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Flow characteristics of multiple plunging jets towards treatment of water and wastewater

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A R T I C L E I N F O

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A B S T R A C T

The aim of the present study was to investigate the effect of flow characteristics of multiple plunging jets. A plunging jet is used for the treatment of water and wastewater in activated sludge process. In this study, two sets of plunging jets (series A and series B) were used to study the flow characteristics of multiple plunging jets. Series A and B have flow area (cross-sectional area) of 615.752 mm^2 and 452.389 mm^2, respectively. Each series has four nomenclatures of 2801, 1404, 1008 and 0716. Four discharge rates were selected: 0.72 ls^{-1}, 0.85 ls^{-1}, 1.28 ls^{-1}, and 1.62 ls^{-1}. The desired disc was placed in the socket jet, and the alteration in flow characteristics was observed. Our results showed that the total surface area per unit length of multiple plunging jets increased $\sqrt{n}$ times in comparison to a single jet for a given flow area. The penetration depth and bubble swarm width were found to be directly proportional to the rate of flow. Also, it was noticed that the composite Froude number is directly proportional to kinetic jet power (kinetic energy) of the plunging jet aeration system. The penetration depth was found to decrease with individual Froude number at a given flow rate when the number of multiple jets is increased under similar flow conditions. The present study showed that multiple plunging jets at optimum configuration under a given flow condition have a better performance than the conventional single plunging jet in the aeration system.

1. Introduction

Water is an essential part of all living organisms, and therefore, it is essential to treat wastewater before disposal. Untreated wastewater contains a higher amount of organic materials, pathogens, micro-organism nutrients, and toxic compounds. Moreover, untreated wastewater is associated with environmental issues and health hazards; thus, making it all the more important to appropriately treat wastewater before final disposal. The main purpose of wastewater management is to protect the environment in accordance with public health and socioeconomic concerns [1]. However, it should be noted that the treatment and disposal of wastewater is a serious problem in India. The treatment of wastewater involves physical, chemical, and biological processes. Among all the existing technology, plunging jet has garnered much interest due to its inherent advantages. In wastewater treatment, the efficiency of activated sludge process basically depends upon the aeration system by which oxygen is supplied to oxidize the organic content of wastewater. It utilizes both diffusions and hydraulic shear to achieve oxygenation as well as mixing efficiently. The plunging jet aerator passes through the surrounding atmosphere, plunges into a water pool, and then entrains a considerable amount of air, which further forms a submerged two-phase region with an air-water interfacial area. The jet may generate a bubble swarm beneath the surface depending on the flow of Reynolds number and the height of falling jets [2].

The plunging jet process involves both hydrodynamic and aerodynamic forces that interact between water jet and ambient air [3]. Some of its major applications include aeration and floatation in the treatment of water and wastewater, biological aerated filter, fermentation, oxygenation of mammalian-cell bioreactors, bubble floatation of minerals, the cooling system in power plants, plunging columns, stirring of chemicals, increasing gas-liquid transfer, and plunging breakers and waterfalls [4–7]. Compared to the existing conventional system, plunging water jet has several advantages such as non-requirement of an air compressor, forming of a closed loop that boosts utilization of oxygen and volatile reactants, simple design, easy construction and operation, and non-requirement of any external stirring device since water can achieve aeration and mixing [8,9]. It is attractive and directs contacting mechanism in fouling or hazardous environments, as well as it is free from operational difficulties such as clogging in air diffusers, limitations on installation of mechanical aerators by tank width, etc.

Many researchers, including van de Sande and Smith (1975) [9],

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Nomenclature

$K_LA_{(20)}$	Volumetric oxygen transfer factor at standard conditions ($m^3 h^{-1}$)
$K_La_{(20)}$	Volumetric oxygen transfer coefficient at standard conditions ($1 s^{-1}$)
P	Jet power (W)
$\frac{P}{V}$	Jet power per unit volume ($kW m^{-3}$)
n	Number of jets
A_s	Surface area per unit length
DSLR	Digital single lens reflex
MPJD	Multiple plunging jets discs
H	Water interface (cm)
Z	Axial coordinate (cm)
r	Horizontal free surface (cm)
h	Differential mercury manometer height (cm)
h_p	Penetration depth (cm)
b	Bubble swarm width (cm)
Fr.	Froude number
$Fr_{(c)}$	Composite froude number
V	Jet velocity ($m s^{-1}$)
D	Jet diameter (m)
G	Gravity force
Q	Discharge
ρ	Density ($kg m^{-3}$)

Tojo and Miyanami (1989) [10], and Bin and Smith (1982) [11], have studied the air-water oxygen transfer by plunging jets. Leung et al. (2006) [12] investigated air/water oxygen transfer in a biological aerated filter. Yamagiwa et al. (2001) [13] investigated the effects of properties of liquid on air entrainment and oxygen transfer rates of plunging jet reactors. Ahmed (1974) [14] examined air-water oxygen transfer by single plunging jets while Deswal et al. (2007) [15] reported oxygen-transfer by multiple plunging jets. The volumetric oxygen transfer coefficient and efficiency of oxygen transfer were found to be higher in multiple plunging jets than in a single jet at standard conditions and a given jet power. Bagatur et al. (2002) [16] studied the effect of nozzle types (circular, ellipse and rectangle duct with rounded ends) and reported that higher air entrainment rate and oxygen transfer efficiency was observed in the rectangle duct with rounded ends nozzle due to water jet expansion. Bagatur & Onen (2014) [17] studied modeling of volumetric air entrainment rate by Artificial Neural Network (ANN) and Gene-Expression Programming (GEP) model and reported that nozzle diameter is the most effective parameter on the volumetric air entrainment rate among water jet velocity, jet length, and jet impact angle. Bagatur (2014) [18] studied flow characteristics (volumetric air entrainment rate, bubble penetration depth, and oxygen transfer efficiency) using truncated and non-truncated circular nozzles and reported that truncated circular nozzles are more effective than non-truncated circular nozzles. Deswal & Verma (2007) [15] further reported that the volumetric oxygen-transfer coefficient gradually increased as the number of jets was increased from 1 to 16. They also suggested that multiple plunging jets device is more effective for aeration/oxygenation at higher jet powers. Chipongo & Khiadani (2016) [19] studied oxygen transfer by multiple plunging jets and reported that water depth in the receiving channel, number of jets, fall height, and jet velocity directly influences oxygen transfer in the pool. Bagatur & Sekerdag (2003) [20] studied the air-entrainment characteristics (volumetric airflow rate, air-entrainment rate, and bubble penetration depth in a plunging jet system using inclined rectangular nozzles with rounded ends) and reported that air-entrainment rate as a function of effective jet expansion ratio by predicting an empirical correlation. Deswal (2008) [21] reported that volumetric oxygen-transfer coefficient and oxygen transfer efficiency of multiple inclined plunging jets for the air-water system were significantly higher than those of a single vertical as well as an inclined plunging jet for the same flow area and other similar conditions. They also confirmed that this system is energy-efficient in practical situations involving the treatment of large volumes of wastewaters since the oxygen-transfer rate increases with the increase in a number of multiple jets under similar flow conditions. Various researchers have reported their data in the form of empirical relationships. But, the simplest relationships for conventional plunging water jets are suggested by Bin and Smith (1982) [11] (Eq. (1)) and Tojo and Miyanami (1982) [22] (Eq. (2)).

$$K_LA_{(20)} = 9 \times 10^{-5}P \tag{1}$$

$$K_La_{(20)} = 0.029 \times \left(\frac{P}{V}\right)^{0.65} \tag{2}$$

where $K_LA_{(20)}$ = volumetric oxygen transfer factor at standard conditions ($m^3 h^{-1}$); $K_La_{(20)}$ = volumetric oxygen transfer coefficient at standard conditions ($1 s^{-1}$); P = jet power (W); and, $\frac{P}{V}$ = jet power per unit volume ($kW m^{-3}$).

Since most of the studies focused on single plunging water jets, there are very limited studies on multiple plunging jets for mass transfer application. Moreover, there has never been an attempt to study the flow characteristics of multiple plunging jets. Hence, this study aimed to ascertain the effect of surface area, swarm width, and penetration depth on the total surface area with respect to single and multiple plunging jets.

2. Experimental methods

2.1. Experimental methods and setup

The present study was carried out in a “closed” system that involved a complete re-circulation of water with a constant water hold up. Experimental set-up consists of a water tank fitted with a scale (for measuring the height of water in the tank), a centrifugal water pump (750 W, Crompton Greaves), a regulating valve, and an orifice meter along with differential mercury manometer. A flat-bottomed square tank (1 mm × 1 mm × 1 mm) made of acrylic walls (for visualization purpose) was used for the experiment. The water level was maintained at 50 cm for all the experiments. For capturing the images of impacts of the jets on water, a high-speed camera was used for each experimental condition for a 10 s long sequence. A long transparent sheet was fixed on one side of the square tank, which was divided into a 2.0 cm square mesh size (the minimum count is 2.0 cm). The jet length or the vertical distance between the exit end of aerating device and water surface in the tank was kept as 0.1 m (10 cm). Water was re-circulated by a centrifugal pump, and the flow rate was measured by using an orifice meter. A control valve was provided in the recirculating pipe line to regulate the flow of water through aerating device. Aerating devices were fabricated such that they can be fitted and tightened to the vertical inflow, which flows centrally in the pool. The schematic representation of experimental setup is shown in Fig. 1. All experiments were carried out with tap water at ambient temperature. Two sets of plunging jets (series A and series B) were used to study the flow characteristics of multiple plunging jets. Series A and B have flow area (cross-sectional area) of 615.752 mm^2 and 452.389 mm^2, respectively. The disc used for generation of plunging jets of the desired configuration and their arrangements are shown in Fig. 2(A). Each series has four nomenclatures: 2801, 1404, 1008, and 0716. For a single jet, the hole of the desired diameter was drilled at the center of discs, but, in the case of multiple jets, the hole of the desired configuration was spaced along the diameter of discs. Table 1 shows the different sizes of the discs. The aeration device consists of a socket that can be fitted and tightened on