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Evaluation of terminal coupling and its effect on the total delta-T of chilled water systems with fan coil units

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ABSTRACT

Most chilled water circulation systems with fan coil units suffer from a low temperature differential between the supplied and returned water. On-site investigation shows that the relationship between total cooling consumption and total water flow rate of real systems is different from that of single coil units mainly as a result of the interaction of the terminals. When certain terminals close their water valves, the other terminals have higher water flow rates and lower water delta-T values. This study presents a quantitative analysis of terminal coupling and its effect on system characteristics. System coupling factor is used as an indicator to describe the total degree of fan coil unit coupling in a system. To observe the effect of the system coupling factor, a dynamic simulation platform is constructed and simulation tests are performed. The results show that the higher the system coupling factor is, the larger is the total delta-T loss under partial load conditions. Based on this indicator, certain problems of system design can be reviewed from the perspective of terminal coupling.

1. Introduction

Fan coil units (FCUs) are widely used in office buildings, hotels, shopping malls, and other buildings. The most common problem in chilled water circulation systems with FCUs is the low delta-T syndrome, where the temperature differential between the water supplied and returned from the terminals, which is referred to as the total delta-T, is significantly lower than its designed value, particularly under partial load conditions. This condition wastes pump power and decreases system efficiency.

One reason for the low delta-T syndrome in chilled water system is the degradation of the heat transfer performance of the coils [1,2], often as a result of increased coil fouling, low in-coil air temperature caused by fresh air, decreased air volumetric flow rate, high supplied water temperature caused by a deficit flow in the bypass line, and so on.

Another reason is the coupling of FCUs [3]. FCUs use on-off controlled water valves. Within a system, when certain FCUs shut down their water valves, the chilled water flow rates of the other FCUs increase and the water delta-T of the other FCUs decrease, which results in lower total delta-T.

Although the coupling of terminals significantly affects total delta-T performance, a quantitative evaluation is lacking in the literature, which limits the current understanding of the characteristics of chilled water circulation systems with FCUs. As a result, certain significant topics of system design have not been studied from the perspective of coupling. For instance, the use of balance valves is disputed in a number of literatures [4–7], but an analysis on its effect on system coupling seems lacking.

This study presents a quantitative analysis of terminal coupling. An indicator is used to evaluate the total degree of coupling within the system. To observe the effects of coupling degree on the system characteristics, a simulation analysis is carried out based on a dynamic simulation platform of a chilled water circulation system.

2. Characteristics of real chilled water circulation systems with FCUs

On-site investigation shows the characteristics of the real chilled water circulation systems with FCUs. Hourly data, including the total cooling consumption and total chilled water flow rate, from two buildings has been collected separately over one year. $\bar{Q}$ is defined as the ratio of cooling consumption to its designed value, and $\overline{q_w}$ as the ratio of water flow rate to its designed value. Fig. 1 shows the real $\bar{Q}$–$\bar{q}_w$ curves of the two systems. The building in Fig. 1(a) is an office building adopting primary pump configuration, while the building in Fig. 1(b) is a shopping center with primary–secondary pump configuration. The water delta-T of each point in Fig. 1 is proportional to the slope of the line connecting the point and the origin. Fig. 1 also shows the $\bar{Q}$–$\bar{q}_w$ curve of a single coil.

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Nomenclature

Symbols

A	incidence matrix
Ar	cross-sectional area, m^2
B_f	fundamental circuit matrix
C_p	specific heat capacity, J/(kg K)
DH	pump head, Pa
F	heat transfer area, m^2
Hz	frequency, Hz
K	heat transfer coefficient, W/(m^2 K)
L	perimeter, m
Q	cooling or heating energy, W
$\bar{Q}$	relative cooling energy
S	resistance coefficient, Pa/(m^3/s)^2
V	volume, m^3
n	operating number
q	volumetric flow rate, m^3/s
$\bar{q}$	relative volumetric flow rate
t	temperature, °C
ΔP	pressure differential, Pa
Δt	temperature differential, K
η	efficiency
ρ	density, kg/m^3
τ	time, s

Subscripts

a	air
av	average
de	design
eq	equipment
ev	environment air
g	heat gain
hu	human
in	in-coil
$inside$	inside
iw	inner wall
ob	measurement object
out	out-coil
$outside$	outside
ow	outer wall
pu	pump
ra	room air
$rated$	rated
me	metal
v	vector
va	valve
w	water

The $\bar{Q}$–$\bar{q}_w$ curves of real systems exhibit two characteristics. First, the total delta-T is always lower than the designed value. Second, according to the single coil curve, the water delta-T increases when the cooling consumption decreases. On the contrary, according to the $\bar{Q}$–$\bar{q}_w$ curves of real systems, the total delta-T decreases as cooling load decreases.

3. Analysis of the characteristics of real systems

In a chilled water circulation system, hundreds of FCUs typically exist. FCUs maintain room air temperature by means of on-off controlled water valves. A valve is turned on when the room air temperature exceeds its upper limit, and shut down when the room air temperature drops below its lower limit. The terminal control loops are coupled hydraulically. When certain FCUs shut down their valves, these actions push water to other FCUs, which increase the water flow rates of latter FCUs. When the building load decreases, more FCUs close their valves, and the water flow rates of the FCUs with open valves increase, resulting in lower water delta-T. The total water delta-T is then determined by the FCUs with open valves. Therefore, the lower the building load is, the lower the total delta-T is.

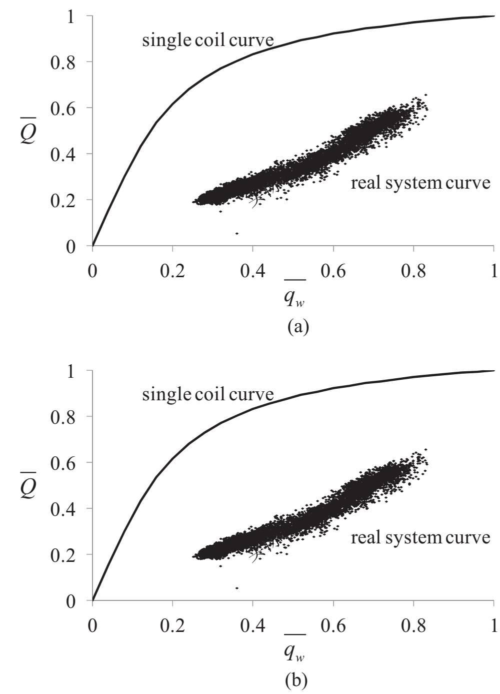

Fig. 1. Characteristics of real chilled water circulation systems. (a) Real system 1. (b) Real system 2.

4. System coupling factor

4.1. Definition of the system coupling factor

The preceding analysis shows that the degree of terminal coupling is a key factor that affects the system. Different degrees of terminal coupling result in different system $\bar{Q}$–$\bar{q}_w$ curves. This study presents an indicator, the system coupling factor, to quantitatively evaluate the comprehensive coupling degree of terminals within a system.

In a system with n terminals, when terminal i opens its water valve and other terminals also open the water valves, the sum of water flow rates of other terminals is defined as $q_{w,on,other}(i)$. When terminal i shuts down its water valve and other terminals keep the water valves open, the sum of water flow rates of other terminals is defined as $q_{w,off,other}(i)$. The influence of terminal i on other terminals can be represented by the terminal influence factor $\beta(i)$, as defined in Eq. (1), showing the relative increment of water flow rates of other terminals.

$$\beta(i) = \frac{q_{w,off,other}(i) - q_{w,on,other}(i)}{q_{w,on,other}(i)} \quad (1)$$

The system coupling factor Ω is defined as the average value of all terminal influence factors, as seen in Eq. (2). This factor represents the degree of comprehensive terminal coupling in a system.

$$\Omega = \frac{\sum_{i=1}^{n} \beta(i)}{n} \quad (2)$$