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Numerical analysis for potential heat reuse in liquid cooled data centres

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Abstract

It is well known that the energy consumption of data centre industry has increased drastically in the last years and has become a worldwide concern. The refrigeration system of state of the art facilities represents up to 40 % of the total energy consumption. In this context, reuse of the heat from data centres can decrease the energy consumption and thus the CO2 emissions of the facility and can provide heat to other applications. First, the paper presents different applications that can reuse heat from IT installations and describes its operational requirements. Second, a dynamic energy analysis of waste heat recovery in data centres for domestic hot water application has been done. A novel trnsys model is proposed based on an already experimentally validated model of liquid cooled data centre. The paper study the thermal feasibility of the connexion of a 1,000 IT kW data centre with 2,500 residential building for domestic hot water supply. The results show that 65 % of the yearly domestic hot water energy demand is covered by the data centre while the IT facility dissipates up to 50% of the heat freely.

Keywords – data centre, liquid cooling, numerical model, heat reuse

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 hours a day, 365 days a year, and the miniaturization of the components and increase of the processing power results in a huge energetic density. As a consequence, the energy consumption and carbon footprint of this emergent industry started to become a considerable worldwide concern. 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. Traditionally the refrigeration in these unique facilities has been done by air cooling systems. However, 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. 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.

Ebrahimi et al. [1] 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. As expected, air cooling provides low quality heat and therefore the heat is difficult to be reused; while water cooling provides intermediate quality heat. In this case, depending on the application (temperature > 65-80 ºC) an auxiliary system such as a heat pump is needed to fulfil the application requirements. Finally, when using two-phase cooling (refrigerant instead of water) high temperature applications can be applied; however, this technology is complex and thus its implementation in real data centre industry is difficult. Lately, various investigators have been focusing on analysing the potential implementation of the aforementioned technologies in data centres portfolio [2][3][4][5][6]. Moreover, there are already some data centres that reuse heat for other applications such [7][8]. Actually, the industry requires robust mathematical models able to provide accurate values of operation. Carbó et al. [5] proposed a dynamic energy model using TRNSYS [9] software for potential heat reuse prediction. This study aims to evaluate numerically the potential heat reuse of liquid cooled data centres in function of the facility characteristics and the heating demanding application. To do so, the dynamic energy model already validated in previous author’s work [5] will be used.

2. Methodology

2.1 Dynamic energy model

The software TRNSYS, a flexible graphically based software environment used to simulate the behaviour of transient systems, is used to model the system. The whitespace is modelled with a single lumped capacitance single-zone building with internal gains (Type 759). This means that the structure is subjected to internal gains (IT and miscellaneous gains) and to building losses. The racks were modelled as lumped mass (Type 963) which means that they can be characterized by the rack temperature and the heat transfer to its surrounding environment which is the whitespace. Here capacitance effects i.e. rack structure and servers are included. The use of this type allows implementing direct cooling technology by means of negative internal gains. Those components were connected according to the system configuration already described and shown in Fig. 1.

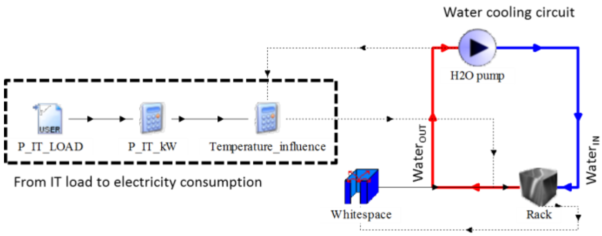

Fig. 1 Scheme diagram of the TRNSYS model for the liquid cooled data centre.

Here capacitance effects i.e. rack structure and servers are included. The main parameters to characterize the system and in particular the lumped capacitance model, such as the volume of the whitespace, the thermal capacitance of the whitespace which include the capacitances of the building materials, furnishings and conditioned air, the overall heat transfer coefficient of the whitespace to the surrounding ambient, the thermal capacitance of the IT equipment, the heat transfer area of the equipment to the air, and the heat transfer coefficient from the racks to the air in the IT room where either calculated and calibrated using experimental data. The dynamic energy model was validated in order to guarantee its robustness and consistency [5]. For each time step in the simulation process, the thermal performance of the whitespace model will respond to boundary conditions. Heat gains due to the IT equipment ($\dot{Q}_{IT}$) together with the effects of direct liquid cooling system ($\dot{Q}_{w}$), as negative internal gains, are implemented in the IT racks component. Therefore, it is possible to calculate average temperature of the racks (Track), air and water inlet and outlet temperatures to and from the IT equipment. Sensible cooling power of the air ($\dot{Q}_{air}$) – Eq. 1 - and liquid cooling power ($\dot{Q}_{w}$) – Eq. 2 - can be calculated using the following equations. Moreover, the effectiveness of the heat transfer can be calculated using Eq. 3.

$$\dot{Q}_{air} = \dot{m}_{air} \cdot C_{air} \cdot (T_{air.Out} - T_{air.In}) \qquad \text{Eq. 1}$$
$$\dot{Q}_{w} = \dot{m}_{w} \cdot C_{w} \cdot (T_{w.Out} - T_{w.In}) \qquad \text{Eq. 2}$$
$$\dot{Q}_{w} = \varepsilon \cdot \dot{Q}_{air} \qquad \text{Eq. 3}$$

2.2 Waste heat recovery applications

In order to study the potential heat reuse from data centres, different heating demand applications have been studied and are detailed below. Table 1 summarizes the main requirements such as operating temperatures and heating demand for the applications studied.

Table 1. Summary of the main requirements of the potential heat reuse applications from data centre facilities.

	Operating temperature [ºC]	Hourly density demand
Conventional district heating network[1]	Supply at 85 – 90 Return at 50 – 60	5 – 20 [W/m^2]
Low temperature district heating network[2]	Supply at 40 – 55 Return at 25 – 41	28.2 – 93 [W/m^2]
Residential building and DHW heating demand	75 ºC for heating 45 – 50 ºC for DHW	Heating demand up to 31 [W/m^2] DHW demand up to 9.5 [W/m^2]
Hospital heating and DHW demand	75 ºC for heating 45 – 50 ºC for DHW	Heating demand up to 31 [W/m^2] DHW demand up to 9.5 [W/m^2]
Hotel heating and DHW demand	75 ºC for heating 45 – 50 ºC for DHW	Heating demand up to 31 [W/m^2] DHW demand up to 22.2 [W/m^2]
Office building heating demand	75 ºC for heating	Heating demand up to 48.7 [W/m^2]
Green house heating	Air at 12 ºC	112.6 – 186.6 [W/m^2]
Indoor swimming pool[3]	Water at 24 – 30 ºC	110 W/m^2

[1] Values for Barcelona [2] Values for North Europe [3] Values for Spain

- District heating network

District heating networks provide heating by water pipes to large areas, while the heat generation is centralized in a way that it is more efficient to produce and distribute. While most district heating systems operates between 60 and 90 °C, the air or water extracted from the IT cooling circuits is hardly at over 50 °C. In order to overcome this issue, there are two possible solutions. On one hand, as happens in most of the Swedish District heating networks [11], involves the use of heat pumps. However, the operator normally wants to control the supply pipeline. On the other hand, the data centre can be connected into the return pipeline. This option allows the operator to regulate much better the network and due to the lower operating temperatures, the data centre infrastructure will probably not need any auxiliary system. The pioneer in this technique was the Finnish ICT firm Academica, which build a 2 MW data centre under the Uspensky Cathedral in Helsinki that transferred its excess heat to the local district heating network to warm up 500 houses [7]. Atos has a 5,000 m^2 data centre also in Helsinki providing 10MW power heating to the city network, feeding 4,500 apartments

[12]. Swisscom Wankdorf data centre in Bern, Switzerland, also feeds the district heating system [13].

- Low temperature district heating

Another solution is to connect data centres to low temperature district heating systems, where obviously the operation temperature is lower than the conventional networks. This kind of systems, proposed by Olsen et al. [14] in Denmark, are planned to provide heating and domestic hot water (DHW) to highly efficient houses at water temperatures of around 50 °C. This system allows reducing heat losses by almost 70 % due to lower temperature differences and smaller pipe diameters [15]. The operative temperatures of this system allow to fully connecting data centres to reuse the waste heat. The next generation of district heating, using low temperature distribution has been successfully deployed in some residential areas in Denmark, Sweden, Germany or the UK [16].

- Building heating and DHW demand

Other solution is to feed directly the warm air/water from data centres to neighbour spaces such as residential building, hospitals, offices, museums, etc. Notice that in some of these applications DHW is also required. Moreover, there is also the option of thinking a data centre as a portable IT facility located directly at its destination [17]; however, this option still present some problems of market penetration. The optimum connection between the data centre and heating consumers depend on distribution and temperature of the energy supply, temperature requirements and rates of charge/discharge. Ortiz et al. [18] presented the heating and DHW needed to warm an average residential apartment of 78.8 m^2 in Barcelona which can be seen in Fig. 2 and Fig. 3. For more realistic DHW draw off profiles, the *DHWcalc* profile generator tool from the IEA Task 26 [19] is preferred. Heating demand profiles for hospitals, hotels [20], and office buildings [21] [22] can also be used to study the data centre interaction with these applications. An example of building heating by a data centre can be found in the city of Winnipeg (Canada). The Quebecor data centre, distributes the exhaust air from its 100 servers to the next-door building [23]. Similarly, the Telehouse West data centre (5,000 m^2) in London, exchange the heat from the hot air coming from the IT facility to neighbour offices in the Docklands [24]. In the Vaucanson building in France, the heat from the data centre is heated up to 45 ºC by a heat pump to warm directly the building [25].

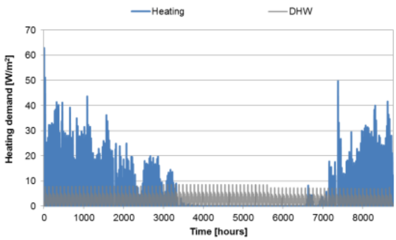

Fig. 2 Annual heating and DHW demand for a typical refurbished flat in Barcelona.

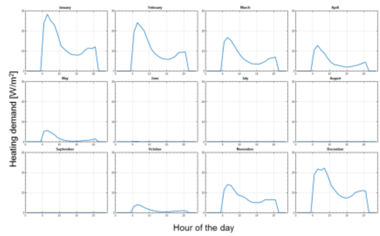

Fig. 3 Monthly average heating demand for a typical refurbished flat in Barcelona

- Greenhouse heating

Heat from data centres can also be reused in low-temperature industrial processes such as greenhouses. Brenner et al. [26] used the waste heat from the University of Notre Dame's cluster in the US to warm a greenhouse that simulated desert conditions, saving thousands of dollars in the process. The same concept was applied in the 6.4 MW IT Telecity data centre in Paris, where the waste heat from the facility was used to heat the *Climate Change Arboretum* [27].

- Indoor swimming pool heating

Indoor swimming pools also require a large amount of energy to maintain a comfortable temperature in the water. The heating demand of three different indoor swimming pools in Spain was analysed showing a heating demand almost constant over the year with an average power ratio of 110 W/m^2 [29]. There is already a swimming pool using the waste heat from an IBM data centre reusing 2,800 MWh yearly [8].

3. Results and Discussion

The feasibility of using the waste heat from a 1,000 kW IT data centre for a residential DHW demand is studied numerically. Fig. 4 shows schematically the thermal scheme connection between the data centre and the DHW system. The system requires a water storage tank and an auxiliary boiler to guarantee the DHW demand. Moreover, Fig. 5 shows the connection between the different components according to the system configuration. Notice that for this application, 4 servers are connected in series while the others are coupled in parallel. To simulate the power consumption of a real data centre a heterogeneous IT workload profiles has been used.

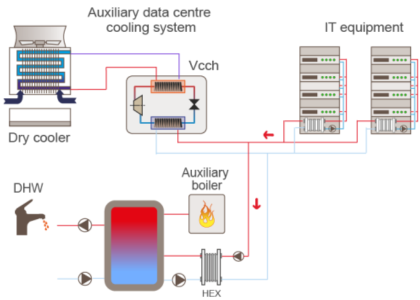

Fig. 4 Thermal scheme of a liquid cooled data centre connected to a residential building DHW system.

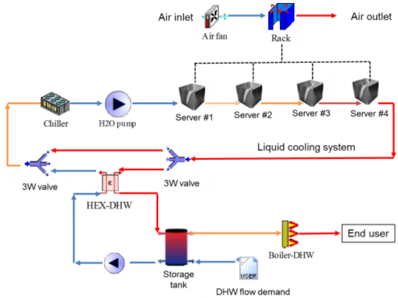

Fig. 5 Scheme diagram of the TRNSYS model for the heat reuse application.

On one hand, the peak power requirement per a residential building is less than 0.8 kW while the total energy demand over the year is above 2,240 kWh. On the other hand, even though the IT capacity of each rack of the data centre is 20 kW, the heat peak generation is lower than 15 kW while the average heat generation is 13.9 kW. Therefore, a 1,000 kW IT liquid cooled data centre composed of 50 liquid cooled racks of 20 kW each can provide waste heat for DHW to an approximately 2,500 residential buildings. The authors want to highlight that for a complete thermodynamic analysis an optimization process of the main parameters of the system is required. There are many constrains such as the volume of the water storage tank and the water flow rate from the tank to the heat exchanger that play an important role and affects the results. For the present analysis, a water storage tank volume of 3 m^3 has been considered for each 50 apartments while the water flow rate ratio in the heat exchanger is 1:1. Under these boundary conditions, the results show that in normal operation the data centre potential heat reuse is around 700 kW producing more than 6,000 MWh of heat during an operational year. However, due to the liquid cooling technology implemented, just part of the heat is removed by the liquid while other is removed be air cooling. Therefore not all the heat generated can be reused. Fig. 6 shows the duration curve for the DHW power demand and the data centre heating generation. On one hand, the DHW power demand is higher than the heating power from the data centre for more than 4,000 hours per year. On the other hand, for more than 2,500 hours per year the available heating power generated in the data centre is higher than the DHW demand and therefore an additional cooling system is also needed. Fig. 7 shows the data centre water temperature profiles for the first week of the year. Part of the data centre heat generation is dissipated by exchanging heat to the DHW application, representing up to 48 % of the total heat dissipation. The additional cooling system ensures that the return water temperature to the IT equipment is always lower than 30 ºC ($T_{\_return\_DC}$) when the water temperature coming from the heat reuse application is high. Fig. 8 shows the power and energy consumption of the heater needed to guarantee the DHW temperature during a week for the system studied and for a conventional system with the same energy demand. As expected, the consumption of the conventional system heater's is higher. Thus, the 65 % of the yearly DHW energy demand is covered by the waste heat from the data centre. Notice that the data centre not only can sell the heat to other applications but the operational cost of the cooling system is being reduced drastically.

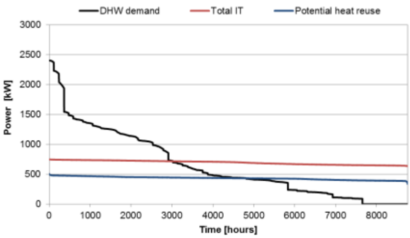

Fig. 6 Duration curve for 2,500 buildings DHW power demand and the data centre heating power generation.

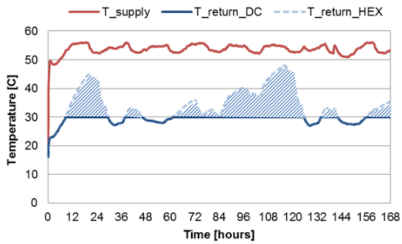

Fig. 7 Water temperature profiles in the data centre for 1 week of January

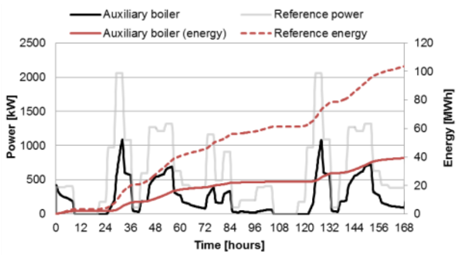

Fig. 8. Heater power and energy consumption for the system and reference system furing a week.

4. Conclusions

In the last years, the energy consumption of data centre industry has increased drastically and it is already a worldwide concern. Up to 40 % of the energy consumption of these unique infrastructures can be associated at the cooling system. Therefore the reuse of the heat from a data centre can first, decrease the energy consumption and carbon footprint of the facility and second, provide heat to other applications. However, most of the waste heat reuse' technologies, in particular liquid cooling technology, for data centres are still in the design or validation phase. The objective of the present paper is first to describe the operational characteristics of different applications that can potentially use waste heat from data centre and second to study numerically the potential heat reuse. To do so, an already developed and validated model by the authors is used. The paper presents the main requirements such as operating temperatures and heating demand for district heating networks, low temperature district heating networks, residential building heating and domestic hot water (DHW), offices building heating, hospitals building heating and DHW, greenhouse heating and swimming pool heating. All these applications can potentially reuse heat from data centres. The analysis has been focused on analysing the feasibility of using the waste heat from a 1,000 kW IT data centre for 2,500 residential building DHW demand. On one hand, the results show that up to 48 % of the yearly cooling needs of the data centre can be dissipated freely by heating up the water for the buildings DHW demand. On the other hand, the 65 % of the yearly DHW energy demand is covered by the data centre. Therefore, the data centre not only can sell the waste heat to other applications such as the studied here but the operational cost of the cooling system of the data centre can be reduced severely.

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