Chemical Engineering Journal 287 (2016) 337–349

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Experimental investigation and prediction of oxygen transfer in vortex flow regulators

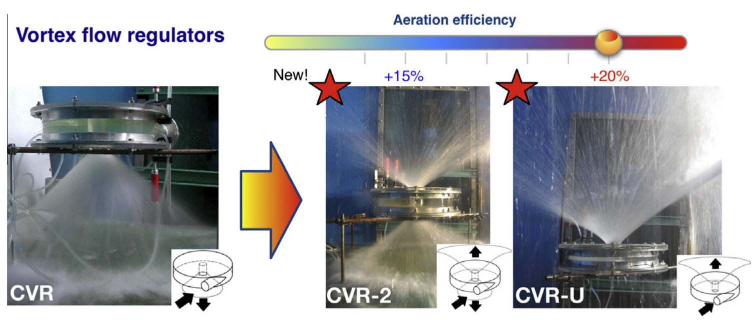
Patryk Wójtowicz *, Małgorzata Szlachta

Faculty of Environmental Engineering, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

HIGHLIGHTS

- This pilot-scale study is the first to examine the aeration efficiency of vortex flow regulators.
- Empirical formulas are reported for predicting oxygen mass transfer parameters.
- The construction of novel vortex regulators with increased aeration efficiency is presented.
- The aeration performance of a standard vortex regulator can be increased by 20%.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 August 2015
Received in revised form 3 November 2015
Accepted 5 November 2015
Available online 18 November 2015

Keywords:
Aeration
Oxygen transfer efficiency
Reaeration
Mass transfer
Wastewater
Vortex flow regulator

ABSTRACT

We are the first to report pilot-scale experimental results on aeration efficiency of standard and newly developed cylindrical flow regulators (CVRs), conducted over a wide range of operational conditions, geometries and regulator types. In this work, two new (patented) constructions (CVR-2 and CVR-U) are introduced; they are aimed at enhancing reaeration capacity. They are compared with a standard cylindrical vortex regulator (CVR) optimised for flow control and throttling only. The aim of the study was also to understand the mechanisms that govern the aeration of vortex regulators. We have selected and studied the influence of key parameters on oxygen mass transfer in the vortex flow regulators in head-to-head comparisons. We prove that the reaeration capacity of CVRs is not linearly proportional to the number of active outlets, as multiple competing phenomena are responsible for the final aeration efficacy. We show that by changing the arrangement of the active outlets, it is possible to increase the aeration efficiency up to 20%. In the practical situations, this feature is beneficial in enhancing the aeration capacity of flow regulators and it does not degrade throttling properties. In order to allow practical application, the empirical formulas were developed to predict oxygen transfer efficiency. The investigations reported in this paper are expected to be transferable to other vortex regulators that exhibit similar flow hydrodynamics, especially those with a conical vortex chamber.

1. Introduction

Proper oxygen levels are important not only for humans but also for aquatic environments. It is well known that a dissolved oxygen deficit can be problematic in natural waters and in sewage collection systems [1–3]. Furthermore, it is desirable to know reaeration rates when sewer processes are to be quantified, modelled or simulated [4–6]. Depleting oxygen in a sewer leads to anaerobic conditions and production of volatile fatty acids, hydrogen sulphide and unpleasant odour [7]. The resulting aquatic hypoxia in water that receives sewage is a threat to biodiversity. In addition, excessive amounts of H_2S can cause corrosion of

* Corresponding author. Tel.: +48 605 422 606.
E-mail address: patryk.wojtowicz@pwr.edu.pl (P. Wójtowicz).

http://dx.doi.org/10.1016/j.cej.2015.11.035
1385-8947/

Nomenclature

a	specific surface area, m^{-1}
A_{in}	inlet area, m^2
C	concentration of oxygen, mgO_2/dm^3
C_{sat}	equilibrium or saturation concentration of oxygen, mgO_2/dm^3
CoVR	conical vortex regulator
CVR	cylindrical vortex regulator
CVR-2	cylindrical vortex regulator discharge through top and bottom plate
CVR-U	cylindrical vortex regulator discharge through top plate
D	vortex chamber diameter, mm
d_{in}	inlet diameter, mm
d_{out1}	bottom outlet diameter, mm
d_{out2}	top outlet diameter, mm
DO	dissolved oxygen
Eu	Euler number
FN	flow number, m^2
g	acceleration due to gravity, m/s^2
h_c	vortex chamber height, mm
K, K_1	geometric constant
K_L	oxygen transfer coefficient, m/h
$K_La_{(20)}$	standard overall oxygen transfer coefficient, h^{-1}
$K_La_{(T)}$	overall oxygen transfer coefficient in temperature t, h^{-1}
LES	Large Eddy Simulation
m	oxygen mass, kg
q_m	mass flow rate, kg/s
q_v	volumetric flow rate, dm^3/s
R_o	swirl radius, m
RSM	Reynolds stress model
Re	Reynolds number
S	swirl number
SAE	standard aeration efficiency, $kgO_2/kW\,h$
SOTR	standard oxygen transfer rate, kgO_2/h
SMD	Sauter mean diameter (d_{32}), mm
T	temperature, °C
t	time, s
URANS	unsteady Reynolds-averaged Navier Stokes
v	average velocity, m/s
VFR	vortex flow regulator

Greek symbols

ΔH	operating head, m
Δp	pressure drop, kPa
θ	temperature coefficient ($\theta = 1.0241$)
ρ	density, kg/m^3
ζ	minor loss coefficient

concrete, metal and installed equipment. Damage to pipe materials originates from the formation of sulphuric acid.

As a result, it is important to restore oxygen balance with effective and inexpensive methods and devices [8–10], but weirs, spillways, chutes or cascades are not always suitable for use in urban drainage systems; furthermore, their aeration potential is limited as a result of the low available pressure head. Moreover, sewer reaeration rates caused by varying flow conditions [11] are not stable and in certain situations cannot restore balance with microbial oxygen uptake. For example, Balmer and Tagizadehnasser [12] tested, in a laboratory setting, the oxygen transfer rate in gravity flow sewers (diameter 0.23 m) for various slopes, relative depths and flow rates of tap water. They reported standard overall oxygen transfer coefficient ($K_La_{(20)}$) values between 4.28 and 29.71 h^{-1}. In contrast, Jensen [13] investigated oxygen transfer in the laboratory and in field studies of 0.15 and 0.60 m sewer pipelines at various flow rates and found much lower values of $K_La_{(20)}$ that ranged between 0.34 and 2.74 h^{-1}.

Vortex flow regulators (VFRs, also termed hydrodynamic flow regulators) are used to automatically regulate flow in urban drainage systems, especially for flood protection and sewer network expansion. Our investigations have indicated that they can also be used to restore dissolved oxygen levels in sewer systems and receiving waters. Vortex flow regulators are usually placed in locations prone to hydrogen sulphide corrosion – storage tanks, wet wells and backdrop manholes, in particular. They can contribute to the reduction of energy consumption at wastewater treatment plants. Passive hydrodynamic flow regulators are a robust and cost-effective alternative to other throttling devices commonly used in urban engineering [14]. The formation of a confined vortex core and fine exit spray from a hydrodynamic flow regulator creates an effective atomiser that enables accelerated absorption of atmospheric oxygen.

Vortex devices have been studied extensively in a wide range of applications, but research has focused on understanding and describing hydrodynamic behaviour and performance (e.g., bi-stable vortex flow and throttling performance [14,15]). We have also contributed to studies of vortex devices, especially in the areas of hydraulics, design and optimisation of throttling capacity [16,17], resulting in several patents. Our research efforts include laboratory- and pilot-scale experiments using custom-built test rigs as well as extensive CFD simulations.

To our knowledge, the study reported here is the first to systematically evaluate the aeration efficiency of a wide range of hydrodynamic flow regulators. Brombach [18] cites an unpublished technical report (from 1979) by Giesecke [19] from the University of Stuttgart. Unfortunately, we have not been able to obtain a copy of this report. The citation notes only a single result (4 mgO_2/L) referring to the oxygen transfer capacity of one flow regulator of an unknown type, and thus it is not possible to interpret or compare it. Generally, the field lacks experimental data, research methodology and methods for measuring aeration efficiency of vortex flow regulators.

The current study attempts to fill this gap in the literature by investigating the aeration mechanism and efficiency of cylindrical vortex regulators. In particular, we wanted to determine whether and how throttling capacity is linked to the reaeration performance of VFRs. We present results of our pilot-scale investigation that has led to the first formulas correlating geometry and regulator type with aeration efficiency. These represent the first reports of formulas for predicting standard overall oxygen transfer coefficient, standard oxygen transfer rate and standard aeration efficiency ($K_La_{(20)}$, SOTR and SAE, respectively) of vortex flow regulators. To test our approach for evaluating oxygen transfer efficiency in vortex regulators, we conducted a set of preliminary tests [20] aimed at evaluating methodologies, experimental configuration and methods.

We have constructed and tested two new designs that increase the aeration performance of existing flow regulators without impacting their throttling capacity. These patented new designs have a high potential for application in sewer systems and can deliver up to 20% better aeration compared to basic designs. In total, seven Polish patents for these types of the innovative vortex flow regulators were granted in 2013. We have compared the aeration capacity of a standard – single discharge cylindrical vortex regulator with that of the two new types.