FLYWHEEL: JURNAL TEKNIK MESIN UNTIRTA

Home page journal: http://jurnal.untirta.ac.id/index.php/jwl

Experimental Study of the Effect of Air Flow Rate Variation on the Three-Phase Flow Characteristics in the Uplift Section of an Airlift Pump

Yunita Rahayu, Sigit Mujiarto*, Nurmala Dyah Fajarningrum, Arif Rahman Saleh

Program Studi Teknik Mesin Fakultas Teknik, Universitas Tidar

*Corresponding author: *sigitmujiarto@untidar.ac.id*

ARTICLE INFO

Received: 28/07/2025
Revision: 31/07/2025
Accepted: 01/08/2025
Available online: 01/08/2025

ABSTRACT

A three-phase airlift pump is a pumping system that utilizes compressed air to lift fluid and solid particles, widely used due to its efficiency and minimal mechanical components. The injected air flow rate plays a crucial role in influencing the flow pattern, velocity, and phase distribution within the system. This study aims to examine the effect of varying air flow rates on the three-phase flow characteristics in an airlift pump with a 15° injector angle, including the critical condition, superficial velocity of each phase, flow patterns, and changes in solid, gas, and liquid hold-up values. Experiments were conducted with air flow rates ranging from 30 to 60 LPM and a water column height of ¾h. Data were analyzed using image processing techniques to calculate flow velocity and hold-up. Based on the experimental results, it was found that the solid hold-up increased from 0.7592 to 0.9030, and gas hold-up from 0.0531 to 0.0819, while liquid hold-up decreased from 0.1877 to 0.0151 as the air flow rate increased. The superficial liquid velocity also rose from 0.056 m/s to 0.158 m/s, with the value recorded at 50 LPM representing the most optimal operating condition of the airlift pump and serving as the ideal reference for system operation. This research is expected to contribute to the development of airlift pump applications in industrial applications.

Keywords: *airlift pump, air flowrate, characteristics, flow velocity, image processing*

1. INTRODUCTION

Indonesia is a country rich in natural resources, including oil and natural gas. Activities related to the oil and gas (O&G) sector exploration, production, processing, marketing, and transportation continue to play a strategic role in national development. Despite their significant contribution to the national economy, these activities also pose considerable environmental risks, particularly due to the large volume of waste generated [1].

One of the primary waste products resulting from oil refinery processes is drilling mud or residual sludge. According to Faoziyah [2], this sludge consists of materials generated during oil and gas exploration, which, on a large scale, can negatively affect water quality around exploration sites. The high hydrocarbon content in oil sludge has the potential to contaminate soil, surface water, and groundwater[3]. Moreover, many oil and gas industries still discharge their waste directly into rivers and oceans, resulting in the accumulation of pollutants and sedimentation in aquatic environments, which harms ecosystems and degrades water quality.

Numerous studies have explored the behavior and performance of airlift pumps under various conditions. Ahmed et al. [4] identified several flow regimes within airlift pumps, such as bubble, slug, churn, and annular flows, which are influenced by parameters like submergence ratio and air flow rate. Swirl phenomena and backflows were also observed in the suction region[5][6].

Visualized the three-phase (gas-solid-liquid) flow patterns in airlift pumps, showing that slug flow is the most effective regime for transporting solid particles. Factors such as particle size and volumetric flow rate were found to have a significant impact on performance [7].

Further research by Fujimoto et al. [8] focused on the transport characteristics of gas-liquid-solid mixtures in airlift pumps, emphasizing the influence of gas flow rate, particle size, and solid concentration on transport efficiency. Examined the effect of a 15° injection angle, demonstrating that such a configuration can produce more stable spiral flows, enhance microbubble-particle interactions, and improve upward thrust under certain conditions[9].

Based on these findings, the present study aims to determine the critical condition of a three-phase airlift pump for lifting water and solid particles under varying air flow rates and to investigate the flow characteristics of a three-phase (solid-liquid-gas) airlift pump system. Specifically, it seeks to analyze flow behavior such as bubble and slug motion, as well as liquid and solid hold-up, under various air flow rates. By varying the injected air flow rate, this research aims to understand how it influences the internal flow dynamics within the airlift pump and contributes to the optimization of sediment removal in environmental applications.

2. METHODOLOGY

An experimental study was conducted to investigate the behavior of three-phase flow (gas-liquid-solid) in a vertical airlift pump system. The system comprises a transparent vertical acrylic pipe with an inner diameter of 50 mm and a height of 2.54 meters, as illustrated in Figure 1.

Airlift pumping was achieved by injecting air at the bottom of the riser pipe through a nozzle with an injection angle of 15°, directed toward the sediment layer. This configuration was chosen to enhance bubble-particle interaction and flow stability, based on previous research [9].

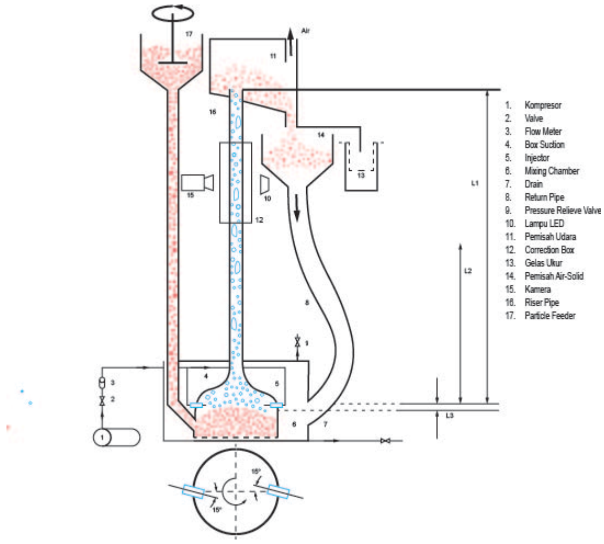


Figure 1. Three-phase airlift pump schematic

The main variable examined in this study is the inlet air flow rate, which plays a key role in determining the critical condition of a three-phase airlift pump. Experiments were conducted at air flow rates of 30, 40, 50, and 60 L/min, while other variables such as water volume, solid type, and column height (1.9 m) were kept constant. The water flow rate was calculated using the formula (1):

$$Q = \frac{V}{t} \tag{1}$$

where Q is the volumetric flow rate (m^3/s), V is the volume of water (m^3), and t is the time (s).

The solid phase consisted of granular particles (e.g., sand or simulated sludge) with a density of 1184 kg/m^3. Water was used as the liquid medium. Air served as the gas phase and was injected at varying flow rates[10]. Air and water flow rates were measured using a digital flowmeter and manually timed volume collection. These were converted into superficial velocities using the following formulas[11][12]:

$$J_G = \frac{Q_G}{A} \tag{2}$$

$$J_L = \frac{Q_L}{A} \tag{3}$$

$$J_S = \frac{M_S}{\rho_L A} \tag{4}$$

Where J_G, J_L, and J_S is superficial gas, liquid, and solid velocity (m/s). Q_G and Q_L is gas and liquid flow rate (m^3/s). M_S is solid mass flow rate (kg/s), ρ_L is solid density (kg/m^3), and A is cross-sectional area of the pipe (m^2).

To identify the flow regimes within the airlift pump, high-speed video recordings of the flow inside the riser were analyzed using MATLAB 2021**.** The objective was to classify flow patterns such as bubble**,** slug, and churn flow based on the behavior of gas-liquid-solid interactions observed in the recorded images. MATLAB was used to calculate object displacement between frames, with time intervals determined from frame rate (fps), using[7]:

$$Velocity = \left| \frac{(pix_2 - pix_1)}{(\Delta frame) \times \left(\frac{total\ time\ in\ video\ recorder}{total\ frame}\right)} \right| \quad (5)$$

To quantitatively determine the gas, liquid, and solid hold up within the airlift pump system, an image processing technique was employed using MATLAB 2021. This approach utilized frame-by-frame analysis of high-speed video recordings to extract volumetric distribution information of each phase in the riser section.

The total phase holds up satisfied the following equations (6):

$$H_s + H_l + \alpha = 1 \quad (6)$$

Where H_s , H_l, and α represent the solid, liquid, and gas hold-up, respectively. According to each hold-up can be calculated as:

$$H_s = \frac{V_{solid}}{V_{total}} \quad (7)$$

$$H_l = \frac{V_{liquid}}{V_{total}} \quad (8)$$

$$H_g = \frac{V_{gas}}{V_{total}} \quad (9)$$

where V denotes volume (m^3).

3. RESULTS AND DISCUSSION

Based on the results of the study, the experimental data are presented in the following Table 1.

Table 1. Test data

Submergence Ratio	Air Flow Rate (lpm)	Water Volume (ml)	Lifted sand mass (gr)	Time (s)
$\frac{3}{4}h$	30	1000	28.3	2.40
	40	1000	31.6	1.54
	50	1000	53.0	1.20
	60	1000	91.0	0.89

From the table above, the resulting water flow rates are presented in the following Table 2.

Table 2. Water flow rate measurement data

Air Flow Rate (L/s)	**Water Flow Rate (L/s)**
0.50	0.416
0.67	0.649
0.83	0.833
1.00	1.223

Based on the data presented in Table 2, a graph can be created as illustrated in Figure 2.

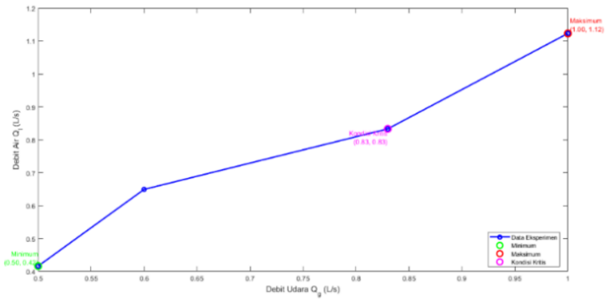


Figure 2. Graph of the critical operating condition of the airlift pump

At an air flow rate of 0.83 l/s, the airlift pump system reaches its critical condition, characterized by optimal water and solid lifting performance with stable flow behavior. Although the maximum water flow rate of 1.233 l/s occurs at 1.00 l/s air flow, this exceeds the critical point. Thus, 0.83 l/s is considered the most efficient operating condition based on both graphical data and visual observation.

By inputting the values of gas, liquid, and solid flow rates, the superficial velocities for each phase were obtained, as shown in Table 3.

Table 3. Superficial velocity values of each phase

J_g (m/s)	**J_l (m/s)**	**J_s(m/s)**
0.25477707	0.212314225	0.00504747
0.33970276	0.330879312	0.00883090
0.42462845	0.424628450	0.01900786
0.50955414	0.572532742	0.04400378

Figure 2 shows the comparison graph between the inlet gas superficial velocity and the outlet particle superficial velocity, while Figure 3 presents the comparison graph between the outlet water superficial velocity and the inlet gas superficial velocity.

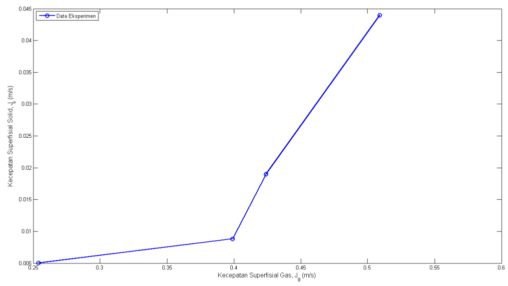


Figure 2. Graph of the comparison between solid superficial velocity and gas superficial velocity in a three-phase airlift pump

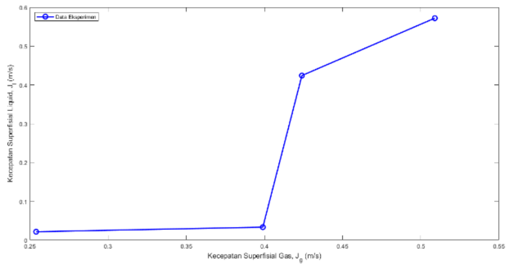
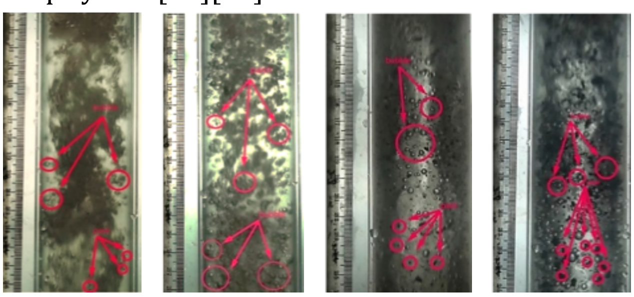


Figure 3. Graph of the comparison between liquid superficial velocity and gas superficial velocity in a three-phase airlift pump

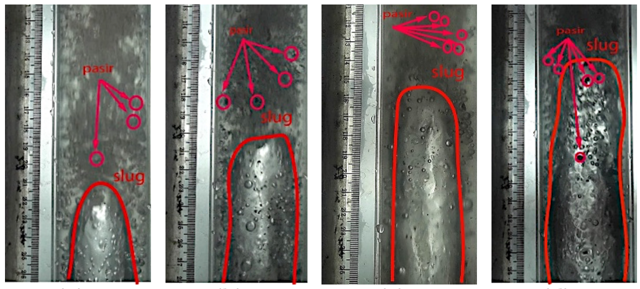
An increase in the superficial gas velocity injected into the system significantly enhances the superficial velocities of both liquid and solid phases, particularly within the air flow range of 40–60 l/min. This indicates a direct correlation between gas velocity and the transport efficiency of the other two phases, especially after surpassing the critical condition where the flow regime transitions to slug and churn. These flow patterns facilitate more effective particle lifting in the three-phase airlift pump system[13][14].



(a) (b) (c) (d)

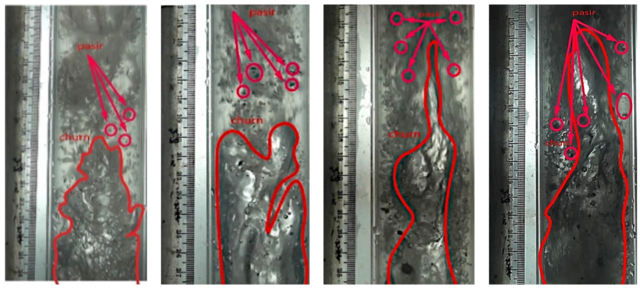
Figure 4. Bubble with airflow rate (a) 30 lpm, (b)40 lpm, (c) 50 lpm, and (d) 60 lpm

Based on visual observations during data collection, it was observed that in the initial condition inside the upriser pipe, many bubbles were formed due to air injection. These bubbles then merged with others, forming slugs. The formation of slugs becomes larger as the injected air flow rate increases. For a clearer explanation, refer to the description of each flow pattern below.



(a) (b) (c) (d)

Figure 5. Slug with airflow rate (a) 30 lpm, (b)40 lpm, (c) 50 lpm, and (d) 60 lpm



(a) (b) (c) (d)

Figure 6. Churn with airflow rate (a) 30 lpm, (b)40 lpm, (c) 50 lpm, and (d) 60 lpm

This study observed bubble, slug, and churn flow patterns at ¾h riser height. Increasing air flow resulted in more dynamic flow regimes and greater particle lifting. Particles were propelled upward by slug and churn flows but tended to fall back into bubble or churn tails when the flow subsided, only to be re-lifted by subsequent slug or churn pulses. At low air flow rates, slug flow rapidly transitions to churn due to insufficient gas pressure[7][11].

Table 4. Flow velocity data

Flow pattern	Flow velocity (m/s			
Bubble	0.768	0.819	0.894	1.024
Slug	1.280	1.536	2.043	2.560
Churn	1.536	2.048	2.554	3.072

From the data, the following graph was obtained

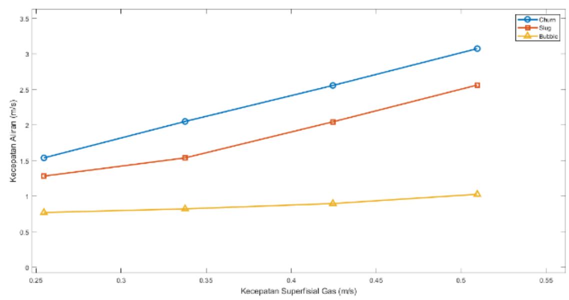


Figure 7. Graph ratio superficial gas velocity with flow velocity.

The graph of the relationship between gas superficial velocity and flow velocity shows that each flow pattern (bubble, slug, churn) has a different effect on fluid velocity. An increase in gas velocity has a minor impact during the bubble regime, a more significant effect during slug flow, and the highest impact during churn flow due to greater turbulence and gas dominance[15].

Table 5. Phase hold-up analysis results using image processing method

J_g (m/s)	*Solid hold up*	*Gas hold up*	*Liquid hold up*
0.2547	0.7592	0.0531	0.1776
0.3397	0.8320	0.0653	0.1027
0.4246	0.8723	0.0698	0.0578
0.5095	0.9030	0.0726	0.0244

From the data, the following graph was obtained.

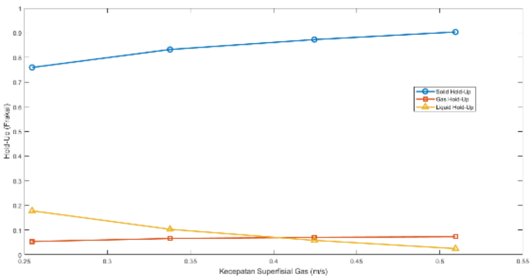


Figure 8. Graph of the relationship between gas superficial velocity and hold-up values of each phase

The variation in phase hold-up values reflects a transition in flow patterns as gas velocity increases. Initially, high liquid hold-up and low solid/gas hold-up indicate bubbly flow. As gas velocity rises, slug flow develops, marked by increased solid hold-up. At higher gas velocities, churn flow dominates, characterized by low liquid hold-up and greater solid and gas dominance, indicating stronger turbulence and enhanced particle transport [16].

4. CONCLUSION

Based on the results obtained:

1. The critical condition of the three-phase airlift pump was found at an air flow rate of 50 l/min, representing the optimal point for maximum lifting with stable flow.
2. An increase in air flow rate leads to higher gas superficial velocity, which also increases liquid and solid superficial velocities.
3. Flow patterns observed include bubble, slug, and churn flows, with more developed patterns forming at higher air flow rates, enhancing solid lifting.
4. Furthermore, higher gas velocity increases both gas and solid hold-up while reducing liquid hold-up, indicating a shift in phase distribution favoring gas and solid dominance.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the Mechanical Engineering Department of Universitas Tidar for providing the facilities and support throughout the research. Special thanks are extended to our supervisors, Dr. Ir. Sigit Mujiarto, S.T., M.Eng and Ir. Nurmala Dyah Fajarningrum, S.T., M.Eng**,** for their valuable guidance, constructive feedback, and continuous encouragement during the completion of this study.

REFERENCES

1. Desrina R. Penelitian dan Kajian Limbah Bahan Berbahaya dan Beracun Kegiatan Eksplorasi dan Produksi Minyak dan Gas Bumi. Lembaran Publ Lemigas [Internet]. 2008;42(3):27–34. Available from: https://journal.lemigas.esdm.go.id/index.php/LPMGB/article/view/118
2. Faoziyah S. Pembangunan Kawasan Industri Migas Berkonsep Sustainability. 2023. 1–235.
3. Darojat I, Herlica I, Wulandari D, Yulianto A. Pengolahan Limbah Lumpur Minyak Bumi (Oil Sludge) Kegiatan Hulu Migas Di Bob PT. Bumi Siak Pusako – Pertamina. 2024;9(2):102–8.
4. Ahmed WH, Aman AM, Badr HM, Al-Qutub AM. Air injection methods: The key to a better performance of airlift pumps. Exp Therm Fluid Sci [Internet]. 2016;70(April 2019):354–65. Available from: http://dx.doi.org/10.1016/j.expthermflusci.2015.09.022
5. Hanafizadeh P, Karimi A, Saidi MH. Effect of step geometry on the performance of the airlift pump. Int J Fluid Mech Res. 2011;38(5):387–408.
6. Mansour H, Khalil M. Effect of Air Injection Method on The Performance of Air-Lift Pump.(Dept.M). MEJ Mansoura Eng J. 2021;15(2):107–18.
7. Fajarningrum ND, Deendarlianto, Indarto, Catrawedarma I. Visualization Study on the Flow Pattern of Gas-Solid-Liquid Three-Phase Flow in Upriser Airlift Pump. AIP Conf Proc. 2020;2248(July).
8. Fujimoto H, Nagatani T, Takuda H. Performance characteristics of a gas-liquid-solid airlift pump. Int J Multiph Flow. 2005;31(10–11):1116–33.
9. Supraba I, Irfan A. Case Studies in Thermal Engineering Experimental investigation on the fl ow behavior during the solid particles lifting in a micro-bubble generator type airlift pump system. Case Stud Therm Eng [Internet]. 2019;13(March 2018):100386. Available from: https://doi.org/10.1016/j.csite.2018.100386
10. Sadatomi M, Kawahara A, Nishiyama T. Experiment and performance prediction of bubble-jet type air-lift pump for dredging sediments on sea and lake beads. Adv Fluid Mech Heat Mass Transf. 2012;(January):311–6.

11. Fujimoto H, Ogawa S, Takuda H, Hatta N. Operation performance of a small air-lift pump for conveying solid particles. J Energy Resour Technol Trans ASME. 2003;125(1):17–25.

12. Zuo J. Experimental Study on Multiphase Flow Characteristics in Air Lift Pump. 2024;

13. Hu D, Tang CL, Cai SP, Zhang FH. The effect of air injection method on the airlift pump performance. J Fluids Eng Trans ASME. 2012;134(11):1–7.

14. Yosinaga T, Sato Y. PERFORMANCE OF AN AIR-LIFT PUMP FOR CONVEYING COARSE PARTICLES. 1996;22:223–38.

15. Ramdhani, Indarto, Deendarlianto, Gnb Catrawedarma I. Experimental study on the effect of submergence ratio and air flow rate on the characteristics of liquid-gas-solid three-phase airlift pump. AIP Conf Proc. 2020;2248.

16. Kassab SZ, Kandil HA, Warda HA, Ahmed WH. Experimental and analytical investigations of airlift pumps operating in three-phase flow. Chem Eng J. 2007;131(1–3):273–81.