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Water system integration and optimization in a yeast enterprise

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ABSTRACT

Water system integration is an effective way to save freshwater and reduce wastewater in enterprises. Water system integration treats the water system in an enterprise as a whole and utilizes water resources more effectively by optimizing the water utilization network. In this study, water system integration was applied to a yeast enterprise. According to the characteristics of the water utilization processes in the yeast enterprise, the water utilization processes were classified as fixed-load, fixed-flow, no-output flow, and no-input flow processes. Optimization schemes for the no-output flow and no-input flow processes were obtained through qualitative judgment. Optimization schemes for the fixed-load and fixed-flow processes were obtained using a mathematical programming method. Through the adjustment of the water utilization network, it was demonstrated 27% of freshwater consumption could be saved and 23% of the COD could be reduced.

1. Introduction

Water is necessary for industrial production processes as a raw material and process medium. In recent years, with the rapid development of the Chinese industrial economy, the shortage of water resources has become an increasingly serious issue.

The yeast industry has a high consumption rate of freshwater, approximately 60–100 ton water per ton yeast. The yeast industry also discharges large amounts of wastewater, including wastewater from the pretreatment of molasses, yeast fermentation and separation, cooling, and ground and equipment cleaning. With the increasingly stringent discharge standards and rising water prices in China, it has become important to conserve water in yeast enterprises.

Recently, many attempts to reduce freshwater consumption have been made, including studies of water system integration to minimize freshwater consumption. Current studies of water system integration have focused mainly on water pinch technology and mathematical programming methods. The advantages of water pinch technology are intuitive and produce clearly visible benefits, but water pinch technology can manage only a single contaminant or a simple problem with multiple contaminants. In contrast, mathematical programming can easily handle situations involving multiple contaminants, and has been used widely in water system integration optimization processes.

Takama et al. (1981) first constructed a water utilization network superstructure model for a single contaminant situation using mathematical programming, and they used the model to design the structure of a water utilization network. Doyle and Smith (1997) applied mathematical programming to a water utilization network for multiple contaminants and solved the problem of multiple contaminants in a water utilization network by combining linear and nonlinear programming. Zheng et al. (2006) proposed rules to determine the contaminants and their limiting concentrations. Faria et al. (2009) constructed a nonlinear programming model to minimize freshwater consumption and investigated the cost and freshwater consumption under conditions with and without a regeneration unit. Matijasevic et al. (2010) constructed a mixed integer linear program (MILP) for water use and wastewater treatment systems that is solved using MATLAB. Khor et al. (2014) proposed a mixed-integer quadratically constrained quadratic program (MIQCQP) for a fixed-flow total water network synthesis problem under uncertain conditions. Poplewski (2015) constructed a mixed integer linear problem (MILP) for a flexible water network (FWN) that would ease process operation and control.

Originally water system integration could only handle mass transfer water-using networks. Dhole et al. (1996) reported that not all of the processes in a water network could be described as mass transfer processes, and should be considered to be non-mass-transfer processes. Prakash and Shenoy (2005) proposed that water-using processes can be classified as fixed-flow and fixed-load

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Nomenclature

COD	Chemical oxygen demand (ppm)
SS	Suspended solids (ppm)
H	Hardness (ppm)
MVR	Mechanical vapor recompression

Sets/indices

min	Minimum value
max	Maximum value
$n_{out,j,s}$	The order of the contaminants based on the limiting outlet concentration for process j
$n_{in,j,s}$	The order of the contaminants based on the limiting inlet concentration for process j
$R_{out,j}$	Final order based on the limiting outlet concentration for process j
$R_{in,j}$	Final order based on the limiting inlet concentration for process j
P_j	Set of precursors of process j
η	The coefficient of the upper limit of water consumption
z_j	Minimum fresh water consumption of process j (t/d)

Subscripts

j	Index of processes (j = 1,2,. . ., J)
s	Index of contaminants (s = 1,2,. . ., S)

Parameters

G	Baseline water consumption (t/d)
G_j	Baseline water consumption of process j (t/d)
M	Mass load of contaminant (t/d)
$M_{j,s}$	Mass load of contaminant s for process j (t/d)
C_{out}^{max}	Limiting outlet concentration (ppm)
$C_{out,j,s}^{max}$	Limiting outlet concentration of contaminant s for process j (ppm)
$C_{out,i,s}^{max}$	Limiting outlet concentration of contaminant s for process i $(ppm)_{out,j,s}$
C_{in}^{max}	Limiting inlet concentration (ppm)
$C_{in,j,s}^{max}$	Limiting inlet concentration of contaminant s for process j (ppm)
W_i	Wastewater discharged from process i (t/d)

Variables

F_j	Freshwater consumption of process j (t/d)
$X_{i,j}$	The reused wastewater from process i to process j (t/d)

processes, and proposed a new water pinch method for these processes. Teles et al. (2008, 2009),) applied linear programming (LP) methods and mixed integer linear programming (MILP) approaches to explore all of the possible water reuse and recycling alternatives for networks designed for fixed-load and fixed-flow processes. Fan et al. (2012) analyzed the difference between fixed-flow and fixed-load processes, and proposed the Concentration Potential of Demand (CPD) calculation for fixed-flow and fixed-load processes. Shenoy and Shenoy (2015) proposed a new zero wastewater discharge (ZWD) network design method for fixed-load and fixed-flow processes, with and without water loss.

The superstructure of a water utilization network can be modeled and solved through nonlinear programming (NLP), but solving the corresponding NLP model usually requires considerable computational resources and a good initial guess is almost always required to start the search process. To overcome the difficulty of obtaining global optimal solutions, some researchers have proposed that the water utilization processes can be ordered first and then be individually optimized. Savelski and Bagajewicz (2001) ordered water utilization processes according to the limiting outlet concentration and then optimized the water utilization processes individually in that order. Hu et al. (2002) proposed that the water utilization processes can be ordered by the limiting inlet concentration, and designed a water network with multiple contaminants using a step-by-step linear programming method. Xu et al. (2003) proposed a step-by-step nonlinear programming method based on a step-by-step linear programming method. Li and Fei (2005) used a rapid step-by-step linear programming method that ordered the water utilization processes according to the limiting outlet concentration, and then they optimized the water utilization processes in that order using a linear programming model. Liu et al. (2009) proposed the concept of Concentration Potential of Demands (CPD) and Concentration Potentials of Source (CPS), and ordered the water utilization processes by CPD. Li (2013) proposed a new manual strategy to order the water utilization processes and synthesize batch water-using networks with multiple contaminants.

According to the characteristics of a yeast enterprise with a complex water utilization network, we propose that water utilization processes can be further classified as fixed-load, fixed-flow, no-output flow, and no-input flow processes. The classification of the water utilization processes simplifies the water utilization network superstructure model. Different optimization strategies were then proposed for different water utilization processes. No-input flow processes can only be treated as a water source for other processes. A novel step-by-step linear programming method was proposed for fixed-load and fixed-flow processes, which ordered the processes according to the limiting outlet concentration and then constructed a corresponding linear programming model for fixed-load and fixed-flow processes. No-output flow processes were ordered according to the limiting inlet concentration, and then optimization schemes for the no-output flow processes were obtained through qualitative judgment.

This study set a constraint on the upper limit of water flow in the mathematical model because too much water consumption will affect the production of yeast. Different coefficients of the upper limit of water consumption were set according to the characteristics of the fixed-load and fixed-flow processes, allowing the mathematical model to be applied to both processes. The mathematical model proposed in this study was based on a linear programming model that would ensure a globally optimal solution.

2. Characteristics of the water utilization system

2.1. Water utilization network in a yeast enterprise

The yeast enterprise studied here in southern China mainly produces dry yeast for bread making, with a production capacity of 1000 ton yeast every year. The water utilization network of the yeast enterprise before optimization is shown in Fig. 1, and includes a molasses treatment system, the yeast production system, and a circulating cooling system. Each day, 1784 ton of freshwater were consumed and 1116.5 ton of wastewater were discharged.

2.1.1. Molasses treatment system

The molasses were diluted and purified in the molasses treatment system. Water was consumed in the molasses treatment system during the pretreatment of molasses, filtration in a plate and frame filter press, the idling of the centrifuge after the separation of molasses, flash vaporization and condensation. The freshwater consumption of the molasses treatment system was 59.5 t/d.