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The Optimal Model of a Fluid Machinery Network in a Circulating Water System

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In process industries, compressors or pumps are widely used to increase fluids' pressure if necessary, and expanders are used to generate work for fluids with excess pressure. These fluid machinery forms a fluid machinery network if there are associations among these fluid machinery. Pumps and water turbines in a circulating water system is just such a fluid machinery network. Energy consumption could be reduced while the economic profit improved by means of setting fluid machinery appropriately. In this paper, aims at the fluid machinery network in a circulating water system, a superstructure of the network is built taking into account the main and auxiliary pumps system for delivering circulating water as well as the water turbines system for recovering pressure energy. Then based on the superstructure, an optimal mathematic model of the network is proposed with the annual total cost as the objective function. A case study is used to validate the applicability of the model finally.

1. Introduction

In process industries, many fluid streams need to be pumped to increase pressure while others with excess pressure need to decrease pressure. The rich liquid with high pressure in wet decarburization process of synthetic ammonia production (Ma et al,2014) and the high concentrated brine with high pressure in the seawater desalination process (Xue et al,2016) are examples of streams with excess pressure. Recovering the energy of excess pressure will reduce utility consumption. There are two ways to do so: one is direct work exchange from a work source to a work sink by a work exchanger, and the other one is indirect work exchange, in which the fluid with excess pressure coverts the redundant energy to mechanical energy by an expander (turbine), and the fluid needing to be increased pressure is pressurized by a compressor or pump.
A lot of studies on direct work exchange have been made. Zhou et al. (2011) proposed a problem table method for the work exchange network, and the analysis of the work exchange network of an ammonia plant shows that a lot of utilities could be saved by work exchange network integration. But the optimization of the minimum pressure difference of the network and the match between corresponding work source and sink did not been taken into account. Liu et al. (2014) provided a graphical method for targeting the maximum mechanical energy recovery and the minimum mechanical energy consumption, some auxiliary lines and matching rules are proposed to assist identifying the feasible match. However, not all the streams can exchange work directly. A necessary condition of work exchange directly between a work source and work sink is that, the streams' pressure difference must be greater than the minimum pressure difference Δp_{min}, which is between 5~10 lb/sq.in (Cheng et al,1967). So the direct work exchange is rarely applied in industries.
In process industries, compressors or pumps are widely used to increase fluids' pressure if necessary and expanders are used to generate work for fluids with excess pressure, which is equivalent to the indirect work exchange. The associations among these fluid machineries (compressors or pumps and expanders) might not exist in this kind of indirect work exchange network. Feng and Chen (2012) presented some matching rules between the fluids with excess pressure and those which need to be pumped, for targeting both the system energy performance and the system economical performance. Whether an expander is added could be evaluated by means of the economical critical point at a certain expected payback period.
The theoretical work required by a pressurization stream or recovered from a depressurization stream is constant in a work exchange network no matter which is a direct or indirect one. If some of the theoretical

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work are variables, when there are associations among these fluid machinery, the formed network can be defined as a fluid machinery network. Pumps and water turbines in a circulating water system is just such a fluid machinery network. The theoretical pump work and recoverable power by water turbines differs between each branch in a circulating water system with different combination between main pumps and auxiliary pumps. Equipment should be considered comprehensively rather than separately when designing a fluid machinery network, obviously.

Some work has been done on energy saving of pump networks in a circulating water system. Pettersson and Westerlund (1996) proposed a solution for pump configuration problems. The method separates the problem as a two level optimization problem, in which the low level problems are convex MINLP problems and can globally be solved with existing MINLP codes, while the upper level problem contains nonconvex functions and the minimization task has been formulated as a Binary Separable Programming problem consisting only of binary variables. Sun et al (2014) proposed a novel pump network structure for a cooling water system by adding auxiliary pumps to parallel branch lines, which can provide significant energy savings as the power consumption of the main pumps is reduced. The MINLP model was established with the total cost taken as the objective function. Simulated annealing algorithm is used to solve this model, and a satisfied economic benefit is obtained. Then Sun et al (2015) further presented the thermodynamic model for obtaining the optimal cooler network and the hydraulic model for obtaining the optimal pump network considering the optimization of the two networks simultaneously, to optimize the cooling water system step by step.

Recovering energy by water turbines in circulating water systems has been applied gradually in industrial practices. Yankuang Guizhou Kaiyang Chemical Co., Ltd. employs an external tubular turbine and internal double-impulse turbines to two cooling towers respectively of the No.2 circulating water system (Tang 2016). Qingdao Petrochemical Co. adopted efficient Francis turbines in cooling towers of the circulating water system (Gao and Li,2014). The Francis turbine technology applied in industrial cooling towers has been inducted into the national key technology promotion directory of energy saving and low carbon od China, which describes that the total capacity of renovation by water turbines in cooling towers in China is about 241,570,000 t. This technology will be generalized to 10% in next five years while the total reformable cooling towers in China amounts to 6,000, with 2.4 M TCE of annual saving capacity, 6.34 millions tons of CO_2 of annual reduction capacity, and about 7 billions of total investment. This technology has applied in some enterprises such as Daqing Petrochemical Company, Yangzi Petrochemical company, Jinan Iron and Steel Company, and Nanjing Iron and Steel Company (National Development and Reform Commission,2015).

But up to now literatures relating to integrating the pump network and water turbine network as a whole has not been found yet.

In this paper, to aim at circulating water systems composed of fluid machineries (pumps and water turbines) with the characteristics of interrelations among each other, the concept of fluid machinery networks is proposed. Then based on a superstructure of the fluid machinery network in a circulating water system, a mathematical model to optimize a fluid machinery network is proposed with the annual total cost as the objective function.

2. Structure and superstructure of a fluid machinery network in a circulating water system

2.1 Traditional structure of the fluid machinery network in a circulating water system

A traditional circulating water system setting in a refinery is using the parallel main pump system to guarantee the pressure head of cooling water in all the branches to meet their need, as shown in Figure 1(1), and the fluid machinery network consists of only a main pump system at this time. The main pump lift should meet the pressure head requirement of all coolers'. The branch with coolers which have a smaller demand for pump lift must increase resistance by means of turning down the valves to match the designed flow distribution, as the characteristics of pressure drop are identical to all of the parallel branches (Sun,2014). Both the flowrate and the lift of the main pump system are big, resulting in energy waste due to this kind of network structure and running style.

2.2 Consideration of auxiliary pumps

Sun et al (2014) introduced auxiliary pumps to a pump network aimed at the defect of using main pumps alone. Auxiliary pumps are mainly set in the branches which need higher pressure head relatively to reduce the power consumption of the main pumps, as well as the whole pump network furtherly.

The superstructure of a pump network, as shown in Figure 1(2), is built to determine the position to add auxiliary pumps, with an example of the traditional circulating water system as Figure 1(1). The superstructure of a pump network consists of main pumps and auxiliary pumps, then the optimal combination is determined by the requirement for pressure head of every branch.

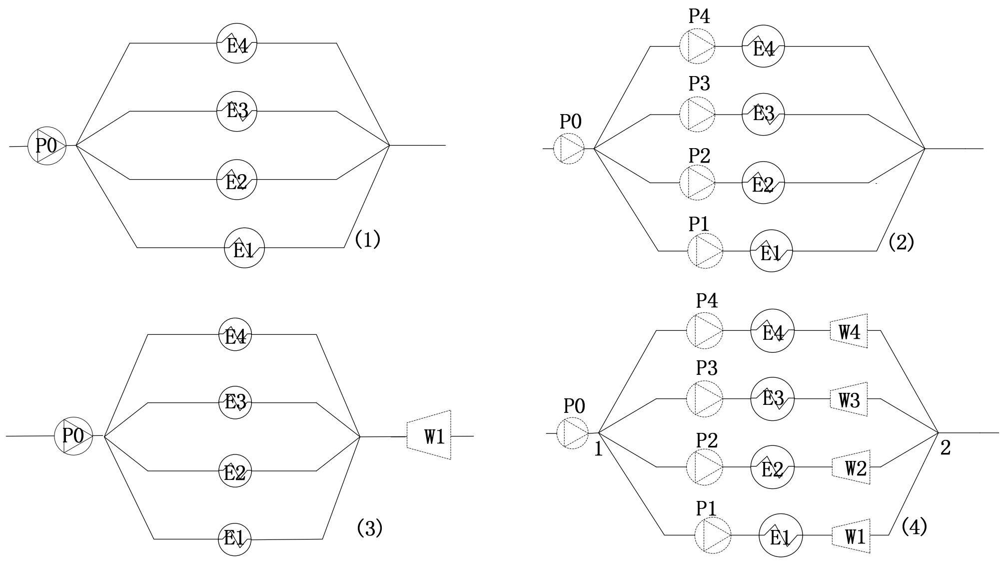

Figure 1: Structures of fluid machinery network

2.3 Usage of water turbines

Optimization of a pump network is to reduce unnecessary energy input from utilities, while optimization of a water turbine network is to recover excess energy in the end of the system. For a traditional pump network without auxiliary pumps, excess energy exists in the circulating water when it is flowing back to the cooling tower if the height of some coolers is much higher than that of the cooling tower. A relief valve is used to reduce the pressure head for this part of excess energy commonly in the traditional system, instead of recovering it. When a water turbine is used to recovery the energy, the structure of the fluid machinery network is shown as Figure 1(3).

When the pump network with auxiliary pumps is applied in a circulating water system, the streams with higher pressure head should be depressurized generally by relief valves for successful converge with all streams, otherwise, partial flow or reflux flow may occur in the pump network (Gao and Feng,2016). A more superior economic performance of the whole fluid machinery network will be obtained if this part of excess energy is recovered through usage of water turbines.

The difference between adding a water turbine in a water turbine network and adding an auxiliary pump in a pump network is that adding an auxiliary pump only subjects to pressure head of circulating water, while adding a water turbine subjects to recoverable power of circulating water, which depends on both pressure head and water quantity flowing in the branch. For a traditional circulating water system, a water turbine should be placed after the converge point of branches if necessary for the pressure head of each branch in the converge point is equal, because a single turbine is obviously more economical than more turbines when recovering the same amount of energy. For a pump network with auxiliary pumps, the pressure head of circulating water in branches with auxiliary pumps is higher than those with no auxiliary pumps because the existence of auxiliary pumps, so that each branch with an auxiliary pump should be taken into consideration respectively when considering setting water turbines, as the pressure head of each branch in the converge point is not equal.

2.4 Superstructure of fluid machinery network in a circulating water system

The optimization of a fluid machinery network in a circulating water system actually is the optimization of both the pump network and water turbine network of the circulating water system simultaneously, and the superstructure of the fluid machinery network is shown in Figure 1(4). It can be seen that a fluid machinery network is considered as the combination of a pump network and water turbine network which have interaction between each other.

A two-step method is put forward in this paper for solving the problem. The structure of the fluid machinery network will be obtained after the optimal pump network and the water turbine network structures are determined in sequence. For the pump network, the flowrate of each branch subjects to the requirement of each cooler in the branch and is a constant value while the minimum input pressure head is determined by the cooler network structure, so the optimization of the pump network is to meet the objective function by reasonable setting the main pump head and each auxiliary pump head. The recoverable power of each branch can be determined when the pump network is confirmed. Based on the optimization objective function, the water turbine network can be determined. So the whole fluid machinery network will be obtained. The functions of a fluid machinery network will focus on not only offering the required energy for the circulating water system but also giving consideration to both energy saving and energy recovery when adding auxiliary pumps for redistributing the pressure head of each branch and water turbines for recovering energy from fluids with excess pressure in the traditional circulating water system.

3. Mathematical model of fluid machinery network in circulating water system

3.1 Objective function

The goal for optimization is to determine the optimal economic combination of pumps and water turbines, so the objective function is the annual total cost consisting of the annual operation cost and annual capital cost (Seider et al,2009).

$$\mathrm{Min}\,TC = OC + AC \tag{1}$$

where TC is annual total cost (\$/y); OC is annual operation cost (\$/y); AC is annual capital cost (\$/y).
The annual operation cost, OC, mainly consists of the electricity consumption of the electric motors driving pumps and electricity recovery by the water turbines, represented by the power consumption P_C of each pump and the power recovery P_R of each water turbine.

$$OC = \Sigma(P_{C,i} - P_{R,i}) \bullet h \bullet e \tag{2}$$

where h denotes the annual operation hours of the fluid machinery network (h), and e is the unit cost of electricity (\$/kWh).
For convenience when calculating the annual capital cost of a fluid machinery network, a straight-line depreciation is applied on the base of total capital cost, CC, with t denoting fixed assets service life (year) and ratio of remaining value equalling 5 %, to obtain the system annual capital cost with Eq(3) (Seider et al,2009).

$$AC = (1 - 5\%) \bullet CC / t \tag{3}$$

The total capital cost of a fluid machinery network includes capital cost of pumps, electric motors, water turbines (Seider et al,2009):

$$CC = CC_{pump} + CC_{motor} + CC_{hy} = \frac{I_{CE}}{I_{CE_{base}}}(\Sigma F_{T,pump,i}F_{M,pump,i}C_{B,pump,i} + \Sigma F_{T,motor,i}C_{B,motor,i} + \Sigma C_{B,hy,j}) \tag{4}$$

where $F_{T,pump}$ and $F_{T,motor}$ denote pump and electric motor type factors, respectively. F_M is pump material factor. $C_{B,pump}$, $C_{B,motor}$ and $C_{B,hy}$ are the base cost of pump, electric motor and water turbine, respectively. I_{CE} and $I_{CE_{base}}$ denote current chemical equipment index and base chemical equipment index.

3.2 Pump related cost

The correlations introduced by Seider et al.(2009) are applied in this paper to calculate the capital cost related to pumps and water turbines. The base cost of pump is shown in Eq(5).

$$C_{B,pump} = \exp\{9.2951 - 0.6019\ln(S) + 0.0519[\ln(S)]^2\} \tag{5}$$

where S is size factor of pump and can be computed from Eq(6).

$$S = Q(H)^{0.5} \tag{6}$$

where Q is the water flowrate through pump in gal/min, and H denotes the pressure head offered by pump in ft.
The power consumption of an electric motor, P_C, can be determined from Eq(7).

$$P_C = \frac{P_T}{\eta_P\eta_M} = \frac{P_B}{\eta_M} = \frac{QH\rho}{33000\eta_P\eta_M} \tag{7}$$

where P_T is the theoretical power of pump, η_P and η_M represent the efficiency of pump and electric motor, respectively.
The cost correlation of an electric motor is shown in Eq(8) (Seider et al,2009).

$$C_{B,motor} = \exp\{5.4866 + 0.13141\ln(P_C) + 0.053255[\ln(P_C)]^2 + 0.028628[\ln(P_C)]^3 - 0.0035549[\ln(P_C)]^4\} \tag{8}$$

3.3 Water turbine related cost

The capital cost formula of a water turbine is shown in Eq(9) (Seider et al,2009).

$$C_{B,hy} = 1100P_R^{0.70} \tag{9}$$

where P_R denotes recoverable power in hp.
The annual recoverable electric benefit is:

$$CR = h \bullet e \bullet \Sigma P_{R,j} \tag{10}$$

The maximum recoverable power by adding a water turbine can be derived from Bernoulli Equation:

$$P_{R,max} = q_m[\frac{(p_1 - p_2)}{\rho} + w_e - w_f] \tag{11}$$

where 1 and 2 represent the separation point and the converge point, respectively, as shown in Figure 1(4). w_e denote the power offered by the pump.
The actually recoverable power by a water turbine can be determined by Eq(12).

$$P_R = P_{R,max} \bullet \eta_{hy} \tag{12}$$

where η_{hy} represents the efficiency of the water turbine.

4. Case Study

The case is extracted from Sun et al (2014), with the original network as shown in Figure 2(1) and the main parameters of pipe lines and pipe fittings as shown in Sun et al (2014). The network structure of the circulating water system is shown in Figure 2(3) when auxiliary pumps are applied in the pump network after optimization. The optimal fluid machinery network of the circulating water system is shown in Figure 2(4) when solving the mathematical model. The height of the cooling tower, z_D, is taken as 15m, the efficiency and the assets service life of water turbine are taken as 0.5 and 10 (The State Council of the People's Republic of China,2007), respectively.
The costs of the four cases in Fig. 2 are shown in Table 1: the original circulating water system Figure 2(1), the system applied a water turbine for recovering energy Figure 2(2), the system after optimization of the pump network by Sun et al (2014) Figure 2(3), and the system after optimization of the fluid machinery network adopting the model in this paper Figure 2(4). Compared with the original circulating water system, the optimization of the water turbine network alone achieves a saving of 0.44×10^6 CNY or 13.58 % for annual total cost, the optimization of the pump network alone achieves a saving of 0.48×10^6 CNY or 14.81 % for annual total cost, and the optimization of the whole fluid machinery network achieves a saving of 0.73×10^6 CNY or 22.53 % for annual total cost with remarkable economic benefits.

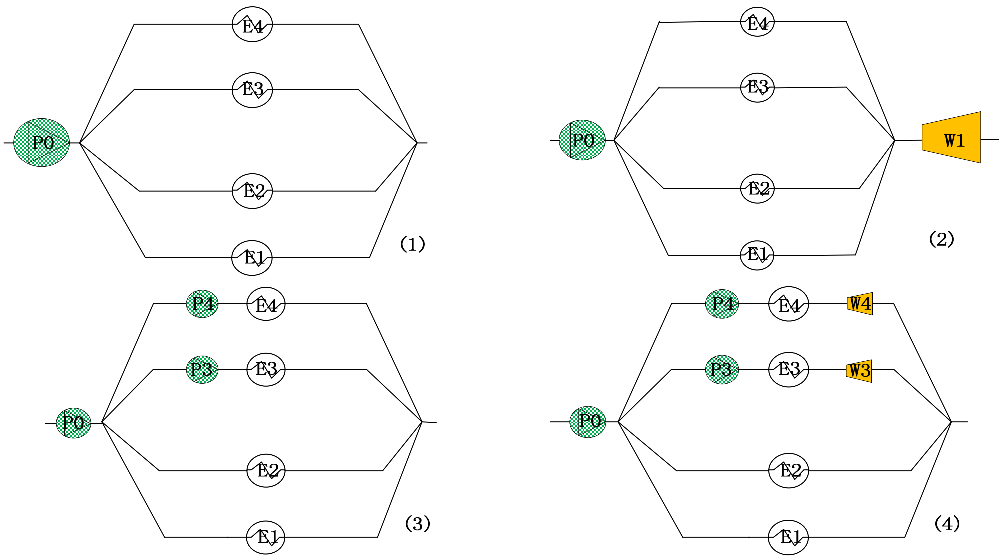

Figure 2: The structures of the fluid machinery network before and after optimization

Table 1: Cost of four cases in circulating water system

Scheme of fluid machinery network	$OC\times10^6$ (CNY/y)	$AC\times10^6$ (CNY/y)	$TC\times10^6$ (CNY/y)
Figure 2(1)	2.52	0.72	3.24
Figure 2(2)	2.04	0.76	2.8
Figure 2(3)	1.94	0.82	2.76
Figure 2(4)	1.66	0.85	2.51

5. Conclusion

In this paper a new concept about a fluid machinery network is proposed, a specific case of which is the combination of the pump network and water turbine network in a circulating water system. For this specific fluid machinery network, a superstructure is established, and a mathematical model of optimization for the fluid machinery network is proposed with the annual total cost as the objective function. A case is taken to validate the feasibility of the model. Compared to applying only water turbines or auxiliary pumps, the optimization of the whole fluid machinery network obtains more remarkable benefits on energy saving and cost saving.

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