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Experimental and numerical dynamic investigation of an energy efficient liquid cooled chiller-less data center test facility

Tianyi Gao[a,*], Milnes David[b], James Geer[a], Roger Schmidt[b], Bahgat Sammakia[a]

[a] *Department of Mechanical Engineering, Binghamton University—SUNY, Binghamton, NY 13905, United States*
[b] *STG Advanced Thermal Energy Efficiency Lab., IBM Corp., NY, United States*

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ABSTRACT

Data centers cooling systems constitute a large portion of the total data center energy consumption, therefore, many new cooling technologies have been developed to improve the energy efficiency. A data center cooling facility proposed by IBM is constructed to reduce cooling energy use to less than 5% of the total Information Technology energy use through a combination of warm water cooling servers and liquid-side economization. In this work, several experimental tests are conducted on this cooling test facility and the results are reported and analyzed. The detailed dynamic responses of each component used in the cooling infrastructure design are investigated using the test results combined with simulation results. The experimental tests designed and the corresponding analyses present a brief understanding of the dynamic performance of this data center test facility, including both inside and outside of the computer room. A transient effectiveness method is introduced and used to analyze the heat exchangers performance. The work presented provides an analyzing method which can be used to investigate and characterize the transient performance of heat exchangers which are working in the cooling and heating systems with multiple coupled heat transfer loops, in which multiple heat exchanger units are used.

1. Introduction

Energy consumption by data center rooms are a significant fraction of US and worldwide total energy consumption and are expected to grow in the coming decades. About 1.5% of all U.S. electricity consumption in the year 2006 was related to data centers, while that number increased to 2% in the year 2010 [1]. Data center energy efficiency has become a key issue that has attracted a lot of research concentration from both business perspectives and environmental perspectives. Cooling infrastructure consumes a significant portion of the energy use in data centers, roughly in the range of 25–35% of the total energy that is required by a production data center [2–4]. A great portion of the cooling energy is used by the CRAH units and the chillers. To reduce the energy used by cooling methods, one approach is to reduce or minimize the need for both CRAH units and chiller plants [5].

Many new data center cooling solutions have been developed to improve the energy efficiency and cooling efficiency, such as hybrid cooling and liquid cooling technologies. The rear door heat exchanger is an example of a hybrid cooling solution proposed by Schmidt et al. [6]. A water cooled heat exchanger is installed at the back of the server rack, and is used to cool the hot air before it exits the room. It has been shown that, by using this rear door heat exchanger strategy, this method can significantly benefit the data center by solving the hot spot problem, and at the same time minimize the need of installation of CRAH units to improve the energy efficiency [7,8]. Another hybrid cooling technology is the overhead heat exchanger, which located the water to air heat exchanger above the cold aisle. The overhead heat exchanger supplies the cooling air to the cold aisle more efficiently than using CRAH units. The basic principle of these new hybrid cooling technologies is realized by locating the heat exchangers closer to the IT loads in order to eliminate the requirement of large portions of the cooling airflow supplied from CRAH units and their associated blower energy. Liquid cooled supercomputer designs, such as the IBM Power 575 and Power 775, are examples of liquid cooling technologies. By using building water cooled servers, the energy efficiency within the data center is significantly increased, since a large portion of CRAH units are replaced by the high efficiency water cooling units, which distribute the building chilled water to the servers [9,10].

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* Corresponding author at: SUNY Binghamton University, Mechanical Engineering, Suite B1211, CoE Building, 85 Murray Hill Rd., Binghamton, NY 13902, United States. Tel.:+1 607 372 2798.
E-mail addresses: Tgao1@binghamton.edu, gaotianyi19870225@gmail.com (T. Gao).

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Nomenclature

A	area of heat transfer (m^2)
A_c	area of cross section (m^2)
c_p	fluid specific heat (J/kg K)
C	specific heat of the wall of heat exchanger (J/kg K)
C^o	heat capacitance (J/K)
h	heat transfer coefficient (W/m^2 K)
h'	changing heat transfer coefficient (W/m^2 K)
L	length of heat exchanger (m)
m	mass flow rate (kg/s)
m'	changing mass flow rate (kg/s)
M	mass of the wall of heat exchanger (kg)
T	temperature (°C)
x, y	heat exchanger physical length and direction
H	heat exchanger conductance
t	nondimensional time
C_{min}	minimum capacity rate fluid
RPM	revolutions per minute
HX	heat exchanger
GPM	gallon per minute
CRAH	computer room air handler

Greek letters

τ	time (s)
ε	effectiveness

Subscripts

h	hot fluid
c	cold fluid
wall	heat exchanger wall (core)

Waterside and airside economization have also attracted a great deal of research effort. The basic principle of air side economization is to use the ambient air to cool the server heat load without using any intermediate refrigeration component [5]. Water side economization uses a wet or dry tower attached to a coolant distribution unit, which supplies chilled water to either the rear door heat exchanger or to a fully-enclosed cabinet with a water cooled heat exchanger [11]. Several researchers have reported that significant high energy efficiency can be achieved for air-side economized data centers [12].

Warm liquid cooled server technology is a new cooling technology and has been used in new designs of data center cooling solutions. One example is the chiller-less data center design proposed by IBM by utilizing a combination of warm water cooling of the electronics and liquid-side economization with a dry air heat exchanger [13]. This technology enables a no-chiller and no-CRAH unit design for data center room cooling with extremely high energy efficiency, while also isolating the IT equipment from any potential harmful outside environmental contamination [14]. The detailed description and information of this cooling technology concept and apparatus design are presented in [5,14]. Iyengar et al. have presented a complete introduction combined with detailed photographic representation of this cooling system design, including the infrastructures inside and outside building, internal and external loops, and the server cooling hardware [14]. Comprehensive experimental characterizations of the key cooling component used in this cooling infrastructure are presented by David et al. [5]. The impact of changes in liquid flow rate operating conditions, external liquid fluid type and heat exchanger configurations of the buffer unit, variations in the fluid flow rate conditions and ambient weather conditions, and blower speed of the dry cooler were investigated to determine their impact on the energy consumption and thermal performance. These experimental tests are then used to characterize the thermal resistance and conductance of each individual component. Several one day tests were conducted [5,15] to characterize the energy efficiency of the cooling system during normal operation. It was found that the cooling power utilization effectiveness (PUE) is approximately 1.03 [15], which means that the cooling power consumption is about 3.5% of IT power consumption. All of these results help to optimize the system design and determine the ideal operating conditions to achieve better energy efficiency. Then a dynamic control algorithm is implemented into the system as discussed by David et al. [16]. A 60+ day run of the DELC facility is carried out to investigate the cooling performance and energy efficiency gained by using the energy aware control.

This proposed cooling technology was designed to reduce the cooling energy consumption to less than 5% of the total IT energy consumption. Cooling PUE is a useful metric to measure the energy efficiency of the cooling solutions used to cool the IT rack, with values approaching unity indicating an ideal energy efficient cooling solution. The cooling (mechanical) PUE for this cooling design can be maintained below 1.05 for most days, with an average of 1.035. For a typical air cooled data center, the cooling PUE is about 1.5–1.7, or even higher. More discussion and PUE data of different cooling systems of different production data centers are reported in [5,17]. For example, for a 1 MW data center, the cooling power consumption is about 5 kW for water cooled system. In addition, the capital expense is decreased as well since there is no need for CARH units and chiller plant and cooling tower.

In this work, several experimental test results which were conducted on this data center cooling infrastructure test facility are reported. A method is introduced which can be used to investigate heat exchanger dynamic performance. Detailed analyses of the dynamic response of each component, as well as the whole system are presented under varying server powers and operating conditions. The transient response time and thermal mass effect of each component are also investigated using the experimental test results combined with a transient effectiveness method.

2. Mathematical model

Mathematical simulation models for the side car heat exchanger, the buffer unit and the dry cooler are developed using thermal dynamic models of heat exchangers, including counter flow and cross flow configurations. The full thermal dynamic heat exchanger models have been developed by Gao et al. [18,19] using the conservation of energy for the hot fluid, cold fluid and heat exchanger core. The transient governing equations for a cross flow heat exchanger are shown in Eqs. (1)–(3). For counter flow configurations, the thermal dynamic governing equations are much simpler than the cross flow configurations, which are a set of one dimensional energy conservation equations. The transient heat exchanger models are solved and validated by comparison with multiple literature references and experimental results in [18–20]. Different variation conditions are modeled, including fluid inlet temperature variations [19], mass flow rate variations [20], as well as multiple combinatorial variations of the fluid inlet temperatures and mass flow rates. The numerical simulation models are used in this work by assisting with the investigation of the transient performance of this cooling system, combined with the experimental results.

$$MC\frac{\partial T_{wall}}{\partial_\tau} - \left(h'A\right)_h (T_h - T_{wall}) + \left(h'A\right)_c (T_{wall} - T_c) = 0 \qquad (1)$$