FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 9 No. 12, December, 2025, pp 405 – 408
DOI: https://doi.org/10.33003/fjs-2025-0912-4221

DEVELOPMENT AND PERFORMANCE ANALYSIS OF AN IMPACT JET VANE APPARATUS

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ABSTRACT

This study presents the design, fabrication, and performance evaluation of a laboratory-scale impact of jet vane apparatus tailored for experimental fluid mechanics applications. The apparatus employs a centrifugal pump to generate a high-velocity water jet, which impacts different vane geometries to analyse force-momentum interactions. A key modification in this setup is the integration of digital sensors to ensure higher precision in force measurements and minimize errors, compared to conventional manual method. The experimental results reveal a direct correlation between applied weight and force, substantiating theoretical momentum principles. The findings offer practical insights into optimizing fluid-structure interactions in applications ranging from hydroelectric power systems to aerospace propulsion technologies.

Keywords: Jet Impact, Vane Geometry, Momentum Conservation, Experimental Fluid Mechanics, Force Analysis

INTRODUCTION

Fluid jets play a crucial role in various engineering applications, including power generation, aerospace, and mechanical systems (Bacci et al., 2021). The impact of a jet on a vane governs the transfer of momentum and energy between fluid and solid surfaces, influencing force transmission, energy conversion, and efficiency in turbines, propulsion units, and flow measurement systems (Wilberforce et al., 2023). Theoretically, the impact force of a jet is determined using momentum conservation principles, but discrepancies often arise due to instrumentation limitations and environmental variables (Balakrishnan & Srinivasan, 2017). Conventional impact jet vane apparatuses often rely on manual readings of flow rate, applied weight, and pressure, introducing parallax and timing errors that compromise the accuracy and repeatability of results (Goel et al., 2021). Recent research has attempted to improve accuracy through refined designs and electronic sensors (Rathakrishnan, 2020; Zhou et al., 2023; Lv et al., 2022). However, the high cost of such advanced systems limits their adoption in developing countries. This study therefore designs an optimized impact jet vane apparatus that integrates digital instrumentation to enhance precision while utilizing locally sourced, recyclable materials to reduce cost and support sustainable laboratory development. In parallel, emerging research in renewable energy systems has emphasized the importance of optimizing fluid–structure interaction devices using cost-effective, scalable designs and locally adaptable materials, particularly in resource-constrained environments (Carroll et al., 2025).

MATERIALS AND METHODS

Experimental Setup

The experimental apparatus consists of a centrifugal pump, a nozzle, interchangeable vanes (flat and hemispherical), digital sensors, and a measurement system (Goel et al., 2021). The water jet strikes the vane at varying deflection angles (90° and 180°), and the resulting force is measured using load cells. The flow rate and velocity are calculated based on collected volume and time data.

Plate 1: Impact of Jet vanes Apparatus

Sensor Implementation

The system integrates high-precision digital load cells to measure force exerted on the vanes, providing real-time data with minimal latency (Ferrari et al., 2022). A flow sensor is included to continuously monitor fluid velocity and adjust experimental parameters dynamically. Additionally, an Arduino-based microcontroller system collects and processes sensor data, improving accuracy and reducing manual recording errors. The sensors are calibrated against standard weights to ensure reliability in force measurement.

Plate 2: Sensor placement

Theoretical Background

The force exerted by the water jet on a vane is derived from Newton's second law and momentum equations, expressed as:
Force ($\boldsymbol{F_y}$):$F_y = W = \rho Q v(cos\theta + 1)$

Where ρ is the fluid density, Q is the flow rate, v is the velocity, and θ is the vane deflection angle (Kleinstreuer, 2017).

Data Collection and Analysis

The experiment was repeated for different flow rates, load cells, and vane types. The recorded force values were statistically analysed and compared against theoretical predictions (Sharma & Gandhi, 2022). Error margins were assessed to identify potential sources of deviation, such as turbulence, sensor calibration inconsistencies, and mechanical losses.

RESULTS AND DISCUSSION

Experimental Findings

Results revealed a linear relationship between velocity squared and impact force, aligning with theoretical expectations (Wilberforce et al., 2023). Higher deflection angles (180°) yielded greater forces due to increased momentum change. The integration of digital sensors reduced measurement discrepancies, improving accuracy compared to traditional methods.

Table 1: Results of The Experiment

S/N	α(°)	T (s)	W (N)	Q (m^3/s)	V (m/s)	V^2 $(m/s)^2$	F_y(N)	Theoretical Slope (S)
1	90	33.42	2.5	0.000299	3.81	14.52	1.13919	0.0785
2	90	29.80	5.0	0.000336	4.28	18.32	1.43808	0.0785
3	90	22.68	7.5	0.000441	5.62	31.58	2.47842	0.0785
4	180	31.12	2.5	0.000321	4.09	16.73	2.62580	0.1570
5	180	27.20	5.0	0.000368	4.69	21.99	3.45184	0.1570
6	180	25.55	7.5	0.000391	4.98	24.80	3.89436	0.1570

Error Analysis and Validation

Minor deviations were attributed to turbulence, frictional losses, and experimental uncertainties (Ferrari et al., 2022). Comparing results with existing literature highlighted the effectiveness of the modified apparatus in achieving higher precision. Figures 1 and 2 illustrate the force vs. velocity trends and error analysis, respectively.

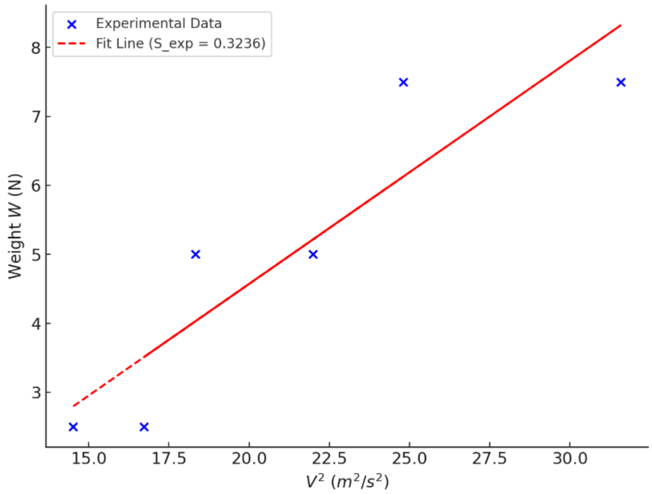

Figure 1: Velocity² (v^2) vs Applied Weight (W)

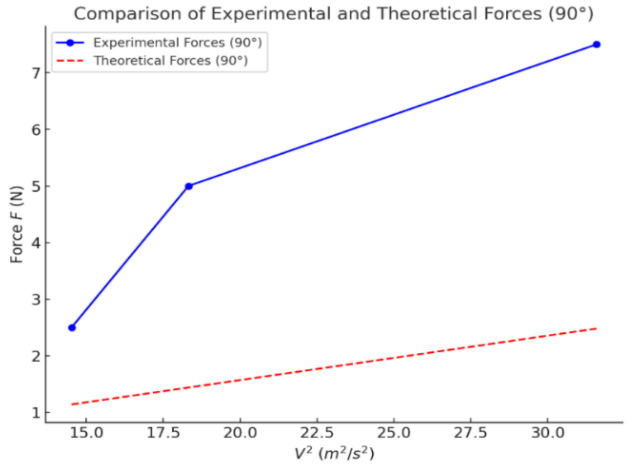

Figure 2: Velocity² (v^2) vs. Force (Fy) for 90˚

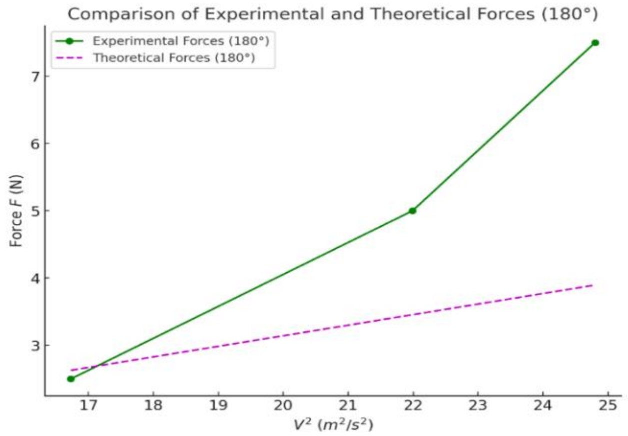

Figure 3: Velocity² (v^2) vs Force (Fy) for 180˚

CONCLUSION

The fabricated impact of Jet vane apparatus demonstrated high reliability for studying fluid-structure interactions, with improved accuracy due to sensor integration. Future enhancements could explore varying nozzle diameters, additional vane geometries, and computational fluid dynamics (CFD) simulations to further refine predictive models and broaden laboratory and industrial applications. The insights gained from this project hold promise for industrial applications, including turbine optimization and propulsion system efficiency improvements.

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