International Journal of Heat and Mass Transfer 113 (2017) 544–555

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Experimental investigation on mixed jet and mass transfer characteristics of horizontal aeration process

Sang Kyoo Park, Hei Cheon Yang *

*School of Mechanical Design Engineering, Chonnam National University, 50 Daehak-ro, Yeosu, Jeonnam 59626, Republic of Korea*

ARTICLE INFO

*Article history:*
Received 27 February 2017
Received in revised form 19 May 2017
Accepted 28 May 2017

*Keywords:*
Aeration process
Horizontal mixed jet
Mass transfer
Air volume fraction
Input power
Annular nozzle ejector

ABSTRACT

Experiments were performed to investigate the mixed jet and mass transfer characteristics of a horizontal aeration process with the primary nozzle distance ratio of an annular nozzle ejector and the control valve opening. A direct visualization technique with a high speed camera was used to capture the images of the horizontal mixed jet, and a binarization technique was used to analyze the images. The clean water unsteady state technique was used for the oxygen mass transfer measurement. The measured data were used to calculate the air volume fraction, specific input power, volumetric mass transfer coefficient and mass transfer efficiency. Experimental results showed that the horizontally discharged mixed jet behaved like a buoyancy jet, a quasi-horizontal bubble jet, or a horizontal momentum jet due to the horizontal momentum of primary flow and the buoyancy force of the suction air bubble. It was found that the input power and air volume fraction decreased with the primary nozzle distance ratio, while the volumetric mass transfer coefficient and mass transfer efficiency increased and then decreased. It was also found that the average volumetric mass transfer coefficients with the primary nozzle distance ratio and Reynolds number for the full valve opening were higher than those for the 1/5 valve opening, while the average mass transfer efficiencies for the full valve opening were lower than those for the 1/5 valve opening. Based on the experimental results, an empirical correlation to predict the effects of Reynolds number, air volume fraction and specific input power on the volumetric mass transfer coefficient was proposed.



## 1. Introduction

Aeration is the oxygen mass transfer process by which air is circulated through, mixed with or dissolved in a liquid. Although there are many types of aeration methods, two basic types are mechanical surface aeration to entrain air into the water by surface agitation, and introducing air or pure oxygen with subsurface diffusers. Mechanical aeration, i.e. aeration without using any diffusers, is essentially the transfer of atmospheric oxygen into water by means of surface agitation with various devices (e.g., propellers, blades, or peddles). Diffused aeration is typically powered by electric air compressors or blowers located away from the aeration site. Diffused aeration works primarily by moving deeper water to the surface and creating a constant mixing effect. Secondarily, oxygen is transferred into the water volume as the air bubbles rise to the surface. The smaller the bubbles and the deeper the water volume, the more oxygen is transferred. However, the major drawback of diffused aeration systems is the clogging or fouling problem with small diffusing holes. These require periodic cleaning and maintenance. Also, they do not efficiently move water horizontally and shallow environments would likely limit their efficiency [1,2].

The most common device for subsurface diffused aeration without clogging or fouling is an ejector (also called a jet pump). In general, an ejector is less efficient because most fluid machinery operates with normal stress on rotating blades, while an ejector only uses a pure shear action between the primary and secondary streams [3–5]. However, an ejector requires no mechanical drive and has no moving components, so it is a very reliable device with practically no maintenance cost and relatively low installation cost [6–8]. Ejectors have been utilized for gas/liquid mixing and mass transfer for a variety of reaction or aeration applications. Jet aeration with an ejector is turbulent and provides efficient air and water mixing with a high mass transfer rate [9,10].

In subsurface jet aeration with an ejector, the fluid is pumped through a primary nozzle, creating a high velocity liquid stream, while atmospheric air is entrained through a suction nozzle. The high velocity fluid stream shears the air into small bubbles which are fed into the primary fluid stream. As the mixed stream is

* Corresponding author.
*E-mail address:* hcyang@chonnam.ac.kr (H.C. Yang).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.05.120
0017-9310/

**Nomenclature**

| | |
|---|---|
| C | dissolved oxygen concentration (mg/L) |
| d | diameter (mm) |
| E | input power (kW) |
| $E_m$ | mass transfer efficiency ($m^3$/kJ) |
| e | specific input power (kW/$m^3$) |
| I | electric current (A) |
| $K_La$ | volumetric mass transfer coefficient (1/s) |
| L | length (mm or cm) |
| Q | volume flow rate ($m^3$/h) |
| Re | Reynolds number |
| t | time (s) |
| U | superficial velocity (m/s) |
| V | electric voltage (V) |
| X | primary nozzle distance ratio |

*Greeks letters*

| | |
|---|---|
| $\alpha$ | primary fluid chamber converging angle (°) |
| $\beta$ | diffuser diverging angle (°) |
| $\varepsilon$ | air volume fraction |
| $\theta$ | suction tube tip angle (°) |
| $\nu_w$ | tap water kinematic viscosity ($m^2$/s) |
| $\eta_M$ | electric motor efficiency |

*Subscripts*

| | |
|---|---|
| d | diffuser |
| m | parallel mixing tube |
| n | annular nozzle |
| p | primary flow or tube |
| s | suction flow or tube |

discharged into the surrounding mixed fluid in an aeration tank, it forms a highly turbulent jet [11]. The jet entrains the surrounding mixed fluid and brings it into contact with the small air bubbles within the jet stream. The resultant oxygen transfer rate is extremely high owing to the high bubble and fluid contact area created by the small bubbles, the turbulence within the jet, and the extended bubble residence time. In addition to the higher oxygen transfer ability inherent with small air bubbles, the turbulent nature of jet aeration produces continuous renewal of the air bubble/fluid interface, further facilitating oxygen transfer [12]. The continuous surface renewal of the air bubble/fluid interface results in additional effects that are higher compared to most other small bubble diffuser technologies. Therefore, the subsurface jet aeration with an ejector achieves higher oxygen transfer efficiency than other aeration systems without an ejector.

Aeration systems are selected based on cost and engineering efficiency. In shallow aeration conditions, such as a recirculation aquaculture system (RAS) [13], vertical diffused aeration is not often selected because the limited oxygen transfer capability costs substantially more than when used under deep conditions. Using conventional disc type diffusers in shallow aeration processes can be less efficient because the rising bubbles are so closely concentrated that they cause localized bubbling over the diffusers and do not positively impact the entire body of water to the extent that horizontal ejector aeration does. Therefore, in aeration processes where the water depth is usually shallow compared to the water surface area, the horizontal aeration is preferred over vertical aeration in order to increase the contact surface area and aeration time thereby increasing the mass transfer rate [14].

Ejectors are used as gas-liquid dispersion devices for many purposes in many industries since they have high mass transfer and mixing rates [9,10,15]. Although two phase ejector jets play an increasingly important role in aeration processes, very little is known about the effect of their macroscopic behavior on mass transfer characteristics. This is because precisely measuring their behavior with high gas bubble density is very difficult [14]. Shah et al. [16] experimentally investigated the effect of mixing tube length on the transport process of an ejector, where flow was visualized only in the converging part of the mixing tube using a high speed camera. Ejector internal flow behavior has been visualized using Schlieren methods to investigate the annular nozzle ejector performance by Zou et al. [17]. Fonade et al. [18] presented the scaling of aeration devices, and the influence of horizontal or transverse flow on the transfer performance of hydro-ejectors. Rainer et al. [19] studied a two phase jet structure issued horizontally from a new type ejector, especially designed for bioreactors. They focused on optimizing the ratio between gas and motive liquid flowrates.

Since the energy crisis in the early 1970s, there has been increased interest in the fine bubble aeration as a competitive method due to its high mass transfer efficiency. Fine bubble aeration results in more bubble surface area per unit volume and greater mass transfer efficiency, as well as lower power costs. To reduce power costs and increase aeration efficiency, more detailed information is required about aeration process operation. The input power necessary for a given mass transfer is an essential characteristic of an aeration process. In many studies [20–23], the input power was estimated through indirect hydraulic energy balance techniques in two forms. One was the hydraulic power needed to drive the primary fluid, and the other is the power needed to compress the suction fluid to overcome the pressure drop of the entire system [23]. However, the indirect hydraulic energy balance technique was based on the Bernoulli principle. Therefore, it would not accurately reflect the actual power transferred to the aerated fluid, and include all system inefficiencies, such as motor and pump inefficiencies.

Achieving a higher mass transfer in an aeration process requires a large amount of entrained air and increased the contact time and area of the two phases. This is done by reducing the size of the entrained air bubbles. Because the annular nozzle ejector has high suction fluid handling capacities [24], it is particularly well suited for aeration systems. However, few experimental studies examining the effect of annular nozzle ejector flow behavior on oxygen mass transfer characteristics have been reported in the literature [4,5]. Also, as reviewed by Lima Neto et al. [14], there are only limited experimental studies on horizontal gas-liquid injection for aeration processes. Therefore, the main objective of this study is to experimentally investigate the mixed jet and mass transfer characteristics of a horizontal aeration process using an annular nozzle ejector in a shallow water tank. In order to examine the macroscopic behavior of the horizontally injected mixed jet, a non-intrusive visualization technique was used with a high speed camera. The input power was directly determined by measuring the electric voltage and current for driving the primary flow.

## 2. Experimental setup and methods

### 2.1. Annular nozzle ejector

An ejector is gas-liquid contactor that directly transfers energy and momentum from a high energy primary fluid to a low energy