Study on Heat Dissipation and Aeration in Hydraulic Jump through Laboratory Experiments and Simulation

SYNOPSIS

for

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by

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Synopsis: -

An open channel is a conduit with a free surface that allows liquid to flow through it. In reality, the contact between the moving liquid below and the fluid medium above is known as the free surface. Water is the most commonly utilised liquid in hydraulic engineering applications, while air at atmospheric pressure serves as the overlaying fluid. Therefore, in this current context, the main emphasis is on the flow of water with a free surface. The hydraulic jump is one topic that has been extensively studied in the field of hydraulic engineering because of its wide range of real-world applications. A hydraulic jump is a sudden transition of flow to subcritical velocity from a supercritical velocity. The phenomenon is observed in canals below sluice gates, at the foot of spillways or when there is an abrupt change in slope from steep to flat. Hydraulic jumps are practically used as energy dissipaters below spillways to avoid scouring in the downstream, for mixing chemicals and aerating water for city water supplies to increase dissolved oxygen or for removing air pockets from water supply lines to prevent air locking.

The process of adding air (or oxygen) to a liquid, usually water, in order to raise its oxygen content is known as aeration. In water or other liquids, dissolved oxygen (DO) is the amount of free oxygen or non-compound oxygen (O_2). Although it is a molecular component of water (H_2O), its associated oxygen atom is not counted in the overall amount of dissolved oxygen that is present. DO is supplied to any body of water by atmospheric aeration and the photosynthesis of aquatic plants. Flowing rivers, falling water through rapids, and wind-driven ripples effectively dissolve oxygen into the water. The term "aeration efficiency" describes how effectively the aeration process distributes oxygen into water, usually in hydraulic structures, rivers, and wastewater treatment systems. With the amount of energy or airflow delivered, it is a measure of how well the air is combined with the water and how effectively oxygen is dissolved.

A DO level that is too high or too low can harm aquatic life and affect the quality of the water. DO is essential to a wide variety of life forms, including fish, invertebrates, microbes, and plants. The amount of DO needed varies from creature to creature. There may be a difference in the amount of dissolved oxygen between two different water bodies that are fully saturated with air. The DO content (measured in mg/l) will vary according to temperature, salinity, and pressure. Increasing temperature reduces the solubility of oxygen. This suggests that in order to achieve 100% air saturation, deeper, colder water requires more DO than warmer surface water. In the context of pressure, the DO will increase with the increase of pressure while the DO will drop with the increasing salinity. Turbulence and vortices are produced when water undergoes an abrupt change in velocity, like in a hydraulic jump. The air and water interact as a result of this turbulence, creating bubbles and increasing the surface area available for gas exchange. The primary determinants of aeration and aeration efficiency are flow velocity, water depth, bubble size, water temperature, and water quality. In the context of hydraulic jumps, aeration is a crucial phenomenon that happens because of the turbulent flow entrains air into the water, improving oxygen exchange and influencing water quality.

It is essential to determine the various parameters like length and location of the jump, amount of energy dissipated etc. to design a hydraulic structure. The theory of jump was developed in earlier days mainly on the basis of extensive experimental and empirical work. The first experimental investigation was made by Bidone in 1818. The oscillating hydraulic jump in an open channel flow is turning out to be an interesting topic in recent researches. Baddour (1987) carried out several experiments in laboratory flume on the performance of a mixing channel and proposed a hydraulic basis for its design in deep and shallow channels. Again the effects of temperature variation on some parameters of hydraulic jump were first investigated by Baddour (1991). Various characteristics of the jump were investigated by Ohtsu et al. (1996). Pagliara et al. (2008) made several number of theoretical and experimental studies concerning the jump condition. Some practical experiments on water cooling in open channels were performed to envisage heat transfer from water to the surrounding air and simulated these results using CFD codes by Rahbar et al. (2008). Alikhani et al. (2013) conducted several experiments with different heights of sill to develop a relationship between sill height and its position, sequent-depth ratio, and stilling basin length. A number of experiments with different Froude and Reynolds numbers were performed to investigate the variable characteristics of roller free-surface and roller position in hydraulic jumps by Wang et al. (2013). While going through the previous works of literature in detail it is found that there is an insufficient amount of studies on the effect of temperature on different jump characteristics. An increase in the temperature of water results in a change in the density as well as the viscosity. *Therefore, this study discusses the comparison of the Reynolds number, change in Froude number, relative energy loss and specific enthalpy at varying temperatures.*

The 21st century has seen tremendous growth in the number of thermal, nuclear and hydel power stations and industrial plants that have been installed and are operational both within the country and abroad. These Power stations and many industrial plants discharge thermally polluted water to the natural water bodies such as rivers, canals, bays or lakes, consequently damaging aquatic life. Though there are several methods to cool the heated water before discharging into the water bodies, the application of the hydraulic jump to enhance the dissipation of heat to the ambient could be of both technological and economic significance. Numerous studies regarding heat transfer from open channels have been conducted in the past by Moss (1976). Heat transfer involved in aeration has also been studied by Argaman (1977), and Novotny and Krenkel (1973). Mollik et al. (2017) numerically simulated heat transfer in flow through a channel using RANS turbulence models and compared the results obtained using DNS. Viti et al. (2018) presented a comprehensive review of the capabilities of different turbulence models for the simulation of hydraulic jumps including their ability to capture the air-water interaction. Wang and Khayat (2019) studied heat transfer involved in circular hydraulic jump. Bayon et al. (2019) conducted a detailed analysis of the simulation of a hydraulic jump using standard k-ε, RNG k-ε and k-ω SST models using Openfoam CFD code. Mondal et al. (2020) performed experiments in order to study the thermal effect on jump characteristics and correlate the variation of temperatures with several jump parameters. *The hydraulic jump could be an efficient and economical means of dissipating heat from the water discharged from power plants and other industries.* However, this topic has not been extensively studied experimentally and in simulation form.

In any open channel flow, the hydraulic jump on aeration efficiency in terms of DO is turning out to be an interesting topic in recent researches. Pagliara and Chiavaccini (2006) performed some practical experiments on ramps of different bed slopes characterized by different bed materials to predict energy dissipation. Kucukali and Cokgor (2009) investigated self-aeration efficiency due to hydraulic jumps with the function of energy dissipation rate per unit width. Bostan et al. (2013) investigated the aeration efficiency developed by the water jet vertically on the turbulence shear layer in the hydraulic jump. Hoque and Paul (2022) analysed the different similarities of air entrainment among the hydraulic jumps, plunging jets, and plunging breaking waves. Bai et al. (2022) conducted several experiments on supercritical flow over a vegetated bottom, changing the downstream flow hydraulics and fluid properties after air-water mixing and energy dissipation. While going through the previous works of literature in detail it is found that there is an insufficient amount of studies on the effect of hydraulic jumps on aeration efficiency on different hydraulic jumps. Increasing the discharge and bed slope from minimum to maximum results in an increase in the inlet Froude number as well as the sequent depth ratio. *Therefore, the present study discusses the effect of hydraulic jumps on their aeration efficiency and energy dissipation at varying bed slopes and discharges.*

The research aims to understand how this jump phenomenon affects energy distribution, water temperature, and air-water interaction in such dynamic environments. The study is divided into two primary methods: laboratory experiments and numerical simulation. In the experimental phase, physical models of hydraulic jumps are constructed in controlled laboratory conditions, allowing the observation and measurement of heat transfer and aeration under varying flow conditions. Parameters like water velocity, temperature variation, and dissolved oxygen are monitored to assess their roles in the dissipation of energy and the amount of aeration. Complementing the experiments, numerical simulations are performed using Ansys Fluent 17, to model the heat dissipation behavior of the hydraulic jump under different scenarios. The simulations help predict and analyse the heat dissipation in conditions that may be difficult to replicate in a physical setup. *The present study investigates the complex phenomena of heat dissipation and aeration during hydraulic jumps, which occur when fast-moving water transitions to a slower-moving condition, creating turbulence and vortex formations.*

The primary research for the thesis is conducted using an experimental setup of an open channel where a series of heaters raise the temperature of the water flowing through the channel, causing the water to flow through it at a constant temperature. The experiment was carried out in a horizontal rectangular flume with smooth glass side walls that are 35 cm wide, 60 cm high, and 7 m long in the Fluvial Hydraulics Laboratory of the School of Water Resources Engineering at Jadavpur University. Controlling the tailgate in the flume hydraulic jumps are developed, and various experiments are conducted to determine the characteristics of such hydraulic jumps while causing them to happen at various temperatures. In this study, in order to observe various jump characteristics for a constant discharge, experiments were conducted by increasing the temperature of the water from the lowest to the highest within the measuring range. A vertical sluice gate with a series of fixed baffle plates at the back allowed the water to enter the flume. At the front of the reservoir, six immersion-type electrical heaters with a capacity of 1 kW each and four immersion-type electrical heaters with a capacity of 1.5 kW each were dipped at equal intervals to form a total of 12 kW of immersion heaters. In addition, to heat the water, two wall mounted type electric heaters, each rated at 3 kW, or a total of 6 kW, were dipped at the hump point of the flume inflow. The characteristics of hydraulic jumps formed on the flume bed surface were investigated in five experiments. The temperature in this research ranged from 32 °C to 40 °C, and the discharge was maintained at 37 lps. In each experiment, the intake gate openings were identical and the discharge as well as the inlet velocity was similar for all experiments. The water surface downstream of the jump was continually undulating. The maximum and lowest levels of these undulations were marked at specific locations, and the depth at those locations was estimated by averaging individual depths. Before the hydraulic jump, the average inlet Froude number (Fr_1) was 2.55 and after the formation of an oscillating hydraulic jump, a considerable decrease in the post-jump Froude number (Fr_2) is seen. This variation in the Froude number, before and after the jump appears to escalate with the increase in water temperature. The Reynolds number (Re) of flow ranges from 133108 to 156221 and has increased as the temperature has increased. In the current work, the specific enthalpy and the relative energy loss in the hydraulic jump have increased with the increase in temperature.

In the next segment, the study of thermal hydraulic jump focuses on simulating a hydraulic jump in a rectangular flume using Ansys Fluent and thereby observing the effect of heat transfer from the water to the ambient on average thermal quantities of flow such as temperature, specific entropy, and specific enthalpy for six different ambient temperatures. All the simulations are carried out considering the inlet water temperature to be fixed at 40 ºC. Six different ambient temperatures of 10 ºC, 15 ºC, 20 ºC, 25 ºC, 30 ºC, and 35 ºC are considered for the six simulations. The mass flow rate for all three simulations is kept constant at 106 kg/s resulting in a constant inlet velocity of 1.893 m/s. It was found that the hydraulic jump tends to increase the drop in temperature, specific enthalpy and specific entropy at a section downstream of the jump as compared to a drop in the corresponding quantities just with natural convective and conduction heat transfer. However, the reason for this and the exact nature of the hydraulic jump in dissipating the heat for different temperature differences between the ambient and the water remains a matter of further study. The following are the main conclusions that may be drawn from the simulation study of the hydraulic jump:

1. The hydraulic jump increases the heat dissipation from the water to the ambient i.e. the average temperature at a cross-section downstream of the hydraulic jump is found to be less than the average temperature across the same section for a flow without the hydraulic jump.
2. Improvement in average temperature drop by the hydraulic jump decreases with the increase in ambient temperature. The same can be concluded for the specific enthalpy and specific entropy. In other words, the more is the difference in temperature between the water and the ambient, the more is the enhancement of heat dissipation by the hydraulic jump.
3. The increase or improvement in temperature drop is found to be a non-linear function of the ambient temperature for a constant water inlet temperature.
4. The maximum improvement in the temperature drop (0.131 ºC) is obtained for the low ambient temperature of 10 ºC.

5. The enhancement in temperature drop fell rapidly for ambient temperatures greater than 15 ºC and became constant at approximately 0.02 ºC for ambient temperatures of 30 ºC and 35 ºC.

6. The increases in specific enthalpy and specific entropy drops due to hydraulic jumps are also a nonlinear function of the ambient temperature for the constant temperature of the water. Both the increase in specific enthalpy drop and specific entropy drop follow almost the same variation with ambient temperature.

7. Maximum improvement in specific enthalpy drop and specific entropy drop occurred at the low ambient temperature of 10 ºC and decreased rapidly for temperatures less than 15 ºC.

The next part is to investigate the influence of hydraulic jumps on aeration efficiency in different types of jumps. The current study therefore addresses how forced hydraulic jumps on a smooth bed affect energy dissipation and aeration efficiency on a horizontal bed and an inclined bed at different discharges. Five different bed slopes ranging from horizontal to 6° and five different discharges ranging from 15 to 35 lps have been investigated during this study. Compared to traditional oxygenation systems, aeration through hydraulic jumps is a simpler and more affordable method of achieving oxygen absorption. Measurements of sequent depths, velocity, jump length, water temperature, and DO were taken during all experiments with different slopes and discharges conducted on smooth beds to experimentally investigate DO. For this, a new experimental setup was developed in the Fluvial Hydraulics Laboratory of the School of Water Resources Engineering. A chain pulley system was used to change the inclination of the flume. The amount of DO in the flow zone, comprising the pre-jump and post-jump sections of the hydraulic jump, as well as before the inlet gate, was measured with a portable DO meter. Stagnant surface water from a water body was used for this current experimental investigation. The DO in the water in the tank was measured before starting the experiments. Each time, this observed DO value was found to be much lower than the saturation value. The aeration efficiency was then calculated by independently averaging the upstream and downstream measurements. The aeration efficiency (E) through hydraulic jumps is solved using the Gameson equation (Gameson 1957). Water temperature affects the solubility of oxygen in water. A standard temperature correction factor is used because aeration efficiency is sensitive to water temperature. The aeration efficiency calculated at different temperatures is converted to the aeration efficiency at a reference temperature of 20°C (E_{20}) (Gulliver et al. 1998). The impact of non-dimensional characteristics of hydraulic jump on the E_{20} is carefully examined. Under real-world flow conditions, the upstream velocity and channel slope are quite comparable for our experimental setup. Therefore, for these two factors, air entrainment in a laboratory environment is not significantly different from air entrainment in a real channel. In the current investigation, a total of 25 tests were carried out to assess the aeration efficiency and jump characteristics for a series of bed inclinations and discharges. When the discharge and bed slope increase from minimum to maximum, the upstream Froude number increases from 2.18 to 8.23 and the sequent depth ratio increases as well. As a result of compiling all of the available results, the key remarks are summarised as:

1. The hydraulic jump was observed to cause large eddies to form. In order to bring air into the water as it flows, ripples are necessary.
2. During open channel flows, the amount of DO measured after the hydraulic jump improves quickly during the first several minutes and after a few occurrences, it starts to decline as it reaches its saturation.
3. As the experimental parameters increase, the sequent depth ratio is found to increase as well. As the sequent depth ratio increases, the aeration efficiency also increases because the inlet velocity increases due to the increase in discharge and bed slope.
4. For the same reason, oxygen transport is significantly influenced by the relative jump length. Aeration efficiency is directly related to the Reynolds number, which is also affected by bed slope and discharge.
5. The main element affecting the aeration efficiency during the hydraulic jump is determined to be the upstream Froude number (Fr_1). There are always fully developed hydraulic jumps for different Fr_1. It has been found that the development of a hydraulic jump can increase the efficiency of aeration by increasing the displacement and the bed slope.
6. The experiment at 35 lps discharge and 6° bed slope, achieved the highest velocity drop by about 89%. For an optimal result in increasing the aeration efficiency, it is recommended to proceed according to the experiment at maximum discharge and maximum bed slope while maintaining similar boundary conditions.
7. Under the current experimental conditions, the experiment at 35 lps discharge and 6° bed slope has a maximum energy dissipation rate per unit width is 90.2%.
8. Hydraulic jumps in the experimental flume have aeration efficiencies ranging from 9.4% to 34%. The results of this experiment show that the most important factors influencing the efficiency of aeration are the discharge and bed slope.
9. To maintain a healthy DO concentration, wastewater can be re-aerated using these techniques to increase aeration efficiency.

The very next part of this investigation of aeration efficiency (E) is connected to hydraulic jumps on a rough bed. In contrast to a smooth bed, the flow characteristics alter significantly when the channel bed is rough due to obstructions, abnormalities, or roughness factors like gravel, boulders, or any developed roughness. The bed roughness has an impact on the character and intensity of the hydraulic jump in addition to flow restriction and energy dissipation. The impact zone of the jump is benefitted from increased turbulence and improved air-water mixing caused by a rough bed. The jump is formed to occur at five different bed slopes varying from 0° to 6°, five different discharges ranging from 15 lps to 35 lps and two different sloped ramps, using gravel of roughness height of 24.77 mm as bed material. The purpose of this study is to investigate the effects of bed material on hydraulic jump characteristics, specifically focusing on sequent depth ratio, energy dissipation, and E. The bed has been paved with gravel to provide the required roughness. To prevent corrosion and make it easier to place gravel on the steel bed, a rectangular tray constructed of acrylic perspex sheet is utilised. The gravel was fixed on the perspex sheet with the help of glue. Then the gravel arranged acrylic perspex sheet was fitted on the experimental flume bed. In this medium gravelled bed, for minimum discharge and minimum slope, the jump was not properly developed. A ramp was used in this arrangement to overcome this difference. The ramp was installed just before the entrance gate was placed. The inflowing water thus reached the pre-jump section through this ramp. These two ramps were used for this experimental work, one was in the ratio of 1:3 in V:H and the other was in the ratio of 1:4. The vertical height of both ramps was the same. The opening of the entrance gate was the same in all experiments. Dissolved oxygen and hydraulic jump parameters were measured several times with varying discharges, bed slopes, and ramp slopes. In this study, a total 50 numbers of experiments were conducted in two different ramp setups with different discharges and bed slopes. A total of 25 experiments were conducted using a ramp of 1:3 slope and another 25 experiments were carried out using a ramp of 1:4 slope to assess the aeration efficiency (E) and jump characteristics for a set of discharges and bed gradients. The study of hydraulic jump characteristics in sloping rough beds through experimentation has great potential to further sustainable development by hydraulic engineering. Overall, the following are the conclusions that may be drawn from this experimental study:

1. Large-scale eddies are generated during the hydraulic jump formation on the rough bed. It is the undulations that are responsible for transporting air into the water as it flows.

2. Reduced flow time from higher discharge rates may lead to inadequate mixing and decreased oxygen transfer when paired with an incorrect bed slope. However, higher discharge rates may aid in more efficient airflow distribution throughout the aeration system when combined with an ideal bed slope.

3. The sequent depth ratio is found to increase with the increase of experimental parameters. The aeration efficiency also improves with the escalation of the sequent depth ratio as the inlet velocity has increased with the increase of discharge and bed slope. Compared to the 1:3 slope ramp, the setup of slope ramp 1:4 the sequent depth ratio is more increased for the identical discharge and bed slope.

4. Compared to the ramp slope of 1:3, the inlet velocity and the inlet Froude number are more in the 1:4 ramp slope. The upstream Froude number (Fr1) is found as the primary factor influencing the aeration efficiency during the hydraulic jump. For various upstream Froude numbers, fully developed hydraulic jumps are always there. It is found that by raising the discharge and bed slope, the hydraulic jump formation can improve the aeration efficiency. So with respect to Fr1, the aeration efficiency is less in the 1:3 sloped ramp.

5. For the same reason, the relative jump length plays a very crucial role in oxygen transfer. The Reynolds number has a direct correlation with aeration efficiency and is influenced by discharge and bed slope. The relative jump length and the range of Reynolds number are more for the 1:4 ramp slope.

6. The maximum velocity drop for using the 1:3 bed slope as high as almost 89.4% is achieved for the experiment of 35 lps discharge and 6° bed slope and the 1:4 bed slope is 89.4% achieved for the experiment at maximum discharge and bed slopes. Maintaining

a similar boundary condition is suggested to follow the experiment at maximum discharge and maximum bed slope for the best result in improving aeration efficiency for 1:3 slope and 1:4 slope respectively.

7. In the present experimental condition using the 1:3 bed slope, the maximum energy dissipation rate per unit width is 97.6% for the experiment at 30 lps discharge and 6° bed slope.
8. In the present experimental condition using the 1:4 bed slope, the maximum energy dissipation rate per unit width is 98.7% for the experiment of 35 lps discharge and 6° bed slope.
9. Aeration efficiency in hydraulic jumps through the experimental flume ranges from 10.8% to 37.0% for the 1:3 bed slope and for the 1:4 bed slope it ranges between 12.6% to 40.1%. The analysis of this experimental circumstance shows that discharge and bed slopes are the most influential parameters in aeration efficiency.
10. These methodologies for the improvement of aeration efficiency can be applied to the re-aeration of wastewater treatment or fermentation to maintain a healthy DO concentration.

The findings from both the laboratory and simulation studies provide valuable insights into the mechanisms of heat transfer, energy loss, and air-water interactions in hydraulic jumps. The research could contribute to improving the design of hydraulic structures, environmental impact assessments, and systems involving water flow regulation, such as dams and spillways. The thesis concludes with recommendations for optimizing energy dissipation, heat dissipation and aeration in hydraulic systems, which could lead to more efficient and environmentally friendly engineering solutions.

List of Publications related to the Ph.D. Thesis:

List of Journal Publications:

- **Saikat Mondal, Rajib Das, Subhasish Das and Sanchayan Mukherjee.** (2024). Experimental investigation of dissolved oxygen improving aeration efficiency by hydraulic jumps. ***Flow Measurement and Instrumentation***, 100, 102715. (**SCIE** and Scopus Indexed) (Impact Factor: 2.3).
  https://doi.org/10.1016/j.flowmeasinst.2024.102715

- **Saikat Mondal, Sanchayan Mukherjee and Subhasish Das.** (2020). Experimental Study of Thermal Effect on Oscillating Hydraulic Jump. ***Indian Science Cruiser***, Volume 34, No 4, pp:15-19.
  https://doi.org/10.24906/isc/2020/v34/i4/205477

List of Presentations in National/International/Conferences/ Workshops:

- **Saikat Mondal, Subhasish Das, Rajib Das and Sanchayan Mukherjee.** (2025). *An Approach to Improve Water Quality by Increasing Aeration Efficiency Through Hydraulic Jumps*. In: Mukhopadhyay, A., Ghosh, K. (eds) Advances in Thermo-Fluid Engineering. INCOM 2024. Lecture Notes in Mechanical Engineering. Springer, Singapore. pp 231–243.
  https://doi.org/10.1007/978-981-97-7296-4_16

- **Saikat Mondal, Subhasish Das, Rajib Das and Sanchayan Mukherjee.** (2024). *Improving Aeration Efficiency in Hydraulic Jump: An Approach to Improve Water Quality*, 2nd International Conference on Mechanical Engineering (INCOM 2024), Kolkata, India.

- **Saikat Mondal, Rajib Das, Subhasish Das and Sanchayan Mukherjee.** (2023). *Effect of Hydraulic Jump on Aeration Efficiency in Terms of Dissolved Oxygen in an Experimental Channel*, 5th Regional Science & Technology Congress, 2022-2023, Kolkata, India.

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