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Experimental analysis of the thermal stability of the pressure control method for a variable flow air-conditioning water system

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ABSTRACT

In this study, we investigate the stability of a pipe network for differential pressure (DP) control of a variable flow air-conditioning chilled water system. First, the hydraulic properties of the pipe network and the thermal properties of the terminal air-conditioning equipment are presented, and the thermal stability is defined to serve as an indicator of the impact that flow regulation in the active branches has on the energy supply capacity of the passive branches. An evaluation indicator of the thermal stability is also developed for online applications. Second, dynamic changes in the hydraulic and thermal properties of the passive branches of a primary pump variable flow dual loop air-conditioning water system were experimentally studied during an active branch regulating valve action stroke cycle using an uncontrolled hydraulic pump, constant DP control and variable DP set-point control. The feasibility and energy savings of various DP control strategies were evaluated in terms of the thermal stability and energy savings for hydraulic pumps. The results show that using a variable DP set-point control strategy produced significant energy savings; however, the thermal stability must be considered when setting the step size in adjusting the DP set-point.

1. Introduction

Adjusting the pump speed based on the differential pressure (DP) to change the chilled water flow rate has been widely used as a control method in the optimization and energy saving retrofit of variable flow air conditioning systems. This DP control strategy can either be a constant DP set-point strategy or a variable DP set-point strategy.

Wang et al. [1] explored the energy savings of DP control strategies and developed an optimal control method for the water pump speed for an indirect seawater cooling system: the DP between the supply and return water pipes of the primary cooling water loop was chosen as the optimization variable and a derivative approach was used. Using this DP set-point method in applications has been shown to reduce the total power consumption by up to 10% and save at least 5% in energy under other operating conditions. Moore et al. [2] optimized the DP set-point based on the terminal valve position signal to ensure that there was at least one fully open control valve; applying this strategy to control a two-stage pump system resulted in significant energy savings. Ma et al. [3] developed pressure drop models for water networks and optimized the DP set-point by monitoring the opening of the terminal control valve and the chilled water flow rate signal. Simulations showed that this strategy produced energy savings from 12% to 32%.

Jin et al. [4] studied DP control strategy optimization and investigated the effect of combining temperature control strategies with a DP control strategy for a variable water volume system using a typical two-stage pump. The results showed that the best strategy optimized the temperature set-point together with the DP set-point. Zhao et al. [5] investigated the control of parallel variable-speed hydraulic pumps and developed a method that could be implemented online to optimize the allocation of parallel variable-speed hydraulic pumps and the number of operating units. Wang et al. [6] developed a class of adaptive control methods based on DP control that could be used for online control applications and effectively improved the robustness of the control system.

In addition to concerns about the energy consumption and energy efficiency of variable flow air conditioning systems, stability problems also affect variable flow adjustment: adjusting the valve opening of the user branch to change the chilled water flow rate of a cooling coil in an air conditioning unit changes the flow distribution in all of the branches of the water pipe network during every period over which the load changes; i.e., actively changing the flow

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rate of a branch produces passive changes in the flow rates of all of the other branches. A passive change that is too large results in poor stability of the pipe network. Jiang [7] quantitatively evaluated the pipe network stability, which was then used to choose adjustment strategies and control algorithms for a variable flow air conditioning water system.

Except several studies [8–10] focusing on optimal control method to improve grid stability of power systems, some scholars investigated the complex performance of pipe network in district heating systems. Yabanova et al. [11] developed ANN pipe network models of geothermal district heating systems and presented an energy efficient control strategy that has more comfortable thermal environments. Stevanovic et al. [12] predicted thermal transients in district heating systems by an energy efficient managing method for heating plant and pump stations, the study can also predicted the hydraulic characteristics involving pressure and flow rates within the complex pipe networks. Tol et al. [13] considered several design issues involving dimensioning of piping networks and network layouts of low-energy district heating system by applying pipe segments computation method.

Very few studies to date have addressed pipe network stability issues associated with DP control in building energy system especially for chilled water system. Sun et al. [14] proposed a multiplexed optimization scheme for air-conditioning system that updated the optimal decision variables sequentially, the presented method was verified to have superior system operation stability (not pipe network stability) and more energy saving amount than GA optimization method.

According to above literature reviews, for building air-conditioning systems, previous research has mostly focused on the energy efficiency [1–4,14] or online optimal strategies [5,6,15] of the HVAC water system, few studies have optimized the DP control method for a variable flow system while considering the pipe network stability in setting the optimization goals.

Researchers in mainland China [16–19] have used pipe network stability evaluation indicators to explore how changing the pipe network layout and control methods for heating and air conditioning systems affects stability; these results have subsequently been used to optimize the variable flow control strategy and the system design. However, in these studies, stability was only investigated from a hydraulics perspective and the impact of variable flow adjustment on the stability of the energy supply capacity for each user was not considered.

From an energy supply perspective, the flow changes in the passive branches certainly affect the heating (cooling) performance of terminal air-conditioning equipment. For example, in air conditioning units that use the supply air temperature as a control variable, the control loop regulates the branch water volume based on the supply air temperature set-point. Thus, variations in the water volume produce fluctuations in the supply air temperature over a certain range, thereby affecting the heating (cooling) capacity of the equipment. Therefore, the concept of hydraulic stability can be further extended to include the stability of the air conditioning equipment heating (cooling) capacity, which is defined as thermal stability in this paper.

Thermal stability issues should be carefully considered in a DP set-point control strategy. Such issues are significant because of the strong coupling between the hydraulic and thermal properties of various branches during the DP control process, i.e., DP set-point changes affect the energy supply of the most favorable thermal loops, which has the maximum AHU supply air temperature deviation with its set-point out of all branches. Various DP set-point affects pressure distribution of each node of pipe network, which is manifested in the valve position of the branch regulating valve: for those branches with increase differential pressure while their chilled water flow supply demand remain the same, their valve position turns out to be lower to meet the control need of supply air temperature, lower valve position will cause hydraulic pumps to consume more energy, whereas branches with a higher valve position that possibly has lower differential pressure during the DP set-point change, then their flow supply capacity possibly could not satisfy their increasing air-conditioning load, these branches may become the most unfavorable thermal loop in the next time period, thus requiring further optimization of the DP set-point in the next reset period, which will bring more unstable effects on the pipe network system and control loops of all branches. This back and forth cycling, together with random variations in the user load, can polarize the branch energy supply capacities such that the valve openings of some branches become increasingly larger and sensitized to pressure fluctuations in the system; the deteriorating adjustability thus worsens the anti-external interference capability. At the same time, the valve openings of the other branches become increasingly smaller; thus, these branches cause more energy to be consumed through water pumping, thereby increasing the system resistance and reducing the energy savings of the optimal DP set-point.

In summary, we investigate a typical variable flow air-conditioning water system and develop the concept of the thermal stability and evaluation indicators of thermal stability that can be used in online applications; we subsequently analyze dynamic changes in the hydraulic stability and the thermal stability in an actual air-conditioning water system and use the results to determine the feasibility of several classes of DP control strategies.

2. Defining thermal stability

2.1. Defining hydraulic stability

The pipe network of an air-conditioning water system with an arbitrary topological structure can be described by Eq. (1):

$$\begin{cases} AG = 0 \\ A^{\mathrm{T}}P = I\cdot S \bullet G \bullet |G| + \Delta Z - \Delta H \end{cases} \tag{1}$$

where $A = [a_{ij}]$ denotes the basic correlation matrix of the pipe network, and the values of a_{ij} are given by Eq. (2). If the pipe network consists of $n+1$ nodes and m branches, A is a $n \times m$ matrix; G is a column vector of order m that represents the flow rates of various branches, i.e., $(G_1,G_2,\ldots,G_m)^{\mathrm{T}}$; P is a column vector of order n that represents the pressures at the n nodes, i.e., $(p_1,p_2,\ldots,p_n)^{\mathrm{T}}$; I is a unit matrix of order m that convert $I \bullet S \bullet G \bullet |.G|.$ to a column vector of order m; S is a column vector of order m that represents the various branch impedances, which evaluates the integrated effect of local pressure loss and friction drag pressure loss of each branch with the unit s^2/m^5, i.e., $(S_1,S_2,\ldots,S_m)^{\mathrm{T}}$; … is the dot product operator; ΔZ is a column vector of order m that represents the rises in the water head in the branches, i.e., $(\Delta Z_1,\Delta Z_2,\ldots,\Delta Z_m)^{\mathrm{T}}$; ΔH is a column vector of order m that represents the pump head in the branches, i.e., $(\Delta H_1,\Delta H_2,\ldots,\Delta H_m)^{\mathrm{T}}$. The pressure at each node and the flow rate in each branch are functions of the impedance (S).

$$a_{ij} = \begin{cases} 1, & \text{fluid at node } i \text{ enters branch } j \\ -1, & \text{fluid in branch } j \text{ flows into node } i \\ 0, & \text{no direct connection between node } i \text{ and branch } j \end{cases} \tag{2}$$

A $k \times m$ matrix, denoted by U, represents the k branches that must be examined out of m branches. The elements of U are either