An Integrated Approach for Industrial Water Systems Optimal Design

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ABSTRACT

An efficient exploitation of resources is fundamental in modern industries. Among these, an essential one is water. Two approaches have traditionally been adopted for the minimization of freshwater consumption, trying to maintain the compliance with environmental regulations (which are becoming more and more stringent) on wastewater discharge. The first approach is based on water pinch technology and is aimed at optimal water network design or retrofit analysis; the second one is aimed at optimizing the operating conditions of existing processes without changes in the network design. Both generally aim at minimizing freshwater consumption or total cost. This paper presents a possibility for integration of the two approaches, together with two case studies intended to assess the feasibility of such integration through simulation of a water network. Results of the case studies show an interesting potential for freshwater saving.

Keywords: process integration, wastewater treatment, industrial water systems, water systems optimization

1 INTRODUCTION

Minimization of freshwater consumption and wastewater generation are fundamental issues in industrial water systems. Such a problem has traditionally been tackled through Process Integration (PI) techniques such as water pinch analysis [1]. In such an approach, the limiting water profile defines the boundary between feasible and unfeasible water using regions. If more operations are involved in a process, the combination of different limiting water profiles can bring to the design of a process limiting composite curve [2]. By analyzing such a curve a water network can be designed that targets the maximum reuse of water and therefore the minimum freshwater consumption. From a computational point of view, the problem of water network design aimed at minimization of freshwater consumption can be solved through optimization of a superstructure in which all the possible connections between water using operations and wastewater treatment are assessed exploiting traditional or advanced optimization algorithms [3]. A drawback of such an approach lies in the fact that, even in its most recent evolutions [4], it does not take into account the influence of the water streams properties, or of the process operating conditions, on the process performances: only very simplified models are considered for optimal water network design.

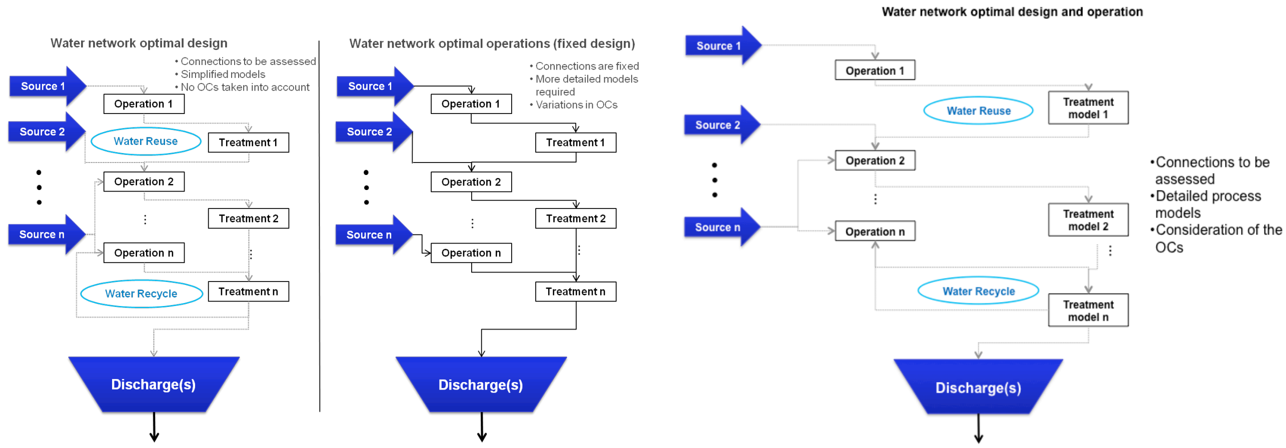
A second approach consists in the search of an improved management of industrial water system performances by considering optimal operating conditions of water using operations and wastewater treatment processes, assessed through exploitation of more detailed process models. In general, such an approach considers the connections between different operations and treatment as fixed: the existing plant layout is taken as a datum of the problem and the optimization study only considers variations in the operating conditions. This approach, that does not allow to carry out a water pinch analysis in order to assess the best design configuration, is less indicated for new design or system retrofit studies.

The present article describes a possible extension and combination of the above described approaches, which is currently under investigation in a research project funded by the European Union. Section 2 presents the methodology that is being pursued within the project; in Sec. 3 a preliminary example describing different alternatives for the minimization of freshwater consumption in an integrated steelwork is presented, while final conclusions are drawn in Sec. 4.

2 METHOD

The two approaches described in the introduction are graphically presented in Figure 1a. An evolution of the two approaches resides in their combination, considering both the optimal network design and the influence of operating conditions onto the treatment process performances. Such a combined approach is currently under investigation and development in an ongoing EU-funded Research Fund for Coal and Steel (RFCS) research project; a schematic representation is shown in Figure 1b.

In order to develop such an integrated approach, a library of water using operations and wastewater treatment models has been created, which includes a set of common industrial processes. Among the modeled processes there are clarification, ammonia stripping, reverse osmosis-based desalination, gas scrubbing and biological oxidation (activated sludge). A detailed description of the models is beyond the scopes of the present paper; however, they have been developed exploiting available literature as well as process knowledge and data coming from the industrial partners of the project. For instance, the clarifier model has been derived from the description given in [5], and provides as output the removal efficiency for a specific contaminant (e.g. total suspended solids) as a function of the particle settling velocity, calculated through application of the Stokes' sedimentation law. The influence of the



a) b)

Figure 1 – a) Different approaches to water system optimization; b) Combined water pinch and system optimization approach

contaminant Particle Size Distribution (PSD) is also accounted in the model equations.

The different models have been validated through comparison with ad-hoc industrial data collected within the framework of the project. A common communication interface has also been defined in order to enable communication of relevant input/output parameters between different treatment models, which are treated as unit operations. Among the information that is passed through different blocks are the water flowrate, temperature, pressure, pH, and contaminant-related information such as concentration, density and mean particle diameter (or PSD). The system is also configured in order to take into account of multiple contaminants. The exploitation of such an interface enables to consider the different unit operations as “black box” models that can be easily embedded within a superstructure optimization that is solved through well-established techniques.

A first demonstrative example of application of the wastewater models within a water network is provided in the next section.

3 EXAMPLE OF APPLICATION

In order to validate the water treatment models, a first analysis has focused on an industrial water sub-network, in order to identify possibilities for freshwater saving by optimized water recycling. To this aim, two case studies have been simulated, that are described in the following sub-sections.

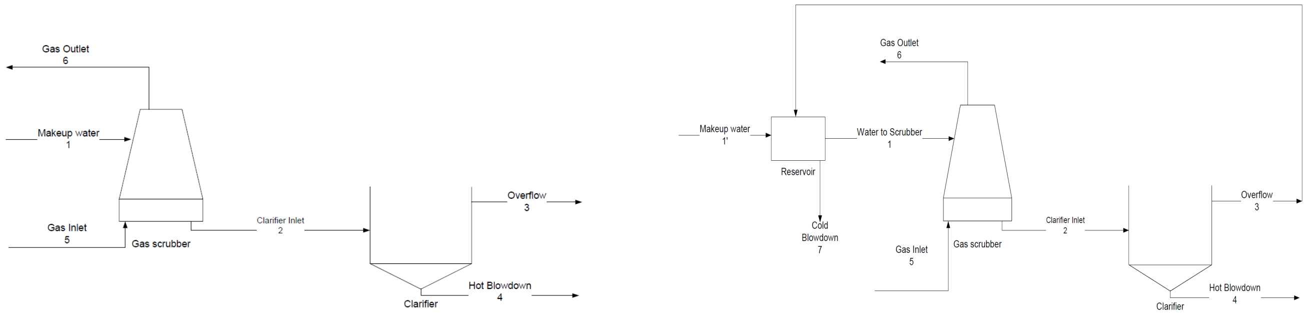
3.1 Case Studies Description

The analyzed system is composed by two main unit operations: a blast furnace gas scrubber and a clarifier. Fresh water is used to wash a gas stream coming from the blast furnace in order to remove the content in entrained solids and to decrease gas temperature. Therefore the water outlet stream is contaminated and it is treated in the clarifier with the aim of decreasing the suspended solids concentration prior to discharge. Figure 2(a) shows the considered system.

The clarifier model is based on the Stokes’settling velocity and predicts the PSD of the overflow and blowdown streams. The recovery ratio is calculated taking into account the maximum settling capacity of a clarifier with a given cross sectional area. Therefore the model output is the overflow and blowdown stream quality. From the outlet information a curve of settling efficiency was created and assumed to be constant, which is based on the solid PSD and on the clarifier design. The model has been validated through comparison with a commercial simulation software, which requires as input the extrapolated efficiency curve. The higher accuracy of the software justifies its use for the water re-use study.

A first simulation has been carried out considering the total amount of water entering the gas scrubber as freshwater. In this case the suspended solid concentration is very low. The gas scrubber type entered in the simulation is a wet Venturi precipitator. The separation takes place in the scrubber throat were the fluid increases its velocity (and is affected by a pressure drop). The solids removal efficiency depends on the PSD: the greater the particles size, the higher the separation efficiency. The gas outlet stream also contains water coming from the humidity of the gas inlet and due to potential evaporation losses. Such contribute is calculated from an energy balance on the scrubber and may not be significant. The contaminated water outgoing from the scrubber need to be treated in the clarifier.

As a result of the high quality of the fresh water, the clarifier overflow solid concentration is low, allowing to plan an internal re-use of such stream instead of discharge. A second case study has therefore been carried out in order to assess such a hypothesis, which is depicted in Figure 2(b). The aim is to evaluate the feasibility of the overflow water re-cycle in the same gas washing process, by also monitoring the solid concentration in the gas outlet from the scrubber, the quality of contaminated water for discharge, the required amount of fresh water and the discharge



(a) (b)

Figure 2 – Representation of the system analyzed in the two case studies: a) with no recycle and b) with recycle.

flowrate. In fact the feasibility is not independent from economic evaluations (i.e. water re-use could significantly increase the contaminants concentration in discharge up to values that are compliant with environmental regulations and thus not environmentally compatible to make necessary other water treatments).

3.2 Results and Discussion

The results achieved by the process models relative to the two cases, i.e. respectively without and with water re-cycle, are shown in Tables 1 and 2.

Keeping a constant (comparable) washed gas quality, freshwater consumption greatly decreases as a consequence of wastewater regeneration and re-cycle: its value decreases from 1,100 t/h to 290 t/h, i.e. a relative 74% decrease. The discharge streams in the case with water re-cycle are constituted by a hot and a cold blowdown, shown in Figure 2(b) and labeled with numbers 4 and 7; the total blowdown amount for discharge decreases if compared with the sum of overflow and blowdown streams of the first case study. It is also worth remarking that in every case the contaminant value was well below the regulatory limits for that particular species.

Discharge water quality is similar in both cases, but it is actually higher in the second one, where water re-cycle occurs. This fact confirms the possibility to re-cycle the overflow from the clarifier within the blast furnace gas scrubbing process.

Obviously the water scrubber inlet has a higher concentration in suspended solids than in the case without re-cycle but this fact does not influence contaminant removal efficiency in the gas washing process. Solids are in fact separated from the gas stream mainly due to contact and this is not directly dependent on initial solids concentration in the liquid stream.

The described system is the basis for a system optimization study, where additional constraints would have to be imposed. For instance, multiple contaminants that have an influence on the process operations should be

STREAM	**1**	**2**	**3**	**4**	**5**	**6**
	Makeup Water	**Clarifier Inlet**	**Overflow**	**Hot Blowdown**	**Gas Inlet**	**Gas Outlet**
Temperature [°C]	20.00	34.32	34.32	34.32	131.00	34.32
Pressure [bar]	1.25	1	1	1	1.25	1
Total Mass Flow [kg/h]]	1100000	1097430	947034	150395	418236	420807
Gas Mass Flow [kg/h]	0.00	1086.26	937.44	148.82	401308	400222
SS Mass Flow [kg/h]	1.87	157.89	88.84	69.05	156.36	0.34
H_2O Mass Flow [kg/h]	1100000	1096190	946008	150177	16772.15	20585.20
CONCENTRATION						
Gas [ppm]	0.00	989.82	989.87	989.51	959525.24	951082.09
SS [ppm]	1.70	143.87	93.81	459.09	373.86	0.81
H_2O [ppm]	1000000.00	998870.09	998916.62	998550.48	40102.12	48918.39
PSD[%wt]						
0-0.5 [μm]	0.550	0.037	0.066	0.000	0.033	0.984
0.5-1 [μm]	0.450	0.116	0.205	0.000	0.111	0.014
1-2.5 [μm]	0.000	0.106	0.187	0.002	0.107	0.001
2.5-5 [μm]	0.000	0.107	0.185	0.007	0.108	0.000
5-10 [μm]	0.000	0.156	0.245	0.042	0.158	0.000
10-15 [μm]	0.000	0.098	0.113	0.078	0.099	0.000
15-30 [μm]	0.000	0.381	0.000	0.870	0.384	0.001

Table 1: Main simulation results for first case study.

STREAM	1'	1	2	3	4	5	6	7
	Makeup Water	**Water to Scrubber**	**Clarifier Inlet**	**Overflow**	**Hot Blowdown**	**Gas Inlet**	**Gas Outlet**	**Cold Blowdown**
Temperature [°C]	20	34.77	39.88	39.88	39.88	131.00	39.88	34.77
Pressure [bar]	1.25	1	1	1	1	1.25	1	1
Total Mass Flow [kg/h]	290001	980228	969529	836698	132832	418236	428935	146471
Gas Mass Flow [kg/h]	0.00	692.02	921.70	795.43	126.27	401308	401078	103.41
SS Mass Flow [kg/h]	0.49	450.76	606.79	517.64	89.16	156.36	0.33	67.36
H_2O Mass Flow [kg/h]	290000	979085	968001	835385	132616	16772.1	27856	146300
CONCENTRATION								
Gas [ppm]	0.00	705.98	950.67	950.68	950.62	959525.2	935055.4	705.98
SS [ppm]	1.70	459.86	625.86	618.67	671.20	373.86	0.77	459.87
H_2O [ppm]	999996	998833.9	998424	998430.7	998373.9	40102.1	64942.3	998832.5
PSD[%wt]								
0-0.5 [μm]	0.550	0.075	0.064	0.075	0.000	0.033	0.966	0.075
0.5-1 [μm]	0.450	0.259	0.221	0.259	0.002	0.111	0.026	0.259
1-2.5 [μm]	0.000	0.236	0.203	0.236	0.009	0.107	0.002	0.236
2.5-5 [μm]	0.000	0.205	0.181	0.206	0.035	0.108	0.001	0.205
5-10 [μm]	0.000	0.181	0.175	0.181	0.141	0.158	0.001	0.181
10-15 [μm]	0.000	0.044	0.058	0.044	0.139	0.099	0.001	0.044
15-30 [μm]	0.000	0.000	0.099	0.000	0.674	0.384	0.003	0.000

Table 2: Main simulation results for second case study with water re-use.

taken into account in the refining of the process and treatment models, such as water conductivity that represents an additional constraint on the recyclability of process water.

CONCLUSIONS

In the current paper, a possibility for integration of two traditional PI methods for the optimization of industrial water systems has been presented. The two approaches are suitable for water network optimal design and for optimization of water-using operation and wastewater treatments, respectively. A combination of the two approached has been proposed and its feasibility is under assessment in a current European Union research project.

Furthermore, a study on the feasibility of wastewater re-cycle within an industrial water sub-network has been carried out. Two alternative layouts have been assessed in different case studies, with or without recirculation of the treated wastewater to the water-using process. The results of the two case studies confirm the possibility for clarifier overflow re-cycle to a blast furnace gas scrubbing process.

The proposed solution allows reaching interesting savings in terms of freshwater consumption. The realized water network model is the basis for a future integration of different process (water using operations and wastewater treatment) models, which take into account flow properties and operating conditions, within a water network design and retrofit tool exploiting the optimization of a superstructure and based on water pinch technology.

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