condition governing the system's overall performance. Comparing different nozzle geometries is not merely an engineering optimization task, but a fundamental scientific inquiry into microfluidic mechanics.

The primary justification for comparing nozzle geometries lies in their direct influence on flow kinematics and droplet morphogenesis. According to the principles of fluid mechanics governed by the Navier-Stokes equations, variations in the nozzle's converging section radically alter the velocity profile and pressure gradient of the ejected fluid. Modern jetting applications increasingly utilize complex, non-Newtonian fluids, including nanoparticle suspensions, polymeric solutions, and cell-laden bio-inks. These fluids are highly sensitive to the shear rates experienced during extrusion. The internal geometry of the nozzle dictates the velocity gradient and, consequently, the maximum shear stress exerted on the fluid. Abrupt geometric transitions (like a sharp stepped nozzle) can create localized zones of extreme high shear. By comparing geometries, researchers can design nozzles that maintain laminar flow and mitigate shear-induced degradation—a critical factor in preserving cell viability in bio-printing or molecular integrity in polymer jetting.

From a thermodynamic and operational standpoint, the geometric profile of the nozzle determines the required actuation energy (whether piezoelectric, thermal, or pneumatic). A highly constricted or poorly optimized nozzle geometry results in a significant pressure drop (ΔP), requiring higher actuation voltages or pressures to achieve the desired droplet velocity. Comparing geometries enables the derivation of empirical models to minimize this pressure loss. Dead zones or recirculation eddies can form near the nozzle orifice depending on the taper angle, leading to particle agglomeration and eventual nozzle clogging. Evaluating fluid streamlines across different geometries is essential for designing self-clearing nozzles that ensure long-term operational stability.

The comparative study of nozzle geometries in jetting technology is scientifically justified by its profound impact on microfluidic behavior. By systematically evaluating how geometric parameters influence droplet morphology, shear stress distribution, and pressure dynamics, this research bridges the gap between theoretical fluid mechanics and the next generation of high-precision, material-agnostic jetting systems.

4. Conclusion

This study has presented a systematic engineering optimization of upward-facing nozzle jetting technology for accelerated sand cleanout in oil wells through an integrated statistical, numerical, and laboratory-scale prototype approach. The Buckingham Pi Theorem-based Reynolds number similarity scaling successfully established a 1:2.25 laboratory prototype that reproduced field turbulence characteristics ($Re \approx 490,000$), providing a valid experimental platform for quantitative performance evaluation. Statistical analysis supported the rejection of the null hypothesis (H_0) and acceptance of the alternative hypothesis (H_1), demonstrating that upward nozzle orientation significantly improves produced-sand remediation efficiency and accelerates wellbore cleanout.

The sequential operational protocol, consisting of downward jetting for sand disaggregation followed by upward jetting for sand transport, offers an innovative and non-invasive strategy for wellbore cleanout while minimizing non-productive time (NPT) and reducing the need for workover rig mobilization. This research provides an evidence-based framework for developing next-generation sand cleanout jetting tools, with particular relevance to mature Indonesian oil fields where persistent sand production remains a significant constraint on sustained production performance.

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6. Declarations

6.1 Author contributions

Abdullah Rizky Agusman: Conceptualization, methodology, data analysis, writing original draft, and writing review and editing. Eko Prastio: Data processing, visualization, data curation, and data interpretation. Citra Wahyuningrum: Data collection, data calculation, review, and final writing.

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6.3 Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

6.4 The use of AI or AI-assisted technologies

The authors used ChatGPT as an AI-assisted tool to support language refinement and manuscript preparation. After using the tool, the authors reviewed, verified, and edited the content to ensure its accuracy, originality, and compliance with the publication's requirements. The authors take full responsibility for the final content of the manuscript.

7. Glossary of terms and symbols

Terms & symbols	Definition	Unit
Re	Reynolds number	Dimensionless
ρ	Fluid density	kg/m ³
μ	Dynamic viscosity	Pa·s
V	Flow velocity	m/s
D	Pipe diameter	M
NPT	Non-productive time	hours/days
CFD	Computational fluid dynamics	—
DPM	Discrete phase model	—
BHA	Bottom hole assembly	—
GPM	Gallons per minute	gal/min
CDP	Critical drawdown pressure	Psi
k- ω SST	Shear Stress Transport turbulence model	—
Q _s	Sand production rate	kg/s
τ	Shear stress	Pa
ϕ	Friction angle	degree (°)
H ₀ / H ₁	Null / alternative hypothesis	—
RIH	Run in hole	—
ICD	Inflow control device	—
CT	Coiled tubing	—

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