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EMULATION-BASED OPTIMAL CONTROL OF CHILLER PLANTS

Zhizhong Huang
Sino-German College of Applied Sciences, Tongji University
Shanghai, China

Yiqun Pan
Sino-German College of Applied Sciences, Tongji University
Shanghai, China

Gang Wu
Weldtech Technology Co., Ltd.
Shangai, China

ABSTRACT

Chiller plants of HVAC systems usually operate in part-load conditions during most time of a year. Energy efficiency (i.e. energy input ratio, EIR) of chiller plant components such as chillers, pumps, and cooling towers are the functions of part-load ratio (PLR) and other variables. However, different chiller plant components have different functions of EIR to PLR and don't reach their respective peaks at the same part-load ratio. Based on this fact, there are possibilities that overall efficiency of a chiller plant can be improved to and maintained at the maximum via optimal control of operating numbers and set-points of various plant components at various part-load ratios.

An emulation-based optimal control strategy for chiller plants is introduced in the paper. The main idea of this control strategy is to set up a virtual chiller plant as a mirror of a real system. The virtual system is composed of mathematical models that are obtained through theoretical derivation, numerical calculation or off-line test. These models can emulate energy performances of the physical components in the real system. An optimization algorithm is first run on the virtual system to search for an optimal combination of the operating number and set-points of various components to achieve the highest overall efficiency of a chiller plant. An objective function of the optimization algorithm is the overall efficiency of a chiller plant, having real-time cooling load and meteorological data as inputs, and energy and mass balance and component capacities and restrictions as constraint conditions. Once an optimal combination is identified, it will be used to control the real system operation.

A mockup system has been installed and operated in a 50,000 m^2 office building in Shanghai, China in order to test and verify the optimal control strategy. Preliminary testing results show that the annual overall energy efficiency of the chiller plant (with constant speed centrifugal chillers) is from 0.7 kW/Ton to 0.75 kW/Ton, about 25% less than that of the same plant controlled by normal strategy.

INTRODUCTION

In typical commercial buildings chiller plants consume a significant amount of energy. Usually a chiller plant consumes 40% ~ 50% of total HVAC system energy use or in equivalence 20% of whole building energy consumption. So improvement of chiller plant energy performance s usually means a great opportunity for energy saving of air conditioning systems in buildings.

Many research works have developed in this field in recent years. T. Hartman [1] raised a new approach to HVAC control called "Demand-based Control". The system is operated using the network capacity of modern building control systems. Combining variable-speed-drive equipment with network-enabled demand-based-control technologies it can make simpler, smaller, and lower-cost building energy systems that operate as much as 30% to 50% more efficiently than conventional system configurations with the same basic HVAC component efficiencies. T. Hartman [2] also raised "Equal Marginal Performance Principle (EMPP)" which states that the energy performance of any system operating with multiple modulating components is optimized when the change in system output (called the marginal system output) per unit energy input is the same for all individual components in the system. The EMPP can help optimize sizing and design criteria for full load design conditions as well as usefully applied to optimize operation of HVAC systems at part load conditions using demand based control. F.W. Yu and K.T. Chan [3] introduced a method of how to apply optimum condensing temperature control and variable chilled water flow to increase the coefficient of performance (COP) of air cooled centrifugal chillers. A thermodynamic model for chillers was developed and validated using a wide range of operating data and specifications. The model considers real process phenomena, including capacity control by the inlet guide vanes of the compressor and an algorithm to determine the number and speed of condenser fans staged based on a set-point of condensing temperature. Based on the validated model, it was found that optimizing the control of condensing temperature and varying evaporator's chilled water flow rate enable the COP to increase by 0.8% to 191.7%, depending on load and ambient conditions. Lu Lu et al. [4] presented global optimization technologies for overall heating, ventilating and air conditioning (HVAC) systems. The objective function of global optimization and constraints are formulated based on mathematical models of the major components. According to characteristics of the operating components, the complicated original optimization problem for overall HVAC systems is transformed and simplified into a compact form ready for optimization.

The efficiency of a chiller plant is mainly influenced by three factors: equipment efficiency, system configuration, and control sequence. During most time of a year a chiller plant runs under part-load conditions because its cooling capacity is designed according to building peak-load that occurs under extreme conditions for only hours through a year. Under part-load conditions energy efficiency of chiller plant components, e.g. chillers, pumps, and cooling towers, etc., are functions of part-load ratio (PLR) and other variables, and peak efficiency of each component doesn't occur at the same PLR. This means that it is possible to achieve highest overall energy efficiency of chiller plant by carefully selecting different PLR for different components.

There are many methods to find out the highest overall efficiency but their essentials are common --- how to calculate the efficiency of each component under different PLRs and other conditions. In this paper an emulation-based method is introduced to find out its applicability for optimizing chiller plant operation. A schematic diagram of typical water-cooled chiller plant with primary-secondary pumps is shown in Fig. 1. The main idea of introduced optimization method is to build up and run a virtual system as a mirror of a real system in main control computer. The virtual system consists of energy efficiency mathematical models of chiller plant components, and it calculates different overall chiller plant efficiency under a variety of real cooling-load and combinations of number of active equipment and set-points of operating parameters (e.g. supply chilled water temperature, chilled and condenser water pump speed, etc.). A global optimization algorithm will be executed on the virtual system to search the highest overall efficiency of whole chiller plant under the latest cooling-load, and the correspondent combination of numbers of active equipment and set-points of operating parameters will be applied to control and regulate the real system operation. Although it requires support of powerful computation capability, this method can ensure a chiller plant to work near the highest efficiency point all the time.

EQUIPMENT MODELS

In a typical water-cooled chiller plant there are three main types of equipment: chillers, pumps, and cooling towers. In order to conduct emulation, energy models of above equipment shall be built.

There are different ways to build equipment energy models. Some models are based on physical principals and built by solving complicated differential equations, but some are built by regression methods based on data from catalogues or on-site measurement.

As it is difficult to adopt the same method to build models for different equipment in chiller plant, authors at last adopt different methods to construct models of chiller plant components.

1. Chillers

There are many researches on chiller models especially centrifugal ones, and these models can be roughly divided into two main types: physical models and regression models. Here a generally acknowledged chiller model [5] is adopted:

$$P_{chiller} = Q_{nom} \cdot COP_{nom} \cdot PLR_{adj} \cdot TEMP_{adj} \tag{1}$$

$$PLR_{adj} = a_0 + a_1\left(\frac{Q_{chiller}}{Q_{nom}}\right) + a_2\left(\frac{Q_{chiller}}{Q_{nom}}\right)^2 \tag{2}$$

$$\begin{aligned} TEMP_{adj} = b_0 + b_1 T_{CHWS} + b_2 T_{CHWS}^2 + b_3 T_{CWS} + \\ b_4 T_{CWS}^2 + b_5 T_{CHWS} \cdot T_{CWS} \end{aligned} \tag{3}$$

where:

$P_{chiller}$: power consumption of chiller;

Q_{nom}: nominal cooling capacity of chiller;

COP_{nom}: nominal coefficient of performance of chiller;

PLR_{adj}: part load ratio adjustment factor of chiller;

$TEMP_{adj}$: temperature adjustment factor of chiller;

$Q_{chiller}$: real cooling capacity provided by chiller;

T_{CHWS}: temperature of chilled water supply;

T_{CWS}: temperature of condenser water supply.

For a multiple chiller system the power consumed by chillers is:

$$P_{chiller} = \sum_{i=1}^{n} Q_{nom,i} \cdot COP_{nom,i} \cdot PLR_{adj,i} \cdot TEMP_{adj,i} \tag{4}$$

where:

n: the number of operating chillers.

2. Pumps

In chiller plant pumps run under two different operating conditions: constant and variable head. Generally speaking primary and condenser water pumps operate under variable head conditions but secondary pumps operate under constant head conditions. Two models are required to describe the two operating conditions. Theoretically the power consumed by pumps operating under variable head conditions can be described as:

$$P_{pump} = \frac{kQ_w^{\ 3} + H_{st.w} Q_w}{\eta_p \eta_c \eta_m} + P_{VFD} \tag{5}$$

where:

P_{pump}: pump power consumption;

k: coefficient related with pipe resistance characteristics

Q_w: flow rate;

$H_{st.w}$: static head (in open-type system only);

η_p: pump efficiency;

η_c: transmission efficiency;

η_m: motor efficiency;

P_{VFD}: power consumption of variable frequency driver.

And the power consumed by the pumps operating in constant head condition will be:

$$P_{pump} = \frac{H_w Q_w + H_{st.w} Q_w}{\eta_p \eta_c \eta_m} + P_{VFD} \tag{6}$$

where:

H_w: operating head of pump.

Unfortunately it is difficult to adopt these pump models mentioned above to real systems because some parameters such as k, η_p, η_c and η_m are not constants but variables of PLR and could hardly be determined, so authors modify these expressions for easier engineering application. For pumps operating under variable head conditions, the power consumption expression of pump is modified to:

$$P_{pump} = \sum_{i=0}^{m} c_i Q_w^i \tag{7}$$

And for the pumps running under constant head conditions the power consumption expression of pump is modified to:

$$P_{pump} = \sum_{j=0}^{n} d_j Q_w^j \tag{8}$$

where c_i and d_j are coefficients and determined by regression method on the basis of on-site measured data; m and n are various depending on pump type and water loop structure and usually less than or equal 4.

3. Cooling-towers

Mass and heat transfer occur simultaneously in a cooling tower, and these transfer processes are affected by many factors such as water flow rate, air flow rate, ambient wet bulb temperature, heat extraction rate, etc. Thus cooling-tower modeling is more difficult than any other equipment in a chiller plant. Authors compared calculation results of existing cooling-tower models including Merkel's model, Effectiveness-NTU method, Stoecker's model, etc. to on-site measured data and concluded that none of them are accurate enough for emulation and optimization especially under low condenser water flow and low ambient temperature conditions. After further research a cooling-tower model introduced by Guang-Yu Jin et al. [6] is finally adopted, and adjustments and modifications are also made to it:

$$Q_{rej} = \frac{c_1 m_w^{c_3}}{1 + c_2 \left(\frac{m_w}{m_a} \right)^{c_3}} (T_{CWS} - T_{wb,i}) \tag{9}$$

where:

Q_{rej}: heat rejection rate of a cooling tower;

m_w: mass flow rate of condenser water;

m_a: mass flow rate of air;

T_{CWS}: condenser water supply temperature

$T_{wb,i}$: wet-bulb temperature of ambient air;

And the coefficients c_1, c_2 and c_3 can be determined by an objective function as follows:

MIN F ($[c_1, c_2, c_3]^T$)

$$= \text{MIN} \sum_{i=1}^{N} \left(\frac{c_1 m_w^{c_3}}{1 + c_2 \left(\frac{m_w}{m_a} \right)^{c_3}} (T_{CWS} - T_{wb,i}) - Q_{rej,i} \right)^2 \tag{10}$$

Detailed procedures may refer to the original text.

OPTIMIZATION STRATAGY

After the virtual system setup a global optimization algorithm will be executed to find out an operation condition with the highest overall efficiency of chiller plant. Input parameters to the global optimization include real-time cooling load and meteorological data. At the same time some restrictions should be taken notice. Firstly all components in a chiller plant have their own limited capacity and operating number Secondly the components in a chiller plant are connected each other and operates in a coordinated manner, e.g. chillers, pumps, and cooling-towers must operate together to produce refrigerating capacity. Mass and energy balance are restrictions of the global optimization algorithm. In operation chiller condenser water flow should be the same as that condenser water pump flow and cooling-tower water flow, and heat extracted by cooling-towers should roughly equal the sum of cooling load and chiller electrical power.

When optimization begins the algorithm will detect real-time cooling load and meteorological data and take them as input conditions, take restrictions mentioned above as constraint conditions, take overall efficiency of the whole chiller plant as an objective function, and take the maximum of objective function as an optimization goal. An evolutionary operation method is adopted to search for the best combination of operating numbers of different components and set-points of operating parameters according to the emulation results from the virtual system. Once the best combination is identified during the search operating numbers of different components and set-points of operating parameters will be applied to the real system to achieve the maximum energy saving. A block diagram is shown in Fig. 2.

The real optimization control system with global optimization strategy has a two-layer structure. Upper layer is an industrial control computer to run globe optimization algorithm and the lower layer is composed of PLC modules. The optimization algorithm is actually a "set-point generator" in whole control system. It determines real-time operating parameters of all equipment in a chiller plant, i.e. the number of operating equipment and set-points of operating parameters. PLCs execute equipment control according to the optimization results.

To realize the objective of global optimization a certain hybrid evolutionary operation method is adopted in the strategy to obtain a balance between complexity of computation and computing time. At the same time, a dynamic on-line correction algorithm is also adopted to correct equipment model errors in operation.

TEST RESULTS

A mockup system has been installed and operated in a chiller plant of a 50,000 m^2 office building in Shanghai, China in order to test and verify savings resulted from the optimal control strategy. The design cooling load of the building is about 6,000kW. There are four water-cooled chillers (three for duty and one for standby) installed in the chiller plant. The chilled water loop is a typical primary-secondary pump system with five primary chilled water pumps (4+1) and three secondary chilled water pumps (2+1). There are five condenser water pumps (4+1) and four dual-speed cooling towers in the condenser water loop. Measurement and verification on energy saving resulted from the global optimization was done in May

2010 by a third party who is a local authority on M&V activities. Two adjacent normal weekdays with almost the same outdoor air enthalpy (shown in Fig. 3) were chosen, and the chiller plant was operated in non-optimization and global optimization mode for comparison. The result of minute-by-minute input power of the overall chiller plant is compared and shown in Fig. 4, and energy consumption breakdown is shown in Fig. 5.

The measured results show that when the chiller plant is operated in global optimization mode the energy consumption of each component is reduced significantly compared to the non-optimization mode. The total energy consumption of the chiller plant under global optimization is reduced by 26.1% compared to the non-optimization operation.

CONCLUSION

An emulation-based optimal control strategy for HVAC chiller plant is introduced and discussed in the paper.

1. Various chiller plant components have different functions of energy efficiency to part-load ratio and do not reach their respective peaks at the same part-load ratio. Based on this fact, it is possible that the overall efficiency of a chiller plant be improved and maintained at the highest via optimal control of operating number and set-points of various chiller plant components at various part-load ratios.

2. The main idea of emulation-based optimal control strategy for chiller plants to set up a virtual chiller plant as a mirror of a real system. The virtual system is composed of mathematical models obtained through theoretical derivation, numerical calculation or off-line test.

3. The global optimization algorithm takes real-time cooling load and meteorological data as inputs, takes equipment and system restrictions described above as constraints, takes the overall efficiency of whole chiller plant as an objective function, and takes the maximum of objective function as optimization goal to search for the best combination of operating number of different components and set-points of operating parameters according to emulation results from virtual system.

4. A mockup system has been installed and operated, and its measured results show that when the chiller plant is operated in global optimization mode energy consumption of the overall chiller plant is reduced by 26.1% compared to the non-optimization operation.

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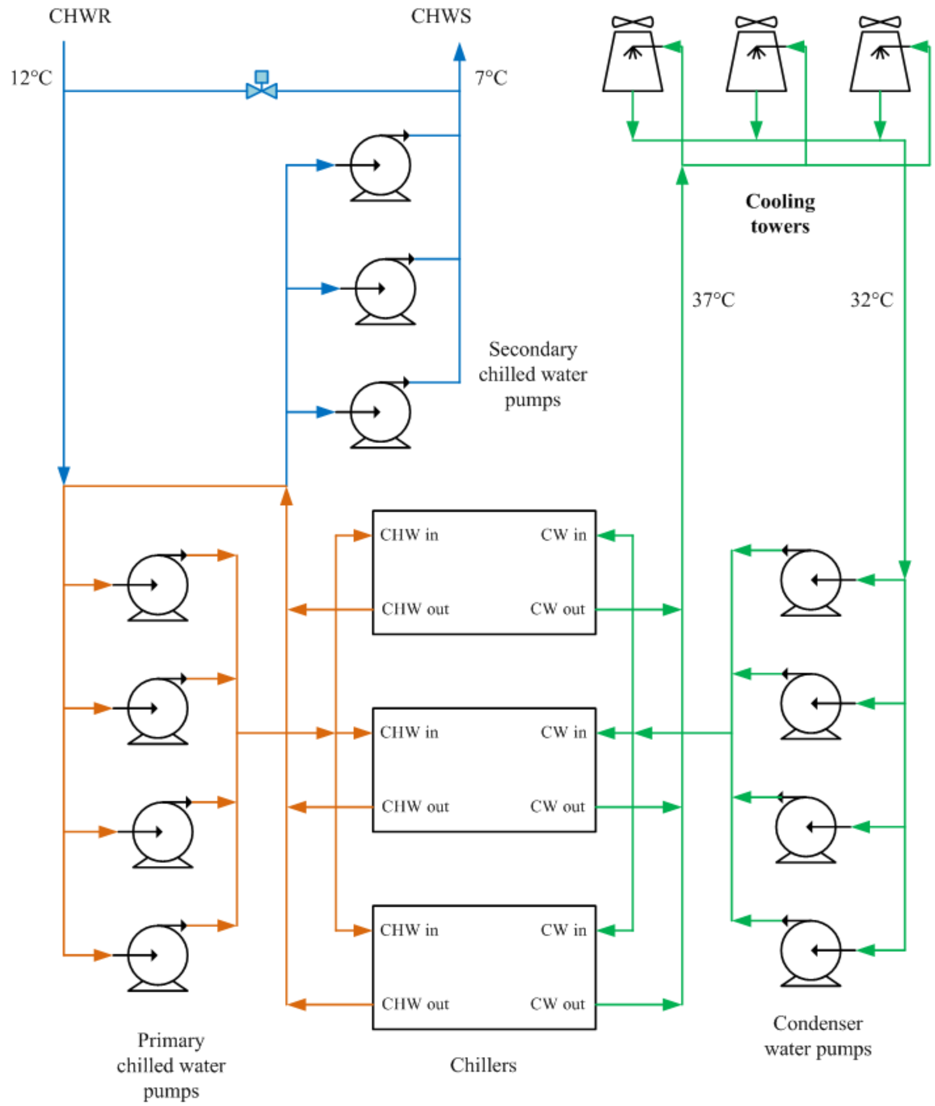

Fig. 1: Chiller plant scheme diagram

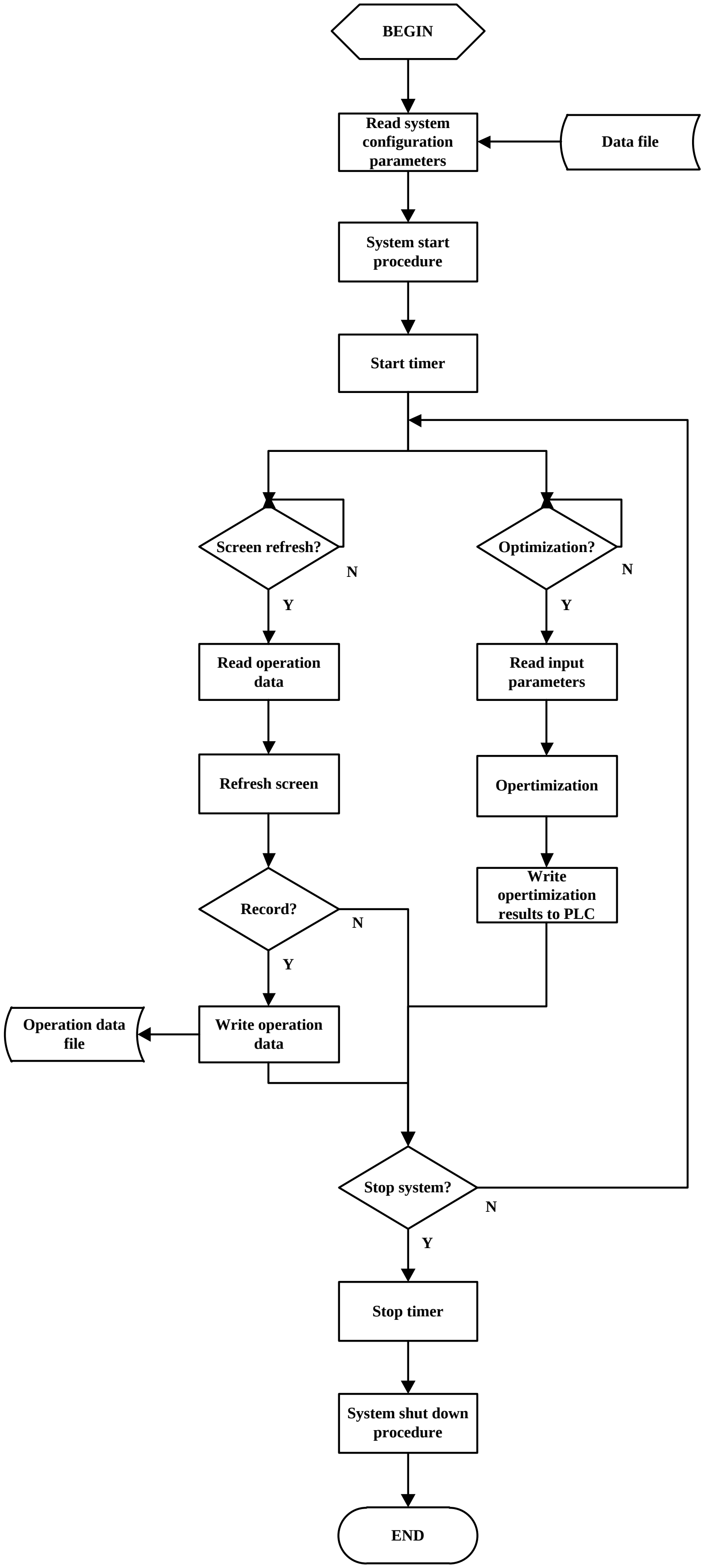

Fig. 2: Block diagram of global optimization strategy

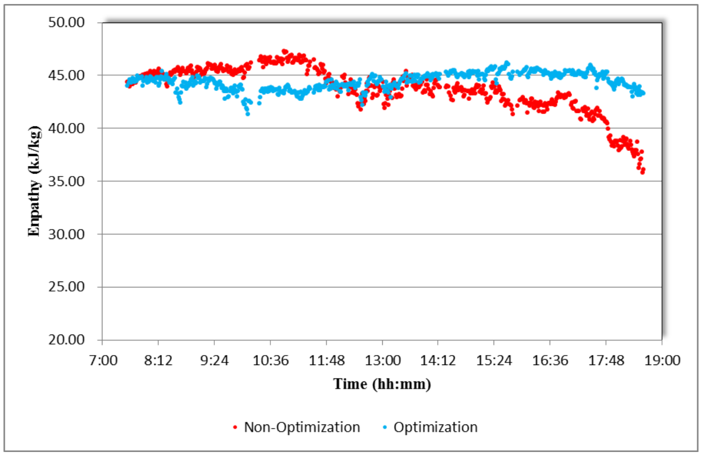

Fig. 3: Outdoor air empathy of test days

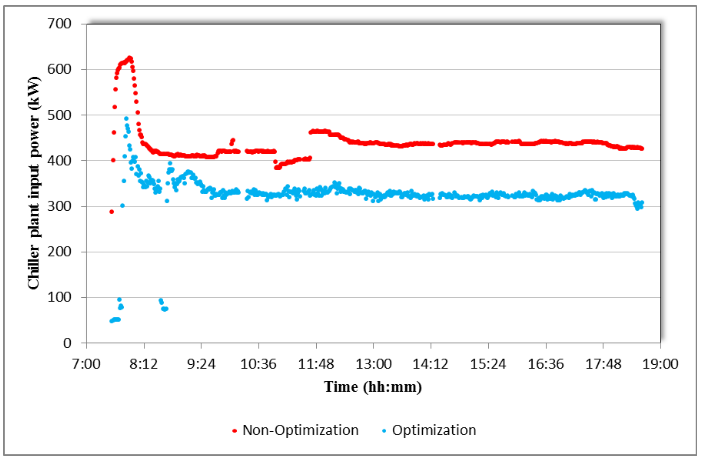

Fig. 4: Chiller plant input power

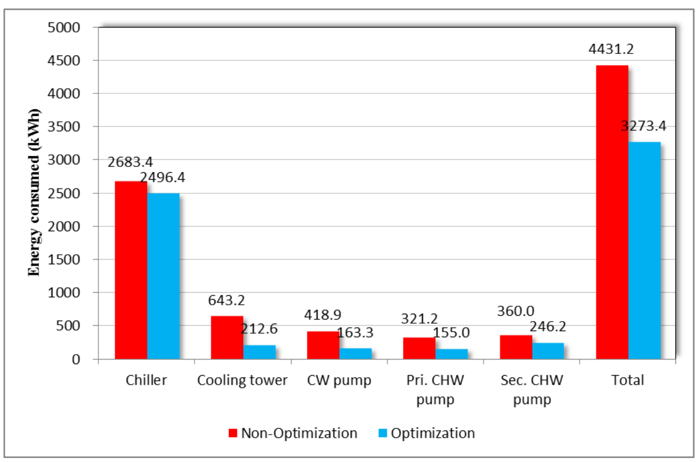

Fig. 5: Energy consumption of components in chiller plant