Energy Conversion and Management 112 (2016) 135–145

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Experimental and numerical analysis for potential heat reuse in liquid cooled data centres

Andreu Carbó [a], Eduard Oró [a,*], Jaume Salom [a], Mauro Canuto [b], Mario Macías [b], Jordi Guitart [b]

[a] Catalonia Institute for Energy Research, IREC, Jardins de les Dones de Negre 1, 08930 Sant Adrià de Besòs (Barcelona), Spain
[b] Barcelona Supercomputing Center and Universitat Politècnica de Catalunya, C/Jordi Girona 29, 08034 Barcelona, Spain

ARTICLE INFO

Article history:
Received 26 October 2015
Accepted 4 January 2016
Available online 19 January 2016

Keywords:
Data centre
Liquid cooling
IT load
Experimentation
Numerical modelling

ABSTRACT

The rapid increase of data centre industry has stimulated the interest of both researchers and professionals in order to reduce energy consumption and carbon footprint of these unique infrastructures. The implementation of energy efficiency strategies and the use of renewables play an important role to reduce the overall data centre energy demand. Information Technology (IT) equipment produce vast amount of heat which must be removed and therefore waste heat recovery is a likely energy efficiency strategy to be studied in detail. To evaluate the potential of heat reuse a unique liquid cooled data centre test bench was designed and built. An extensive thermal characterization under different scenarios was performed. The effective liquid cooling capacity is affected by the inlet water temperature. The lower the inlet water temperature the higher the liquid cooling capacity; however, the outlet water temperature will be also low. Therefore, the requirements of the heat reuse application play an important role in the optimization of the cooling configuration. The experimental data was then used to validate a dynamic energy model developed in TRNSYS. This model is able to predict the behaviour of liquid cooling data centres and can be used to study the potential compatibility between large data centres with different heat reuse applications. The model also incorporates normalized power consumption profiles for heterogeneous workloads that have been derived from realistic IT loads.

1. Introduction

During the last years the rapid increase of cloud computing, data storage and internet use have resulted in a dramatic growth in the number of data centres. These unique installations work 24 h a day, 365 days a year, and the miniaturization of the components and increase of the processing power results in a huge energetic density. Nowadays, the energy demand per square metre of a data centre is approximately up to 100 times higher than a regular office [1]. As a consequence, the energy consumption and carbon footprint of this emergent industry started to become a considerable worldwide concern, being the 1.3% of the world electricity consumption in 2012 [2]. Most of the power consumed by the Information Technology (IT) equipment is converted in excess heat, which must be removed to avoid the damage of the equipment. The energy requirement of the cooling system represents up to 40% of the overall data centre energy consumption [3].

Traditionally the refrigeration in these unique facilities has been done by air cooling systems. Its initial low efficiency has been improved implementing different methods such as hot/cold aisles containment and variable fan speed [4], obtaining savings up to 70% [5]. However, Moore's law [6], which states that transistor density doubles every 2 years, continues to be true nowadays. This means that, due to the exponential increase in IT energy density, in few years the energy density of the IT equipment will reach values up to 50 kW/rack and therefore the solely use of air cooling system will be insufficient to evacuate all the heat generated by the servers [7]. To overcome this problem the data centre industry is already investigating and implementing the use of liquid cooling systems due to the higher heat removal capacity and the ability to cool specific system components to a greater degree [8]. Some applications use mineral oil [9], refrigerants [10], or water, which it is more common, cheaper and presents several possibilities for heat reuse [2].

Recently many researchers have been focusing on the evaluation of the potential heat reuse in data centres. Ebrahimi et al. [2] performed a literature survey about the possible waste heat reuse technologies, and concluded that their applicability depended drastically on the quality of the recovered heat. Table 1 collects the suitability of the waste heat technologies for data centres, for three different cooling strategies. Notice that the air

* Corresponding author. Tel.: +34 933 562 615.
E-mail address: eoro@irec.cat (E. Oró).

http://dx.doi.org/10.1016/j.enconman.2016.01.003
0196-8904/

Nomenclature

Roman letters

A	area [m^2]
C	specific heat [kJ/kg K]
ε	effectiveness
E	electrical power [W]
h	heat transfer coefficient [W/m^2 K]
$\dot{m}$	mass flow (kg/s)
P	pressure [bar]
$\dot{Q}$	power (W)
T	temperature [°C]
U	thermal transmittance [W/m^2 K]
V	volume

Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CPU	Central Processing Unit
GSHP	Ground Source Heat Pump
IT	Information Technology
HVAC	Heating, Ventilation, and Air Conditioning
HPC	High Performance Computing
IREC	Catalonia Institute for Energy Research
RH	Relative Humidity
PSU	power distribution unit
SEILAB	Semi-Virtual Energy Integration Laboratory
TRNSYS	Transient System Simulation Tool
STES	Seasonal Thermal Energy Storage

Subscripts

air	air
in	inlet
MB	motherboard
out	outlet
rack	rack
rack-air	rack to air
s1	shelf 1
s2	shelf 2
server	server
sup	superficial
t	total
w	water
ws	whitespace

cooling provides low quality heat, while with two-phase cooling (refrigerant instead of water) high temperature applications can be applied. Water cooling which obviously is less complex than the two-phase system provides intermediate quality heat.

Lately, various investigators have been focusing on analysing the potential implementation of the aforementioned technologies in data centres. Marchinicen et al. [10] reveal that a large data centre (32.5 MW of IT power) could improve by 2.2% the thermal efficiency of a nearby 175 MW coal power plant by reusing the 60 °C waste cooling water in pre-heating the plant's feed water. Ebrahimi et al. [3] showed that the waste heat extracted from 3 to 5 servers can be used to cool an additional one, with a minimum recovery temperature of 65 °C by using an absorption refrigeration technique. Nonetheless, those temperature values seem complicated to achieve when using water as the refrigerant. In that sense, in the water cooling system proposed by IBM and studied by Gao et al. [11], the temperature recovered after the server rack at full IT load was only 43 °C. There are already some data centres that reuse heat for other applications. The Uspenski data centre located in Helsinki (Finland) uses the warm water from its facility to heat up 500 houses in the neighbourhood [12]. Another example of heat reuse comes from the IBM data centre in Uitikon (Switzerland), which sends its waste heat to warm a public swimming pool located nearby [13]. Here, the hot air generated by the data centre flows through heat exchangers to warm water that is then pumped into the nearby pool. Moreover, IBM proposed a facility that would allow reducing the cooling energy up to 95% utilizing a combination of warm water cooling of the electronics and liquid-side economization with a dry air heat exchanger [11].

However, most of the waste heat reuses technologies for data centres are still in the design or validation phase. An important issue is that the industry requires robust mathematical models able to provide accurate values of operation or to correctly extrapolate experimental results from a small test bench to a large facility. Generally the servers and the cooling system are modelled with the heat transfer equation, considering convection and conduction mechanisms. Breen et al. [7] performed a thermal equilibrium model of an air cooled rack to obtain flow rate, pressure drop and heat transfer coefficients that were used to characterize the system. Douchet et al. [8] described the rack with a nodal model, assigning the nodes to the IT components, and validating the calculations later with thermocouples attached to those components. Another approach was taken by Ham et al. [4], who proposed experimental correlations to model IT power and thermal resistance of the system in function of the measured temperatures. Moreover, Zhang et al. [14] not only performed an energy balance but created a TRNSYS model to simulate the heat recovery system and compare it with other heating supplies as Ground Source Heat Pump (GSHP) or Seasonal Thermal Energy Storage (STES). The study concluded that heat recovered from data centres provides a more stable source of heat than GSHP and at a lower cost than STES.

Table 1
Suitability of each waste heat technology for data centre applications [2].

Technology	Air cooled data centre (waste heat 45 °C)	Water cooled data centre (waste heat 60 °C)	Two phase data centre (waste heat 75 °C)
HVAC/domestic hot water	Yes	Yes	Yes
District heating	Yes, with booster	Yes	Yes
Boiler feed water pre-heating	No	Yes	Yes
Absorption refrigeration	No	Yes	Yes
Organic Rankine cycle	Yes, with booster	Yes	Yes
Piezoelectrics	Yes	No	No
Thermoelectrics	No	No	Yes
Desalination	No	Yes	Yes
Biomass processing	Yes	Yes	Yes