High-rate treatment and disinfection of Combined Sewer Overflows using Advanced Hydrodynamic Vortex Separators

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ABSTRACT

Hydrodynamic Vortex Separators (HDVSs) have been used extensively as solid-liquid separators throughout the water industry. In recent years their application scope has been extended through adaptation to allow unit processes such as solids separation, screening and disinfection to be accomplished within the same vessel. The paper reviews the current state of understanding of HDVS operation, focusing in particular on their use as Combined Sewer Overflow and wet-weather treatment systems for high-rate chemical disinfection. This includes a review of the role Computational Fluid Dynamics (CFD) has played in providing detailed insights into their operating mechanisms, which has lead to the generation of improved knowledge and provided scope for physical (e.g. configurational) and operational (e.g. chemical dosing) design optimisation. It is found that macro flow field behaviour has a key bearing on operational effectiveness, in terms of determining the efficiency with which chemical contacting can take place, and this is an area where CFD analysis offers particular promise. The paper also presents and discusses data from full scale monitoring and performance evaluations including those undertaken as part of regulatory compliance reporting for a full-scale installation in the United States, confirming the efficacy of these devices in practice.

KEYWORDS

Combined Sewer Overflows (CSOs); Computational Fluid Dynamics (CFD); disinfection; hydrodynamic vortex separator (HDVS); residence time; wastewater treatment

INTRODUCTION

Hydrodynamic Vortex Separators (HDVSs) have been traditionally used as solid-liquid separators in the water industry (e.g. for stormwater, wastewater and combined sewer overflow treatment). In more recent times however these devices have been adapted to include a number of unit processes such as solids separation, screening and disinfection within the same vessel (Andoh *et al.*, 2002; Andoh *et al.*, 2008) with their efficacy as contact chambers for chemical disinfection now increasingly being recognised and applied.

The effectiveness of chemical disinfection depends on a number of factors including:

- Potency of chemical disinfectant
- Contact time

- Degree of short-circuiting in the reactor vessel / tank

For a given chemical dose level and contact time, disinfection efficacy becomes dependent solely on the macro-mixing properties of the reactor vessel and the degree of short-circuiting or ineffective contact time which in turn depends on the configuration, geometry and hydrodynamic flow regime established in the vessel. This paper considers these factors in the context of the application of HDVSs for the high rate treatment and disinfection of CSOs and reviews some of the work that has been carried out to explore and optimise their application in this area.

RESIDENCE TIME DISTRIBUTION

Fluid residence time or ‘residence time distribution’ (RTD) is a measure that can be used to characterise the macro flow field in a reactor and determine process effectiveness. The two ends of the spectrum of idealised reactor vessels are:

- CSTR :- Completely Stirred Tank Reactor
- Plug Flow :- Pure advection with no short-circuiting

These idealised regimes do not occur in practice, with the macro flow characteristic of any system, including HDVSs, lying between that of an ideal Plug Flow (PF) reactor and a Completely Stirred Tank Reactor (CSTR). In the PF reactor, pure advection with no longitudinal dispersion occurs whereas complete mixing occurs in the CSTR.

RTD can be characterised by a reactor’s response to a pulse injection (Levenspiel, 1962). Operating conditions in a PF reactor are such that all fluid elements being tracked leave the reactor at the same residence time, indicated in Figure 1A. In a CSTR, the elements of fluid being tracked will leave the device over a range of residence times, shown in Figure 1B. Between these two limits, both advection and dispersion processes occur, producing typical RTDs such as Figure 1C for real (non-idealised) reactors. A PF can be represented by an infinite number of CSTRs in series.

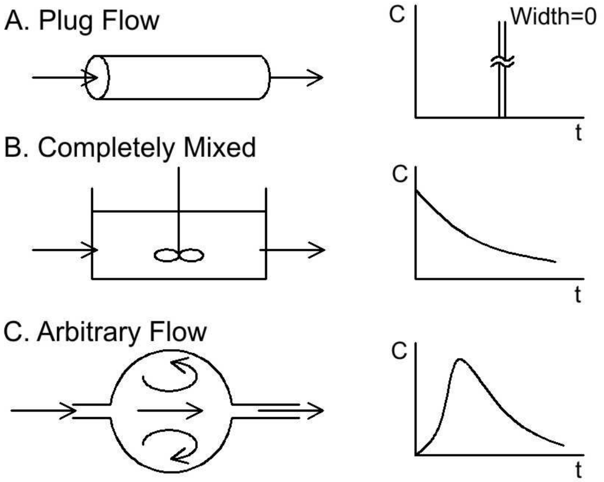

Figure 1. Typical outlet concentration versus time plots in response to different types of flow. (adapted from Levenspiel, 1962)

The RTD of a reactor will determine the strength and quantity of reagents required to aid processes such as the coagulation and flocculation of colloidal particles or disinfectant that is required if a system is to be used to disinfect a flow.

The number of CSTRs that is representative of the macro flow field characteristics for continuous flow through reactors can be derived by fitting the Tanks In Series Model (TISM) to a RTD determined using a pulse injection of tracer through the continuous flow system. The TISM assumes that a series of CSTRs, of equal volume, are connected in series (Levenspiel, 1962).

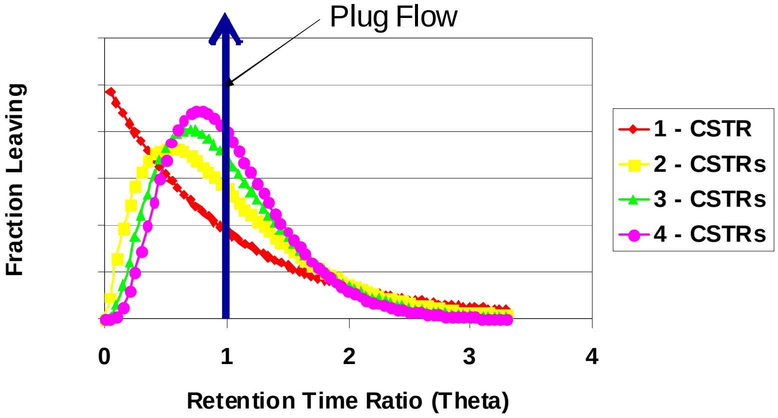

Figure 2. Residence Time Distribution (RTD) curves for CSTRs in series

Figure 2 shows RTD curves in the form of fraction leaving with the progress of time after injecting a pulse in the inlet for different reactor types. This shows that to avoid premature exit and ineffective contact time, the reactor vessel should behave like a number of CSTRs in series. For chemical disinfection, the closer reactor vessel behaviour is to Plug Flow, the better its performance will be.

TRACER STUDIES OF FULL-SCALE HDVSs

Results of tracer studies of full-scale HDVSs used as solid-liquid separators for primary treatment and chemically enhanced solids removals at a wastewater treatment works show that the observed response closely matches that of three CSTRs in series. Figure 3 shows comparisons between observed and predicted responses at Totnes Wastewater Treatment Works in the UK at the plant’s design flow rate. Figure 4 shows results obtained under stress loading conditions with twice the design flows through the HDVS unit.

These results suggest that a stable flow regime over a relatively wide range of flows occurs in the HDVS. The macro flow field characteristics have been described by Andoh and Smisson (1994) to result in relatively long internal flow paths. The HDVS is claimed to have three distinct macro-mixing fields described as an “outer zone” and an “inner zone” separated by a “shear zone”. In practice, the flow regimes in HDVSs have been found to be conducive to both solid-liquid separation and effective contacting for disinfection. For example, performance monitoring over a five year period has shown that HDVSs installed for high-rate treatment in Columbus, Georgia, USA are very effective contact chambers for chemical disinfection helping to significantly reduce capital and operating costs associated with CSO controls while providing necessary and effective preliminary and primary treatment operations and disinfection (Turner *et al.*, 2000).

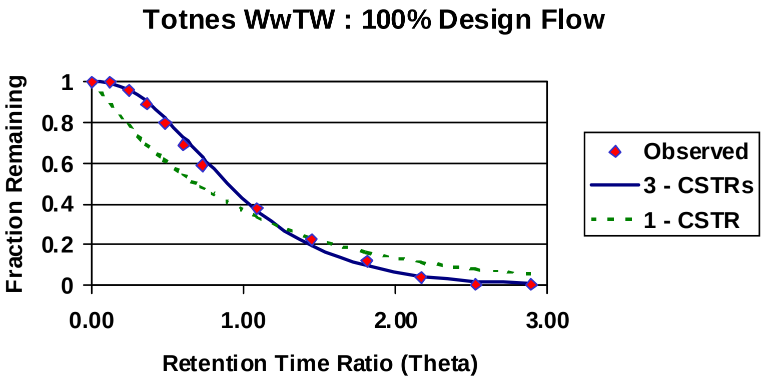

Figure 3. Tracer response of a full-scale HDVS at Totnes Wastewater Treatment Works compared to responses for 1 and 3 CSTRs: Operation at plant design flow rate

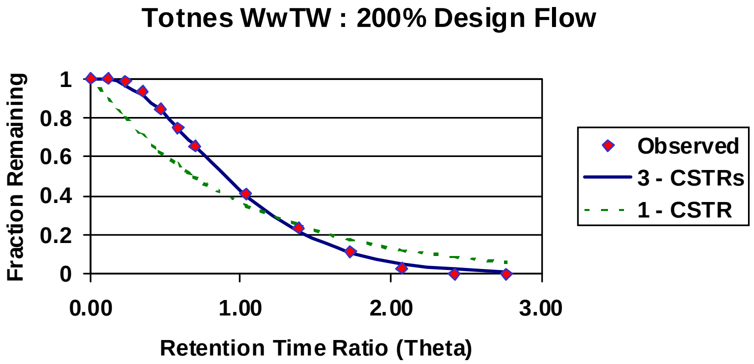

Figure 4. Tracer response of a full-scale HDVS at Totnes Wastewater Treatment Works compared to responses for 1 and 3 CSTRs: Operation under stress loading conditions

EXPLICIT MATHEMATICAL MODELLING

The flow characteristic of an HDVS that includes a hopper region has been further investigated by researchers at Liverpool John Moores University (LJMU) in the UK (Alkhaddar *et al.*, 2002). This work has confirmed the characteristic to lie somewhere between a PF and a CSTR. This work found that the macro-mixing characteristics could be described by a combination of 3-CSTRs in series together with a slow-mixing zone and a by-passing element (Alkhaddar *et al*., 2001). The flow regime in the HDVS configuration investigated was modelled using explicit mathematical functions as a number of CSTRs in series with internal coupling (shown schematically in Figure 5).

The explicit mathematical model which is described in more detail elsewhere (Alkhaddar *et al*., 2001) has allowed predictions to be made of the effectiveness of the HDVS as a contact vessel for disinfection or coagulation/flocculation processes. Though a useful tool, this explicit mathematical model relies on calibration parameters that are derived from physical experimentation, which limits its practical application as a design tool or for process evaluation particularly in situations where changes in configuration have to be made to suit site specific requirements or constraints.

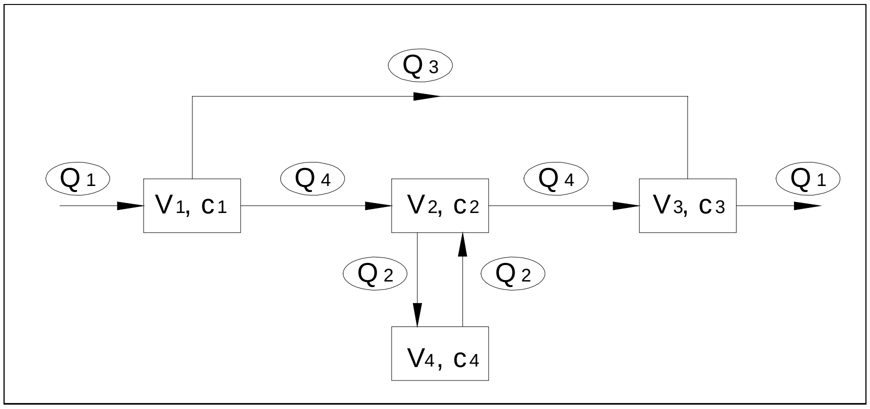

Figure 5. Mathematical model representation of the characteristics of an HDVS

Where, Q_1= Influent flow rate (L/min.); Q_3 = Bypass flow rate (L/min.); Q_2= Exchange flow rate; (L/min.) C_3 = Effluent concentration (mg/L); V_1, V_2, V_3 = Volume of tanks (L); V_4 = Slow mixing volume (L).

COMPUTATIONAL FLUID DYNAMICS (CFD)

Advances in Computational Fluid Dynamic (CFD) modelling have resulted in a significant increase in the ability to predict the performance of hydraulic structures and different tank/vessel configurations. CFD can be used to provide predictions of the flow patterns, solids separation performance and residence time distributions of sewer ancillary structures including CSO chambers (Harwood and Saul, 1996; Faram and Andoh, 2000; Stovin and Saul, 2000; Jarman *et al.*, 2008). There are now many general purpose CFD packages that are capable of modelling fluid flow, heat transfer and chemical reactions and are usually based on finite volume or finite difference methods to solve the governing fluid flow equations.

Figure 6 shows an example of a CFD output for an advanced HDVS highlighting the fact that the macro-mixing flow regime in the active region is fully developed after around 192 seconds (i.e. less than 5 minutes) (compared to a theoretical value of a little over 100 seconds for the chamber modelled) (Egarr, 2005a). This suggests that the hydrodynamic flow regime in an HDVS results in relatively long internal flow paths.

The effectiveness of the flow regime as a macro-mixing contact chamber, conducive to high-rate chemical disinfection achievable in less than 5-minutes compared with the often applied ‘rule of thumb’ design value of 15-minutes, has been demonstrated after more than six years of full-scale monitoring at Columbus, Georgia in the USA (Boner *et al.*, 1993; Turner *et al.*, 2000 and Boner, 2003).

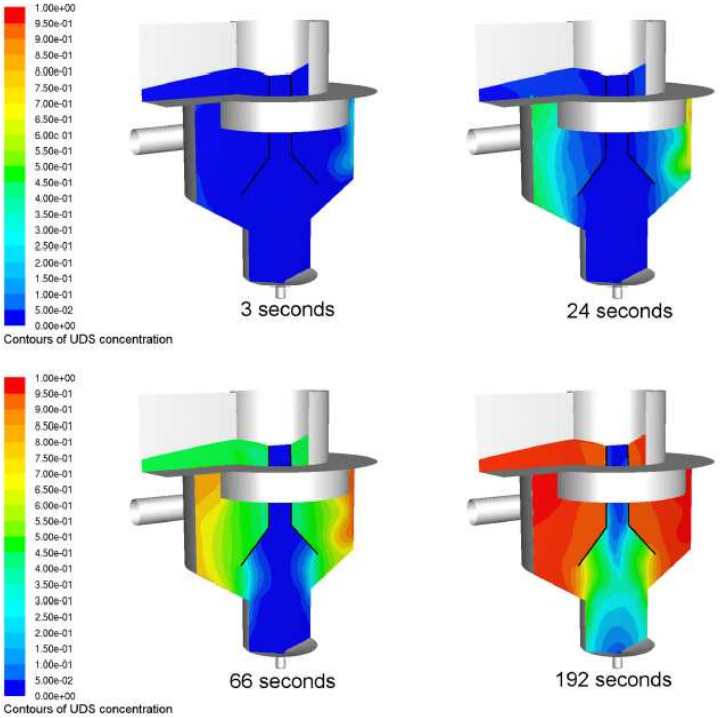

Figure 6: CFD outputs showing evolution of mixing regime in an advanced HDVS (Egarr, 2005a)

CFD modelling has also been undertaken for the assessment of full-scale HDVSs for which RTD characterisations have previously been obtained for a range of laboratory conditions (Egarr *et al.*, 2005b). The CFD outputs were validated against the experimental results, with good correspondence being found. This work has subsequently been extended further using the results from the CFD modelling and batch inactivation results from the disinfection of secondary treated wastewater, to ascertain the theoretical performance of a HDVS as a contact vessel for disinfection (Egarr *et al.*, 2005c). Figure 7 shows an example of the contours of micro-organism survival throughout the HDVS on which work was undertaken. The contours of survival show that the degree of kill of organisms’ increases as the flow passes through the HDVS, as their period of contact with the disinfectant increases with high numbers observed in the outer zone compared with the inner zone and overflow.

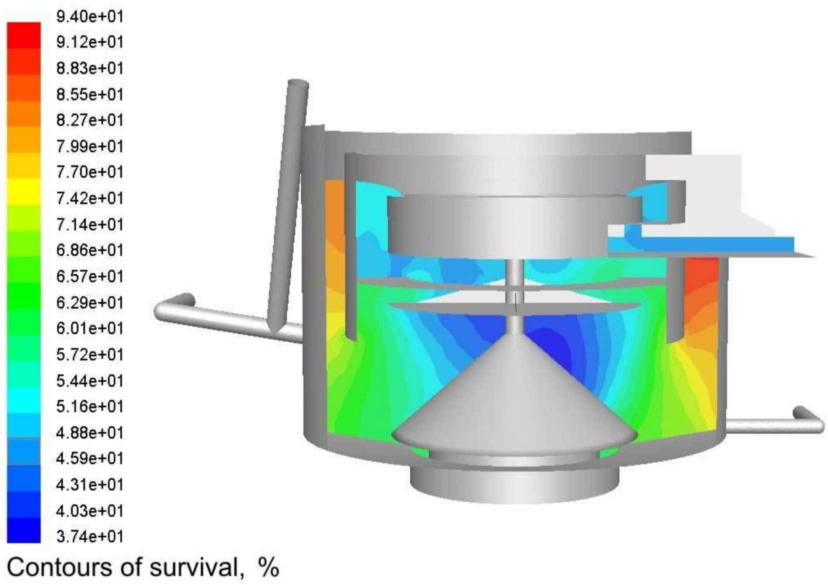

Figure 7 Contours of micro-organism survival in an HDVS (Egarr, 2005a)

One benefit of using CFD compared to experimental techniques is that it provides an insight into the mechanics of a system's operation. For example, the output in Figure 7 highlights a region in the central part of the separator, where a lower survival rate occurs, which would otherwise be difficult to observe through experimental techniques.

This work demonstrates the usefulness of CFD as a tool to provide insights and the potential for predicting the disinfection performance of different HDVS configurations when they are utilised as continuous flow systems applied to disinfection of wastewater.

CONCLUSIONS

Early designs of HDVSs as contact chambers for disinfection have been based simply on theoretical mean residence time, first order kinetics and an assumption that the macro flow field can be characterised as a CSTR. Though effective, this approach results in conservative designs, as demonstrated by recent work, which has found that the HDVS operates more like a number of tanks in series.

Though an explicit mathematical model has been developed for HDVSs that provides a more accurate description of residence time distributions, this model depends on physically based calibration parameters that are dependent on the type and configuration of HDVS.

CFD has been found to be a powerful tool that can be used in conjunction with batch inactivation results to predict the disinfection efficacy of HDVS systems. The further development and validation of such tools will enable systems to be designed more accurately, and with better efficiency with regard to the consumption of chemicals.

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