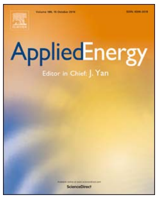
Applied Energy 205 (2017) 847–854

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



# The power target of a fluid machinery network in a circulating water system

Wei Gao, Xiao Feng*

*School of Chemical Engineering and Technology, Xi'an Jiaotong University, Xi'an, Shaanxi Province 710049, China*

## HIGHLIGHTS

- A new kind network, a fluid machinery network is studied.
- The power target of the network can be determined by the proposed model.
- The concept of effective heights of a branch and cooling tower are introduced.
- The necessary condition of a water turbine placement is obtained.

## ARTICLE INFO

*Keywords:*
Fluid machinery network
Power target
Circulating water system
Effective height

## ABSTRACT

A circulating water system is widely used as a cooling system in process industries, and its energy consumption has a great impact on the energy performance of the whole plant. In a circulating water system, the pump network composed of main and auxiliary pumps offers power to the system, while the water turbine network recovers excess energy. A fluid machinery network in the circulating water system is then formed by the pump and water turbine networks. The difference value between the minimum theoretical power requirement of the pump network and the maximum theoretical power recovery by the water turbine network is the power target of the fluid machinery network. The power target is very significant for guiding the energy conservation of a cooling water system, as it means the theoretical limit of the network's energy consumption. In this paper, by analyzing influence factors on the power target in a fluid machinery network, the concept of effective heights of a branch and cooling tower is introduced to obtain the necessary condition of water turbine placement. Then a mathematical model to determine the power target in a fluid machinery network is proposed. A case study is used to validate the applicability of the model finally.

## 1. Introduction

A circulating water system is one of the most important facility systems in process industries, since it provides a vital utility, cooling water, for the operation of many production plants [1]. Pumps are used as power sources in a circulating water system, to deliver circulating water to each cooler of every branch. Of the facility systems, a circulating water system is the largest energy user, consuming 27.2% of the total power used [2].

Traditionally, the circulating water is delivered to each cooler by some main pumps, that is, the pump network is composed of only main pumps in a circulating water system. Such pump network offers the identical pressure head from each pump to every branch pipe in the system, the pressure head of the main pumps should be in accordance with the maximum required by each branch, and valves of those branches with excess pressure head should be turned down, which results in energy waste. If some auxiliary pumps are added to the branches with higher pressure heads, the consumed power can be reduced obviously [3]. In this case, the pump network is composed of main and auxiliary pumps. Comparatively, the pump network composed of main and auxiliary pumps can meet the needs of pressure head for every branch by setting auxiliary pumps, which can reduce energy waste. For a circulating water system with a fixed structure, the pressure head of each parallel branch in the convergence point should be the same when cooling water is returned to the cooling tower. The actual pressure head of each branch is different caused by the auxiliary pumps. The excess energy at the branches with higher pressure head can be recovered by water turbines to improve the energy efficiency of the system, forming a water turbine network.

In a circulating water system, pumps and water turbines interact with each other, forming so-defined hear a fluid machinery network composed of a pump network and a water turbine network. Such a fluid machinery network is similar to an indirect work exchange network, but there is some difference.

---

* Corresponding author.
*E-mail address:* xfeng@xjtu.edu.cn (X. Feng).

http://dx.doi.org/10.1016/j.apenergy.2017.08.024
Received 23 June 2017; Received in revised form 5 August 2017; Accepted 8 August 2017

**Nomenclature**

| | |
|---|---|
| $a$ | flow area in tube side, m$^2$ |
| $A$ | constant related to the pressure head loss in tube side of an exchanger |
| $d$ | inner diameter of tube in exchanger, m |
| $D_i$ | inner diameter of pipe in branch i, m |
| $f_{D,i}$ | frictional factor of pipe |
| $g$ | gravity factor, m/s$^2$ |
| $h_{f_{0-1}}$ | pressure head loss from node 0 to node 1, m |
| $h_{f_E}$ | pressure head loss of exchanger, m |
| $h_{f_{i,line}}$ | pressure head loss of pipe line, m |
| $h_i$ | pressure head requirement in branch i, m |
| $h_{p,i}$ | static pressure head change from node 1 to node 0 in branch i, m |
| $h_{pump}$ | minimum pressure head requirement, m |
| $h_w$ | recoverable pressure head by water turbine, m |
| $H_{B,i}$ | effective height of branch i, m |
| $H_{tower}$ | effective height of cooling tower, m |
| $K_{main,pipe}$ | resistance coefficient of main pipeline |
| $K_E$ | resistance coefficient of exchanger |
| $K_{i,fit}$ | resistance coefficient of pipe fitting in branch i |
| $K_{i,pipe}$ | resistance coefficient of pipe in branch i |
| $L_i$ | length of pipe in branch i, m |
| $n$ | number of tube pass |
| $N$ | tube number of exchanger |
| $p_0$ | pressure in node 0, Pa |
| $p_{1,i}$ | minimum pressure in branch i, Pa |
| $p_b$ | saturation pressure, MPa |
| $P$ | pressure, Pa |
| $P_{total}$ | total power consumption, W |
| $P_{P_i}$ | power requirement of pump in branch i, W |
| $P_{W_i}$ | power recovery by water turbine in branch i, W |
| $q_{m,i}$ | mass flow rate in branch i, kg/s |
| $Re$ | Reynolds number |
| $t$ | temperature, °C |
| $u_{tube}$ | velocity of fluid in tube side, m/s |
| $V_i$ | flow rate in branch i, m$^3$/s |
| $y_i$ | binary variable about the placement of a water turbine in branch i |
| $z_{B,i}$ | actual height of branch i, m |
| $z_{tower}$ | actual height of cooling tower, m |

*Greek letters*

| | |
|---|---|
| $\Delta p_E$ | pressure drop of exchanger, Pa |
| $\Delta p_f$ | friction pressure drop of exchanger tube, Pa |
| $\Delta P_{i,pipe}$ | friction loss of branch i, Pa |
| $\Delta P_{i,fit}$ | local loss of branch i, Pa |
| $\Delta p_r$ | bend back pressure drop, Pa |
| $\Delta p_N$ | pressure drop at the entrance and exit of tube, Pa |
| $\varepsilon$ | absolute roughness, m |
| $\eta_{P_i}$ | pump efficiency in branch i |
| $\eta_{W,i}$ | water turbine efficiency in branch i |
| $\rho$ | water density, kg/m$^3$ |
| $\phi_{dl}$ | correction factor for scaling in the tube side |
| $\phi_i$ | correction factor for viscosity in the tube side |

There are some researches on work exchange network (WEN) in recent years. WEN can be divided into two types: direct and indirect work exchange networks. The former applies a work exchanger to exchange work between the fluid with excess pressure and the fluid needing to be pressurized, directly. The latter recovers work by using turbines and supplies the recovered work to compressors (or pumps).

The direct work exchange network is characterized by higher efficiency. Liu et al. [4] proposed a graphical method to target the maximum energy recovery and the minimum work utility consumption, and some auxiliary lines and matching rules were introduced to identify the feasible match between a work sink and work source. Zhuang et al. [5] proposed a step-wise methodology for synthesis of a direct work exchange network in adiabatic processes involving heat integration, with an extension of transshipment model in isothermal processes. Deng et al. [6] proposed a systematic approach to build a heat-work coupling transfer network. They also [7] introduced a modified state space model to determine intermediate variables and energy exchange positions, which could excellently solve the problem of integrated heat, mass and pressure exchange network optimization.

In the industrial practice, work exchangers are rarely used, so some researches focus on indirect work exchange networks. Razib et al. [8] used the compressor and turbine operating curves to identify high-pressure and low-pressure streams that should be matched for work exchange, and developed a mixed-integer nonlinear programming (MINLP) model to minimize the annual cost. Based on the WEN model proposed by Razib et al. [8] and the HEN (Heat Exchanger Network) model proposed by Yee and Grossmann [9], Onishi et al. [10] introduced a new model for the simultaneous synthesis of the two networks. Several units of single-shaft-turbine-compressor (SSTC), and stand-alone turbines and compressors are used to determine the final network structure with the minimum annual cost as the objective function. Subsequently, Onishi et al. [11] introduced a new multi-objective mathematical model for the optimal work-heat exchanger network (WHEN) synthesis, aiming to enhance environmental and economic performance of the network. Huang and Karimi [12] presented a superstructure-based mixed-integer nonlinear programming (MINLP) model for the synthesis of work-heat exchanger networks (WHEN).

From all the studies on WEN mentioned above, it can be seen that the required work by the fluid needing to be pressurized and the recoverable work from the fluid with excess pressure are all fixed. However, in a fluid machinery network introduced in this paper, these works are variable and need to be determined by optimization. This is the main difference between an indirect work exchanger network and a fluid machinery network. Researches on such fluid machinery network have not been found yet.

There are some research reports on the pump network and water turbines. Zhang et al. [13] proposed a scheduling model of the pump system in a wastewater processing plant to reduce energy consumption. Barán et al. [14] optimized the pump system using four objectives to be minimized: electric cost, maintenance cost, power peak, and level variation in the reservoir. Bonvin et al. [15] proposed a new mathematical programming approach for pump scheduling in a common class of branched networks with one pumping station. Sun et al. [3] proposed a novel pump network structure for a cooling water system by adding auxiliary pumps to some parallel branches, which can obtain significant energy savings as the power consumption of the main pumps is reduced. A MINLP model was established with the total cost being taken as the objective function, and a satisfied economic benefit is obtained. Then Sun et al. [16] further presented the thermodynamic model for obtaining the optimal cooler network and the hydraulic model for obtaining the optimal pump network to optimize of the two networks simultaneously. Researches on water turbines mainly focused on the efficiency of one single turbine. Williamson et al. [17] investigated the operation of a single-jet Turgo turbine at low heads of 3.5 m down to 1 m. Acharya et al. [18] numerically analyzed the characteristics and the fluid flow in a cross-flow hydro turbine and optimized its performance by geometrically modifying several parameters. Efficiency of the