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Research article

Using turbidity for designing water networks

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ABSTRACT

Some methods to design water networks with minimum fresh water consumption are based on the selection of a key contaminant. In most of these “single contaminant methods”, a maximum allowable concentration of contaminants must be established in water demands and water sources. Turbidity is not a contaminant concentration but is a property that represents the “sum” of other contaminants, with the advantage that it can be cheaper and easily measured than biological oxygen demand, chemical oxygen demand, suspended solids, dissolved solids, among others. The objective of this paper is to demonstrate that turbidity can be used directly in the design of water networks just like any other contaminant concentration. A mathematical demonstration is presented and in order to validate the mathematical results, the design of a water network for a guava fudge production process is performed. The material recovery pinch diagram and nearest neighbors algorithm were used for the design of the water network. Nevertheless, this water network could be designed using other single contaminant methodologies. The maximum error between the expected and the real turbidity values in the water network was 3.3%. These results corroborate the usefulness of turbidity in the design of water networks.

1. Introduction

The design of “water networks with minimum fresh water consumption (WN-MFWC)” is a field that has been developed during the last two decades (Bagajewicz, 2000; Klemes, 2013). Some methods imply the selection of a key contaminant and the identification of water sources and water demands (Foo, 2009). A demand is a unity process or activity that requires water. A source is a unity process or activity that provides a water flow that can be recycled (used in the same unit or activity) or reused (used in other unit or activity). For each demand and each source, a maximum allowable contaminant concentration must be established.

Commonly, a two-step procedure is performed to obtain the minimum fresh water consumption and the corresponding water network (Atimtay and Subhas, 2011). In the first step, the minimum fresh water consumption can be obtained graphically and involves only simple calculations such as the contaminant load. Some graphical approaches for the first step are the limiting composite curves (Wang and Smith, 1994), the water surplus diagram (Hallale, 2002), the material recovery pinch diagram (MRPD) (El-Halwagi et al., 2003; Prakash and Shenoy, 2005) and the graphical pinch analysis for partitioning process (Tan et al., 2010). In the second step, the water network is designed by numerical methods (Savelski and Bagajewicz, 2001; Tan and Cruz, 2004) and other strategies like the nearest neighbors algorithm (NNA) (Prakash and Shenoy, 2005). In these type of methodologies the material balances of the key contaminant are used and a set of linear equations must be solved (Savelski and Bagajewicz, 2001; Prakash and Shenoy, 2005).

The key contaminant could be the most concentrated pollutant, the most dangerous compound or the substance with more legal restrictions in the wastewater. Some typical contaminants used in the design of water networks are organic compounds, salts, metals, suspended solids (Agana et al., 2013; Khor et al., 2014; Koppol et al., 2004), dissolved solids (Shukla et al., 2013), total solids (Wenzel et al., 2002), biological oxygen demand (BOD) (Handani et al., 2010; Lee et al., 2014; Manan et al., 2006), and chemical oxygen demand (COD) (Khor et al., 2012; Klemes et al., 2003). These contaminants require measurement methods that can be complex, time consuming and sometimes expensive. Additionally, the

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Nomenclature

CD_J	Contaminant concentration of demand j (mg/kg)
CS_i	Contaminant concentration of source i (mg/kg)
D_J	Mass flow of demand j (kg/h)
MD_J	Contaminant load of demand j (mg/h)
MS_i	Contaminant load of source i (mg/h)
S_i	Mass flow of source i (kg/h)
$S_{i,j}$	Mass flow from source i to demand j (kg/h)
$S_{i,w}$	Mass flow from source i to wastewater w (kg/h)
SS	Suspended solids concentration (mg/kg)
T	Turbidity (NTU)
TD_J	Turbidity of demand j (NTU)
TS_i	Turbidity of source i (NTU)

Greek letters

α	Constant in the correlation between turbidity and suspended solids concentration (mg/NTU kg)

Subscripts

i	Source index
j	Demand index
m	Number of sources to satisfy a single demand j
n	Number of demands that receives a part of the flow from a source i
w	Flow to wastewater

selection of the maximum allowable contaminant concentration is not always straightforward (Wenzel et al., 2002).

Turbidity is a property that can be measured quickly, easily (even online) and it is less expensive than other water properties. Moreover, a series of guidelines have assigned appropriated turbidity levels for some common uses in the industrial field. For example, according to The World Health Organization (2011) the turbidity in drinking water must be between 1 and 5 NTU, and for cooling systems some guidelines recommend maximum values from 10 to 50 NTU (Goldstein et al., 1979; Lapeña, 2000).

For sectors with limited resources such as small companies, turbidity might be attractive because of the low costs required to take the measurement. In sectors where strict pollution control is necessary, an online turbidity measurement is also interesting since turbidity values could be integrated in an automatic control system to maintain the process requirements.

In spite of the afore mentioned advantages, turbidity is not used for the design of water networks since it does not correspond to a contaminant concentration (Foo et al., 2006). Some methodologies belonging to the process integration field have been proposed to minimize the waste discharge and the resource consumption by reuse and recycling of process flows (El-Halwagi et al., 2004, 2003; Kazantzi and El-Halwagi, 2005; Shelley and El-Halwagi, 2000). These methods are applied mainly in mass integration problems and not directly in water networks. Additionally, process integration methods require the transformation of the property in a conservative function, before the integration strategies can be applied. Until now, none of these property-based methods have reported the use of turbidity for the design of water networks.

In this work turbidity is correlated in a linear way with the concentration of suspended solids (SS) as shown in Eq. (1); where T represents turbidity and α is a constant (Earhart, 1984; Rügner et al., 2013; Suk et al., 1998). This linearity depends on the contaminants present in water and can be valid in different ranges like 0.1 to 100 NTU (Schwarz et al., 2011), or 10 to 1000 NTU (Downing, 2006). In cases where water presents color, the linearity range should be validated experimentally.

$$SS = \alpha \times T \tag{1}$$

Based on this feature, it is demonstrated that turbidity can be used directly on the design of water networks, just like a contaminant concentration and without needing a property-based methodology.

1.1. Problem statement

To demonstrate that turbidity can be used for directly in the design of WN-MFWC, just like any other contaminant concentration.

2. Mathematical formulation

In the case of steady state systems without chemical reactions, material balance equations can be expressed in terms of flows and component concentrations only (Reklaitis, 1983). The problem of designing a WN-MFWC with a single contaminant is mathematically represented as the problem to solve a set of material balance equations under the restriction of minimizing the fresh water consumption (Savelski and Bagajewicz, 2001). In that sense, the problem only depends on the flow and concentration of contaminants. This section shows that material balance equations can be expressed only in terms of the flows and their turbidities, hence demonstrating that turbidity can be used directly in problems involving the design of WN-MFWC.

According to Earhart (1984), Rügner et al. (2013) and Suk et al. (1998), a linear relation between the suspended solid concentrations and turbidity can be assumed. In this work, this assumption is represented in Eqs. (2) and (3).

$$CS_i = \alpha \times TS_i \tag{2}$$

$$CD_j = \alpha \times TD_j \tag{3}$$

where CS_i and CD_j represent contaminant concentration of the source i and the demand j. TS_i And TD_j are turbidity of the source i and demand j. α is a constant that relates the contaminant concentration and turbidity.

Eqs. (4)–(6) show general balance equations for any water network. These equations represent cases shown in Figs. 1 and 2.In the first case, a demand j is satisfied by m flows from m different sources. Eqs. (4) and (5) show the flow and the contaminant balances respectively:

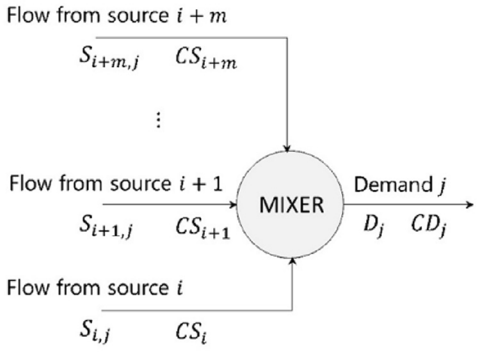

Fig. 1. Diagram for a generic demand j.