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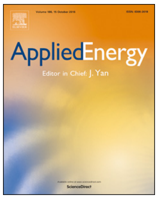

Does magnetic bearing variable-speed centrifugal chiller perform truly energy efficient in buildings: Field-test and simulation results

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HIGHLIGHTS

- The magnetic bearing variable-speed centrifugal chiller was introduced.
- Typical and annual energy performance were field tested and analyzed.
- A simulation was developed and checked by the field test data.
- Optimal control strategies were proposed based on operation characteristics.

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ABSTRACT

The Magnetic Bearing Centrifugal Chiller with variable-speed control (MBCC), also known as an oil-free chiller, is highly recommended as a remarkable energy-efficient solution for space cooling in buildings by manufactures. However, MBCCs have to work coordinately with cooling demand of buildings as well as local climate. The energy performance of MBCCs rather than rated value from factory must be evaluated in operation for future applications. This paper examines actual performance of MBCCs in different buildings and cities through whole year and compares the results to conventional screw chillers and centrifugal chillers. It was disclosed clearly that MBCCs performed much efficiently especially at part load ratio of cooling demand as well as part compression ratio demand. Thus, to fully taking advantage of MBCCs for truly energy efficient in operation, one must optimize MBCCs design and operation based on annul hourly simulation of cooling demand and compression ratio demand rather than just thinking of nominal rated conditions of chillers. Based on time-series operational data log, an empirical model of MBCC was conducted which can help optimizing chiller plant design and operational strategy through annual hourly simulation of energy performance of MBCCs.

1. Introduction

Heating, Ventilating and Air-conditioning (HVAC) systems, which are used to provide a healthy and comfortable indoor environment, are the major sources of energy consumption in commercial buildings. Statistical data shows that space heating and cooling energy comprise nearly 47% of total building energy in the USA [1] and 30–50% in China [2]. Thus, the energy conservation in HVAC systems became a significant consideration in the sustainable development and management of commercial buildings. During the last two decades, numerous studies have examined the energy conservation in HVAC systems. Some analysis and optimization methods were put forward based on field test results. Yu used a Data Envelopment Analysis (DEA) [3] to demonstrate a systematic approach to examine which operating variable should be fine-tuned to improve system performance with higher technical efficiency and then improved energy management of chiller systems. Chung [4] put forward a benchmarking system to evaluate the energy efficiency of commercial buildings and Du [5] raised a dual-benchmark based energy analysis method to evaluate control strategies for building HVAC systems, pointing out the direction of energy conservation based on analysis of energy consumption and energy efficiency index.

Li [6] claimed that the key contributor to poor chiller plant performance was the mismatch between demand and supply sides. Due to improper cooling load calculations or unreasonable safety factors, oversized chiller capacities have become a common phenomenon in HVAC systems. Even a perfectly designed chiller plant could be very significantly oversized in actual operation since the cooling load reached its peak level for only a small proportion of time in a year [7]. These large capacities decrease operational energy performance and waste energy throughout the cooling seasons [8,9].

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Nomenclature

A ~ F	constant coefficients
CCC	conventional centrifugal chiller
CCHP	combined cooling, heating and power
COP	coefficient of performance
DCOP	thermodynamic perfection of chiller
DEA	data envelopment analysis
G_c	flow rate of the cooling water, m^3/s
G_e	chilled water flow rate, m^3/s
HVAC	heating, ventilating and air-conditioning
ICOP	theoretical COP of refrigerant cycle
IGV	inlet guide valve
IPLV	integrated part load value
K_cF_c	overall heat conduction coefficient of the condenser, kJ/K
K_eF_e	overall heat conduction coefficient of the evaporator, kJ/K
MBCC	magnetic bearing centrifugal chiller
N	running number of chillers
N_{max}	maximum number of chillers
P_{LR}	part ratio of cooling load
$P_{LR,b}$	ratio of building cooling load
Q_c	heat transfer capacity of the condenser, kW
Q_b	building cooling load, kW
$Q_{b,0}$	designed building cooling load, kW
Q_e	cooling load of chiller, kW
$Q_{e,0}$	designed cooling load of chiller, kW
T_c	condensing temperature, K
T_{ce}	normalized temperature difference between T_c and T_e
$T_{chw,r}$	temperature of the return chilled water, °C
$T_{chw,s}$	temperature of the supply chilled water, °C
$T_{cw,r}$	temperature of the return cooling water, °C
$T_{cw,s}$	temperature of the supply cooling water, °C
T_e	evaporating temperature, K
THIC	temperature and humidity independent control
VSD	variable speed drives
W	electric power of chiller
W_T	total power of the chillers, kW
ΔT_c	logarithmic mean temperature difference between the cooling water and refrigerant, K
ΔT_e	logarithmic mean temperature difference between the chilled water and refrigerant, K
a,b,c	constant coefficients
c_p	specific heat capacity of water, kJ/(kg·K)
i	equipment number of chiller
λ	lagrangian multiplier
ρ	density of water, kg/m^3

To solve the mismatch issue, chillers and water pumps require a wide range of settings and must be easily adjustable. A Magnetic Bearing variable-speed Centrifugal Chiller (MBCC) is developed and tested in practical applications to solve the aforementioned problems.

A MBCC applies magnetic bearing technology to its compressors and is able to function without oil lubrication. As such, it realizes higher rotation speeds than conventional centrifugal chillers (CCCs) with or without variable speed drives (VSD) [10]. Given the absence of oil return failure and friction loss, magnetic bearing centrifugal compressors can be used to create centrifugal chillers with smaller cooling capacities (i.e., 200 kW to 1 MW) by decreasing the impeller size and increasing the rotation speed. Further, MBCCs have flexible cooling load adjustments, allowing for a 20–100% load ratio by adjusting the rotation speed and maintaining high level of energy efficiency in the part load conditions, performing better than CCCs without VSD.

When compared to the CCCs with VSD, Yu's studies [11] determined that (oil) lubrication-based operations suffered from a 3.2% performance decrease in the chiller as well as accelerated performance degradation. Therefore, an oil-free compressor can enhance MBCC's performance because it has no lubrication-based performance decreases in the evaporators, condensers or compressors. Further, MBCCs have a wider range of settings and are easily adjustable because there is no limitation on the minimum compression ratio for the oil return. This oil-free feature contributes to the further enhancement of the energy performance of MBCCs compared to CCCs with VSD. Theoretically, an oil-free compressor with VSD is a highly efficient method of reducing energy consumption in HVAC systems.

Previous research primarily focused on practical applications of MBCCs. Such studies also examined the optimization of operational performance and control strategies. For practical applications, Yin proposed a system design where concentrated cooling systems were dispersed by using MBCCs in a Combined Cooling, Heating and Power (CCHP) system [12] and Temperature and Humidity Independent Control (THIC) systems [13], leading to significant improvement in operational performance. Guo [14] analyzed the energy saving rate of the data center by replacing conventional chillers with MBCCs. Results showed a 37% (minimum) reduction in energy consumption. However, Guo relied on an Integrated Part Load Value (IPLV) in the design book (for basic information) to calculate the energy-saving efficiency, which lacked an accurate evaluation of the actual (i.e., practical) operational efficiency.

Previous research examined MBCC operational performance. Coefficient of Performance (COP) was put forward to evaluate the energy performance of chillers [15], defined as the cooling load divided by the electric power. And the higher COP means the better energy performance of chillers. Zhu [16], Yang [17], and Liu [18] conducted field studies on MBCCs under typical cooling conditions for China. Results showed that the COP of the chillers reached 10, 8 and 6.5 in each system. These COPs were higher than those of conventional centrifugal chillers and had significant energy-saving effects. Liu [19] measured the COP of MBCCs that supplied higher-temperature chilled water. Results showed that the COP reached 8.9 when the temperature of the supplied chilled water was 17.5 °C. To examine annual performance, Yu [13] investigated a chiller plant in a shopping mall in Hong Kong that replaced conventional centrifugal chillers with MBCCs. After optimization, the annual COP of the chillers reached 6.0 and the energy saving rate was 9.6% across the entire chiller plant. Yik [20] also simulated the annual energy consumption of MBCCs in a hospital; here, the annual COP reached 5.7. These previous studies show that MBCCs are more efficient than conventional chillers and that energy consumption can be reduced by replacing conventional chillers with MBCCs. However, under actual operational conditions, COPs significantly vary. In some cases, the COP is as low as 6, which approaches the energy performance of conventional chillers.

Previous research examined MBCC control strategy optimization. Beghi [21] employed a hybrid optimization technique to determine optimal operation for air-condensed water centrifugal chillers under different cooling load and external temperatures. However, the variation regularity of the chiller performance caused by the cooling load and external temperature was not provided and the algorithm was at risk of non-convergence. Yu used a Data Envelopment Analysis (DEA) to evaluate compressor efficiency and found that the technical efficiency was 60%. Other methods, such as the temperature optimization of chilled water supply, were proposed to enhance technical efficiency [14]. However, technical efficiency has no specific physical significance; as such, it cannot inform the optimization of chiller operating parameters. Other research considered the magnetic bearing compressor, including the optimization of bearing system control strategies [22–24] and geometry diffuser design [25].

In summary, due to lack of detailed field-based measurements