
Literature Review

**A Dynamic Control System
for Energy Efficient
Cooling of Data Centres**

Mark White

Monday 15th August 2011

Overview

This literature review analyses 4 academic papers. The main objectives of the review are to:

1. Trace the evolution of recent (2000 – 2011) data centre energy efficiency research and development
2. Document the most relevant and significant literature relating to energy efficient cooling for high-density data centres
3. Identify opportunities for further research

Consumer demand is increasing for higher volumes of data storage and faster data transmission rates. As a result of the recent economic downturn, data centre operating budgets are being more closely monitored. Crucially, with reduced capital budgets most data centres do not have the option of purchasing additional space. To deal with demand, many have already outsourced a percentage of their operation with many more considering similar moves in the months ahead. For the existing infrastructure in the data centre to remain viable, space has become a priority. The primary solution adopted by the industry in recent times has been to increase the density of IT equipment.

Increasing density is like adding more rooms to a house without extending the property. The house can now accommodate more people but each person has less space. In the data centre there are now more servers (known as blades) resulting in more compute/storage capability per square foot. Despite the space-saving advantages and virtualisation techniques which reduce the number of servers required to host applications even further, the primary disadvantage of increased density is that each blades require significantly more power than its predecessor. A standard rack with 65-70 blades operating at high loads might require 20 - 30kW of power compared with previous rack consumptions of 2 - 5kW. This additional power generates additional heat. Heat in the rack, and resultant heat in the room, must be removed to maintain the equipment at a safe operating temperature and humidity.

In relation to energy efficiency opportunities, the hardware components which constitute the main subsystems of a typical data centre are:

1. Power Supply & Distribution to IT Equipment
2. Servers, Storage Devices & Network Equipment

3. Cooling

Examining these subsystems in a little more detail will help to narrow the focus of this review.

Power Supply & Distribution to IT Equipment

The power being provided to the IT equipment in the racks is typically routed through an Uninterruptible Power Supply (UPS) which feeds Power Distribution Units (PDUs) located in or near the rack. Through use of better components, circuit design and right-sizing strategies, manufacturers such as APC and Liebert have turned their attention to maximising efficiency across the full load spectrum, without sacrificing redundancy. Some opportunities may exist in efforts to re-balance the load across the 3 phases supplying the power to the racks but efficiencies in the power supply & distribution system are outside the scope of this research.

Servers, Storage Devices & Network Equipment

Manufacturers such as IBM and Intel are designing increasingly efficient blades with features such as chip-level thermal strategies, multicore processors and power management leading the way. Energy efficiencies in this subsystem are beyond the scope of most data centres. However, there may be opportunities to harness these technological developments in designs for future cooling systems. Enterprise operators such as Google and Facebook have recently designed and installed their own servers which have demonstrated increased efficiencies but these servers are specifically 'fit-for-purpose'. They may not be sufficiently generic to be applicable for other data centre configurations.

Cooling

There are a variety of standard systems for cooling in data centres but all typically involve Air Handling Units (AHUs) or Computer Room Air Handlers (CRAHs). The majority of modern data centres have aligned their racks in an alternating hot aisle / cold aisle configuration with cold air from the AHU(s) entering the cold aisle through perforated or grated tiles above a sub-floor plenum. Hot air is exhausted from the rear of the racks and removed from the room by the same AHU(s).

Depending on the configuration of the data centre, the heat removal system might potentially consume 50% of a typical data centre's energy. This review focuses attention on possible efficiency gains specific to this subsystem.

Industry is currently embracing a number of opportunities – involving temperature and airflow analysis - for increased efficiency in the cooling system, most notably:

1. aisle containment strategies
2. increasing the temperature rise (ΔT) across the rack
3. raising the operating temperature of the AHU(s)
4. repositioning AHU temperature and humidity sensors
5. thermal management by balancing the IT load layout [1, 2]
6. 'free cooling' – eliminating the high-consumption chiller from the system through the use of strategies such as air and water-side economisers

In addition to temperature maintenance, the AHUs also vary the humidity of the air entering the room according to setpoints. Low humidity (dry air) may cause static which has the potential to create short circuits in the electronics. High levels of moisture in the air may lead to faster component degradation. Although less of a concern as a result of field experience and recent studies performed by Intel and others, humidity ranges have been defined for the industry and should be observed to maximise the lifetime of the IT equipment. Maintaining humidity ranges may increase equipment replacement intervals and, as a result, have a net positive outcome on capital expenditure budgets.

Industry Standards & Guidelines

Standards

Energy efficiency standards are widely recognised across the data centre industry. Power Usage Effectiveness 2 (PUE2) [3a] is now the de facto indicator of a data centre's efficiency. It is defined as the ratio of all electricity used by the data centre to the electricity used just by the IT equipment. In contrast to the original PUE [3b] rated in kilowatts of power (kW), PUE2 must be the highest measured kilowatt hour (kWh) reading. In 3 of the 4 PUE categories now defined, the readings must span a 12 month period, eliminating the effect of seasonal fluctuations in ambient temperature:

$$\text{PUE} = \frac{\text{Total Data Centre Electricity (kWh)}}{\text{IT Equipment Electricity (kWh)}}$$

A PUE of 2.0 suggests that for each kWh of IT electricity used another kWh is used by the infrastructure to supply and support it. The most recent PUE averages [4a, 4b] for the industry fall within the range of 1.83 – 1.92 with worst performers coming in at 3.6 and a few top performers publishing results below 1.1 in recent months. Theoretically, the best possible PUE is 1.0 but a web-hosting company (Pair Networks) recently published a PUE of 0.98 for one of its data centres in Las Vegas, Nevada. Whether additional PUE ‘credit’ should be allowed for contributing to the electricity grid is debatable. If this were the case PUE could eventually reach zero and cease to have any significant meaning. Other, more granular metrics (DCeP and DCiE) have been designed for the industry but have not as yet experienced the same wide spread popularity as PUE.

Surprisingly, efforts to improve efficiency have not been implemented to the extent one would expect. 73% of respondents to the most recent Uptime Institute survey [5] stated that someone outside of the data centre (the real estate/facilities department) was responsible for paying the utility bill. 8% of data centre managers weren’t even aware *who* paid the bill. The lack of accountability is obvious and problematic. If managers are primarily concerned with maintaining the data centre on a daily basis there is an inevitable lack of incentive to implement even the most basic energy efficiency strategy. It is clear that a paradigm shift is required to advance the cause of energy efficiency monitoring at the ‘C-level’ (CEO, CFO, CIO) of data centre operations.

Guidelines

Data centre guidelines are intermittently published by The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE). These guidelines [6a, 6b, 6c] suggest ‘allowable’ and ‘recommended’ temperature and humidity ranges within which it is safe to operate IT equipment. The most recent edition of the guidelines [6c] suggests operating temperatures of 18 – 27°C. The maximum for humidity is 60% Relative Humidity (RH).

One of the more interesting objectives of the recent guidelines is to copper fasten the rack inlet as the position where the temperature and humidity should be measured. The majority of data centres currently measure at the return inlet to the AHU despite the inlet to the racks

being a more accurate position to measure temperature and humidity metrics. The purpose of the cooling system is to maintain the equipment in the racks at safe operating temperatures. It is the temperature (and humidity) at these racks that should be monitored rather than the air returning to the AHU. The closer to the server the measurements are taken the more ‘sensitive-to-reality’ dependent cooling actuations will be.

An even more accurate measurement position than the rack inlet is discussed in Paper 4 of this review where it is suggested that the temperature, humidity and air flow metrics should be collected from the servers themselves. With recent developments in chip design, this is becoming increasingly possible but has not yet been implemented in the wider data centre environment.

2007 EPA Report to US Congress

In response to Public Law 109–431 the U.S. EPA ENERGY STAR Program released a report to the U.S. Congress on 2nd August 2007 [7]. The report included assessment of opportunities for energy efficiency improvements for data centres in the United States. Prior to the report, global energy efficiency efforts were fragmented across the data centre industry. The process of preparing the report brought all the major industry players together and formed the baseline for most of the subsequent research and development which has taken place.

Energy Efficiency Opportunities

In an effort to identify a range of energy efficiency opportunities, 3 main improvement scenarios were formulated by the EPA report:

1. **Improved Operation:** maximises the efficiency of the existing data centre infrastructure by utilising improvements such as ‘free cooling’ and raising temperature/humidity set-points. Minimal capital cost (‘the low hanging fruit’) is incurred by the operator
2. **Best Practice:** adopt practices and technologies used in the most energy-efficient facilities
3. **State-of-the-art:** uses all available energy efficiency practices and technologies

The suggested improvements directly relating to the cooling system included:

1. Improve airflow using Computational Fluid Dynamics (CFD) visualisation techniques
2. Calibrate temperature and humidity sensors
3. Adjust operating temperatures and humidity set-points while maintaining manufacturers' equipment specifications
4. Deploy 'free cooling' using air and water-side economisers
5. Analyse the opportunity for liquid-based cooling (in-chip, in-chassis, in-rack, in-row)
6. Review potential for Combined Heat & Power (CHP) which uses waste heat for cooling

The potential electricity savings and associated capital expenditure (CapEx) calculated for each of the 3 scenarios was:

1. **Improved Operation:** 20% saving - least expensive
2. **Best Practice:** 45% saving
3. **State-of-the-art:** 55% saving - most expensive

A proviso was offered in that, due to local constraints, the best strategy for a particular data centre could only be ascertained by means of a site-specific review - not all suggested scenarios apply to all data centres.

Examination of 4 significant papers relating to energy efficient cooling of data centres follows. The papers were written by both academic and industry researchers. They are dated 2000, 2006, 2008 and 2011 respectively. Many papers [Appendix A] were considered for review but eliminated for one reason or another:

- Issues were repeated
- Bias towards the commercial products or solutions of the publishers
- Papers were clustered in the same time frame and the most relevant to the subject matter of this review had to be chosen in an effort to fulfil objective (1) of this review

Paper 1

2000: Heat Density Trends in Data Processing, Computer Systems and Telecommunications Equipment [8]

The Uptime Institute published this white paper in 2000. It detailed historical and projected trends in power consumption and heat dissipation for IT equipment. The time span used for the study was 1992 - 2010. Most of the major players in the IT manufacturing industry at the time (including Dell, HP, Intel, IBM, Cisco Systems and Sun Microsystems) were involved in the preparation of the paper. They analysed and projected their best estimates of watts-per-square-foot (watts/ft^2) power densities for their own products. Their results also included projected heat dissipation. As increased density was becoming an issue around 2000, this paper serves as a starting point for looking at the more recent impact of densification in data centres and suggested strategies for dealing with the associated increase in cooling demand.

An average of approximately 15% was reported as the potential annual increase in power density for servers manufactured by those involved. Retrospective densities from 1992 – 2000 increased from 250 watts/ft^2 to 900 watts/ft^2 . It was also forecast that the percentage increase would expand year on year through 2010.

It was clear that the increase in power density would need a proportionate response from the cooling system responsible for removing the associated heat. It was predicted in the paper that:

“...and at some point in the not so distant future, hardware manufacturers are going to have to consider a return to water cooling or other methods of removing heat from their boxes”.

The different responsibilities of the equipment manufacturer and the data centre operator were also presented:

“Removing heat from the data centre is not the responsibility of the hardware manufacturer,” the paper states. Manufacturers must exhaust the heat from their own products but it is then up to the data centre operator to remove that heat from both the rack and the wider room environment.

Moving forward, the paper predicts, data centres will have to review their cooling strategies to handle the excess heat dissipated from the increased density. Possible solutions offered included:

- Physical relocation of racks to spread the heat load more evenly
- Increasing sub-floor plenum pressure by permanently blocking unnecessary air escape routes
- Replacing perforated floor tiles (25% open) with grated tiles (40 – 60% open)
- Matching Mean Time To Failure (MTTF) with UPS discharge time

While this paper may have been based on best estimates at the time of publishing (the proviso is included from the manufacturers involved), the trends for increased density which were projected have proven reasonably accurate in the years since [9]. Increasing demand will be placed on cooling systems to handle the rise in heat dissipation as density increases year on year.

Paper 2

2006: Viability of Dynamic Cooling Control in a Data Center Environment [10]

In the context of dynamically controlling the cooling system Boucher *et al.* focused their efforts on 3 requirements:

1. A distributed sensor network to indicate the local conditions of the data centre.
Solution: a network of temperature sensors was installed at:
 - Rack inlets
 - Rack outlets
 - Tile inlets
2. The ability to vary cooling resources locally. **Solution:** 3 actuators which exist in a typical data centre were identified:

2.1 CRAC supply temperature – this is the temperature of the conditioned air entering the room. CRACs are typically operated on the basis of a single temperature sensor at the return side of the unit. This sensor is responsible for taking an average of the air temperature returning from the room. The CRAC then correlates this reading with a set-point which is configured manually by data centre staff. The result of the correlation is the basis upon which the CRAC decides by how much the temperature of the air sent back out into the room should be adjusted. Variation is achieved in a Direct Expansion (DX) system with variable capacity compressors varying the flow of refrigerant across the cooling coil. In a water-cooled system chilled water supply valves modulate the temperature.

The crucial element in the operational equation of the CRAC, regardless of the system deployed, is the set-point. The set-point is manually set by data centre staff and generally requires considerable analysis of the data centre environment before any adjustment is made. Typically, the set-point is configured (when the CRAC is initially installed) according to some prediction of the future cooling demand. Due to a number of factors (including the cost of consultancy) it is all too common that no regular analysis of the room's thermal dynamics is performed (if at all). This is despite instalment of additional IT equipment (and increased work load on the existing infrastructure) throughout the lifecycle of the data centre. Clearly a very static situation exists in this case.

2.2 CRAC fan speed – the speed at which the fans in the CRAC blow the air into the room (via a sub-floor plenum). In 2006 (at the time of this paper), typical CRACs had fans running at a set speed and without further analysis no reconfiguration took place after installation. Most CRACs since then have been designed with Variable Speed Drives (VSDs) - which can vary the speed of the fan according to some set of rules. However, with no dynamic thermal analysis of the data centre environment taking place on a regular basis, the VSD rules are effectively hardwired into the system. The VSDs are an unused feature of the CRAC as a result.

2.3 Floor tile openings – the openings of the floor tiles in the cold aisle. The velocity at which the cold air leaving the CRAC enters the room is dependent upon a number of factors. Assuming it has passed through the sub-floor plenum with minimal pressure loss, the air will rise into the room at some velocity (via the floor tile openings). Floor tiles are either perforated or grated. Perforated tiles typically have 25% of their surface area open whereas grated tiles may have 40 – 60% of their surface open. The more open surface area available on the tile the higher the velocity with which the air will enter the room. The authors had previously designed and implemented a new tile - featuring an electronically controlled sliding damper mechanism which could vary the size of the opening according to requirements.

So it is evident that as a typical data centre matures and the thermodynamics of the environment change with higher CPU loads and additional IT equipment, the cooling system should have a dynamic cooling control system to configure it for continuous maximum efficiency. Boucher et al. propose that this control system should be based on the 3 available actuators above.

3. The knowledge of each variable's effect on data centre environment. **Solution:** the paper focused on how each of the actuator variables (2.1, 2.2 and 2.3 above) can affect the thermal dynamic of the data centre.

Included in the findings of the study were:

- CRAC supply temperatures have an approximate linear relationship with rack inlet temperatures. An anomaly was identified where the magnitude of the rack inlet response to a change in CRAC supply temperature was not of the same order. Further study was suggested.
- Under-provisioned flow provided by the CRAC fans affects the Supply Heat Index (SHI*) but overprovisioning has a negligible effect. SHI is a non-dimensional measure of the local magnitude of hot and cold air mixing. Slower air flow rates cause an increase in SHI (more mixing) whereas faster air flow rates have little or no effect.

*SHI is also referred to as Heat Density Factor (HDF). The metric is based on the principle of a thermal multiplier θ_i which was formulated by Sharma *et al.* [11]

The study concluded that significant energy savings (in the order of 70% in this case) were possible where a dynamic cooling control system was appropriately deployed.

Paper 3

2008: Impact of Rack-level Compaction on the Data Centre Cooling Ensemble [12]

Shah *et al.* deal with the impact on the data centre cooling ensemble when the density of compute power is increased. The cooling ‘ensemble’ is considered to be all elements of the cooling system from the chip to the cooling tower.

Increasing density involves replacing low-density racks with high-density blade servers and has been the chosen alternative to purchasing (or renting) additional space for most data centres in recent years. New enterprise and colocation data centres also implement the strategy to maximise the available space. Densification leads to increased power dissipation and corresponding heat flux within the data centre environment.

A typical cooling system performs two types of work:

1. Thermodynamic – removes the heat dissipated by the IT equipment
2. Airflow – moves the air through the data centre and systems

The metric chosen by Shah *et al.* for evaluation in this case is the ‘grand’ Coefficient of Performance (COP_G) which is a development of the original COP metric suggested by Patel *et al.* [13, 14]. It measures the amount of heat removed by the cooling infrastructure per unit of power input and does so at a more granular level than the traditional COP used in thermodynamics, specifying heat removal at the chip, system, rack, room and facility levels.

In order to calculate the COP_G of the model used for the test case each component of the cooling system needed to be evaluated separately, before applying each result to the overall system. Difficulties arose where system-level data was either simply unavailable or, due to high heterogeneity, impossible to infer. However, the model was generic enough that it could be applied to the variety of cooling systems currently being used by ‘real world’ data centres.

The assumption that increased density leads to less efficiency in the cooling system is incorrect. If elements of the cooling system were previously running at low loads they would

typically have been operating at sub-optimal efficiency levels. Increasing the load on a cooling system may in fact increase its overall efficiency through improved operational efficiencies in one or more of its subsystems.

94 existing low-density racks were replaced with high-density Hewlett Packard (HP) blades. The heat load increased from 1.9MW to 4.7MW. The new load was still within the acceptable range for the existing cooling infrastructure. No modifications to the ensemble were required.

Upon analysis of the results, COP_G was found to have increased by 15%. This was, in part, achieved with improved efficiencies in the compressor system of the CRACs. While it is acknowledged that there is a crossover point at which compressors become less efficient, the increase in heat flux of the test model resulted in raising the work of the compressor to a point somewhere below this crossover. The improvement in compressor efficiency was attributed to the higher density HP blade servers operating at a higher ΔT (reduced flow rates) across the rack. The burden on the cooling ensemble was reduced - resulting in a higher COP_G .

With the largest individual power consumption (about 40% in this case) typically coming from the CRAC - which contains the compressor - it makes sense to direct an intelligent analysis of potential operational efficiencies at that particular part of the system.

The paper states that: “The continuously changing nature of the heat load distribution in the room makes optimization of the layout challenging; therefore, to compensate for recirculation effects, the CRAC units may be required to operate at higher speeds and lower supply temperature than necessary. Utilization of a dynamically coupled thermal solution, which modulates the CRAC operating points based on sensed heat load, can help reduce this load”.

In this paper Shah *et al.* present a model for performing evaluation of the cooling ensemble using COP_G , filling the gap of knowledge through detailed experimentation with measurements across the entire system. They conclude that energy efficiencies are possible via increased COP in one or more of the cooling infrastructure components. Where thermal management strategies capable of handling increased density are in place, there is significant motivation to increase density without any adverse impact on energy efficiency.

Paper 4

Data Center Efficiency with Higher Ambient Temperatures and Optimized Cooling Control [15]

Ahuja *et al.* introduce the idea of deviation from design intent. When a data centre is first outfitted with a cooling system, best estimates are calculated for future use. The intended use of the data centre in the future is almost impossible to predict at this stage. As the lifecycle of the data centre matures, the IT equipment will deviate from the best estimates upon which the cooling system was originally designed to operate. Without on-going analysis of the data centre's thermal dynamics, the cooling system may become decreasingly 'fit-for-purpose'.

As a possible solution to this deviation from intent, this paper proposes that cooling of the data centre environment should be controlled from the chip rather than a set of remote sensors in the room or on the rack doors. Each new IT component would have chip-based sensing already installed and therefore facilitate a "plug 'n' play" cooling system.

The newest Intel processors (since Intel® Pentium® M) on the market feature an 'on-die' Digital Thermal Sensor (DTS). DTS provides the temperature of the processor and makes the result available for reading via Model Specific Registers (MSRs). The Intel white paper [16] which describes DTS states that:

"... applications that are more concerned about power consumption can use thermal information to implement intelligent power management schemes to reduce consumption."

While Intel is referring to power management of the server itself, DTS could theoretically be extended to the cooling management system also.

Current data centres control the air temperature and flow rate from the chip to the chassis but there is a lack of integration once the air has left the chassis. If the purpose of the data centre is to house, power and cool every chip then it has the same goal as the chassis and the chassis is already taking its control data from the chip. This strategy needs to be extended to the wider room environment in an integrated manner.

The industry has recently been experimenting with positioning the cooling sensors at the front of the rack rather than at the return inlet of the AHU. The motivation for this is to sense the air temperature which matters most – the air which the IT equipment uses for cooling. The disadvantage of these remote sensors (despite being better placed than sensors at the AHU return inlet) is that they are statically positioned, a position which may later be incorrect should changes in the thermal dynamics of the environment occur. The closer to the server one senses - the more reliable the sensed data will be for thermal control purposes. Ahuja *et al.* propose that the logical conclusion is to move the sensors even closer to the server – in fact, right into the processor. If those sensors already exist (as is the case with the Intel processors) then use should be made of them for a more accurate cooling management system.

The paper investigates the possible gains by moving the temperature sensors (and changing the set-point accordingly) to a variety of positions in the data centre:

1. AHU return – 28°C
2. AHU supply – 18°C
3. Rack inlet – 23°C
4. Server - 30°C

The first test was carried out on a single isolated rack with those results then extrapolated to a data centre model with a cooling capacity of 100kW. 4 perimeter down-flow AHUs (N + 1 redundancy) performed the heat removal. While the 4 rows in the data centre were not contained they did follow the standard hot / cold aisle arrangement. The tests showed that use of the server sensors resulted in more servers being maintained within the ASHRAE guideline temperature range of 18 – 27°C. Controlling the cooling system at the server yielded maximum benefit.

Ahuja *et al.* concluded that a processor-based set of metrics capable of controlling a power management scheme on the server should, by extension, also be capable of controlling a dynamic cooling control system outside the rack. If every server in a data centre was intermittently reporting its operating temperature (and air flow*) to a cooling control system, the cooling system would be operating on a more robust data set – more accurate readings -

and deliver higher energy efficiency savings than possible with previous data centre configurations.

*As of March 2011, Intel proposes to add air flow sensors to future processor designs.

Conclusions & Further Research

The functional dependency for a Thermal Management System (TMS) as mentioned in Shah *et al.* (Paper 1) involves:

1. The heat load sensed somewhere in the data centre (most likely calculation(s) based on multiple values sensed in numerous locations throughout the data centre). Which set of locations are optimal for any particular data centre requires analysis specific to that data centre.

Despite a widely published Green Grid case study [17] recommendation to “Reposition the CRAH temperature/humidity sensors from the inlets of the CRAHs to the front of the IT equipment racks”, only 12% of 525 respondents to the ‘Inaugural Annual Uptime Institute Data Center Survey’ [18] stated that they control their data centre temperature in this way. 40% still measure the control temperature at the return side of the air handling unit.

2. The consequent modulation of the CRAC or AHU operating set-points. Modulation of the CRAC or AHU typically involves:
 - a) The compressor - which controls the temperature of the refrigerant flowing through the heat exchanger - the thermodynamic work
 - b) The blowers – controlling the velocity of the cold air entering the room – performing airflow work

A typical TMS would operate dynamically. It would have an interval set according to the requirements of the specific data centre e.g. 5 minutes. At each occurrence of this interval the TMS would go through the process of identifying the heat load in the data centre and checking whether the current configuration is ‘fit-for-purpose’. It would reconfigure the AHUs by:

1. Adjusting temperature and humidity set-points automatically or
2. Logging suggestions for appropriate temperature and humidity changes. Data centre operations staff would include these suggestions in a decision-making process before applying any required AHU reconfiguration manually or via a software interface

Cooling systems are traditionally configured for operation at higher loads than those identified during installation. Consequently, no reconfiguration takes place when additional IT equipment is added to the environment. This reconfiguration would require dedicated consultancy to determine a strategy to accommodate the increased density – a consultancy which is typically beyond the scope of most operating budgets. Even if the consultancy were to take place it would result in a static (‘snapshot’) view of the data centre and would need to be repeated for further reconfigurations – required by changes in the thermal dynamics of the data centre.

With additional IT equipment retrospectively added to the environment or increased load on existing IT equipment, the locations within the data centre at which the sensing is performed would also require review:

1. Hardware sensors result in additional expense above and beyond the cost of the new servers.
2. Sensors available in the servers would eliminate the additional expense on hardware sensors. DTS is already embedded into most new Intel servers – eliminating the cost of new hardware sensors. Including the new values in the sensing component of the TMS could be automated – requiring little or no additional configuration by data centre staff

Regardless of how and where the sensing is performed, a modular system where the individual decision functions are kept separate from each other (heat load calculations are performed in isolation from the modulation decisions for the AHU) would be more scalable than a non-modular decision-making system.

It is questionable whether the heat distribution in the room really matters at all if each server or IT component is intermittently reporting its status. If a server reports that it is heating up towards its maximum junction temperature (via on-chip DTS) a dynamic cooling system would be capable of deciding how best to reduce the load on the server by:

1. Increasing the air flow to the server
2. Decreasing the temperature of the air supplied to the server

3. Redistributing the work in a virtualised environment

While strategies (1, 2) are already deployed in server power / thermal management systems, a similar set of operational rules could be extended to the cooling system of the data centre. (1, 2) above directly involve actuation of cooling system components. It is clear, however, that an integrated modular approach would be required to implement (3) because ‘handing off’ of responsibility to the virtualisation manager is necessary. From a software point of view, the virtualisation interface would accept a single parameter – which server is approaching its junction temperature – and take responsibility for redistributing the load, reporting back to the cooling system when the virtualisation task has been completed. The virtualisation manager would not receive any communication from the cooling system controller unless it had already been established that action was required. Detailed analysis of the data from the DTS would involve intelligent pattern identification which would eliminate anomalies and outliers from the equation.

With a modular system, the type of cooling system deployed becomes irrelevant as it is decoupled from the management system. Water-based systems would act in a similar manner to air-cooled systems – receiving instructions from the management system to increase or decrease cooling. Actuation of the instructions would be specific to each particular cooling system.

A modular chip-based cooling system would scale naturally (adapting to installation of additional IT equipment) and would also resist technological changes in IT equipment or cooling system components.

It is clear that, as data centre power densities increase in the coming years, more accurate and robust cooling solutions will be required to increase COP, achieving consequent energy efficiencies and lowering Total Cost of Ownership (TCO). Manufacturers are beginning to design their hardware products with this in mind and integrated software solutions will inevitably follow.

References

- [1] Sharma, R.K.; Bash, C.E.; Patel, C.D.; Friedrich, R.J.; Chase, J.S., "Balance of Power: Dynamic Thermal Management for Internet Data Centers," *Internet Computing, IEEE*, vol.9, no.1, pp. 42-49, January 2005
- [2] Moore, J.; Sharma, R.; Shih, R.; Chase, J.; Patel, C.; Ranganathan, P., "Going Beyond CPUs: The Potential of Temperature-Aware Solutions for the Data Center", Hewlett Packard Labs, 2002
- [3a] Data Center Efficiency Task Force, "Recommendations for Measuring and Reporting Version 2 – Measuring PUE for Data Centers", 17th May 2011
- [3b] C. Belady, A., Rawson, J. Pfleuger, and T., Cader, "Green Grid Data Center Power Efficiency Metrics: PUE and DCIE," *The Green Grid*, 2008
- [4a] Koomey J.G., "Estimating Total Power Consumption by Servers in the U.S. and the World", 2007
- [4b] Koomey J.G., "Growth in Data Center Electricity Use 2005 to 2010", report by Analytics Press, completed at the request of The New York Times, August 2011
- [5, 18] The Uptime Institute, "Inaugural Annual Uptime Institute Data Center Industry Survey", Uptime Institute, May 2011
- [6a] ASHRAE, "Datacom Equipment Power Trends and Cooling Applications", ASHRAE INC, 2005
- [6b] ASHRAE, "Environmental Guidelines for Datacom Equipment - Expanding the Recommended Environmental Envelope", ASHRAE INC, 2008
- [6c] ASHRAE, "Thermal Guidelines for Data Processing Environments – Expanded Data Center Classes and Usage Guidance", ASHRAE INC, August 2011

- [7] Energy Star Program - U.S. Environmental Protection Agency, "EPA Report to Congress on Server and Data Center Energy Efficiency", EPA, Aug 2007.
- [8] Uptime Institute, "Heat Density Trends in Data Processing, Computer Systems and Telecommunications Equipment", Uptime Institute, 2000
- [9] ASHRAE, "Datacom Equipment Power Trends and Cooling Applications", Chapter 3, Fig 3.10 new ASHRAE updated and expanded power trend chart, ASHRAE, 2005
- [10] Boucher, T.D.; Auslander, D.M.; Bash, C.E.; Federspiel, C.C.; Patel, C.D., "Viability of Dynamic Cooling Control in a Data Center Environment," Thermal and Thermomechanical Phenomena in Electronic Systems, 2004. IThERM '04. The Ninth Intersociety Conference on, pp. 593- 600 Vol. 1, 1-4 June 2004
- [11] Sharma, R.K.; Bash, C.E.; Patel, C.D.; Friedrich, R.J.; Chase, J.S.; , "Balance of Power: Dynamic Thermal Management for Internet Data Centers," Internet Computing, IEEE , vol.9, no.1, pp. 42- 49, Jan.-Feb. 2005
- [12] Shah, A.; Patel, C.; Bash, C.; Sharma, R.; Shih, R.; , "Impact of Rack-level Compaction on the Data Center Cooling Ensemble," Thermal and Thermomechanical Phenomena in Electronic Systems, 2008. IThERM 2008. 11th Intersociety Conference on, pp.1175-1182, 28-31 May 2008
- [13] C. Patel, et al., "Energy Flow in the Information Technology Stack: Coefficient of Performance of the Ensemble and its Impact on the Total Cost of Ownership," Technical Report No. HPL-2006-55, Hewlett Packard Laboratories, March 2006
- [14] C. Patel, et al., "Energy Flow in the Information Technology Stack: Introducing the Coefficient of Performance of the Ensemble," Proc. ASME IMECE, November 2006
- [15] Ahuja, N.; Rego, C.; Ahuja, S.; Warner, M.; Docca, A.; "Data Center Efficiency with Higher Ambient Temperatures and Optimized Cooling Control," Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM), 2011 27th Annual IEEE, pp.105-109, 20-24 March 2011

[16] Berktold, M.; Tian, T., “CPU Monitoring With DTS/PECI”, Intel Corporation, September 2010

[17] Green Grid, “The ROI of Cooling System Energy Efficiency Upgrades” Green Grid, White Paper #39, 2007

Appendix A

Other Papers Considered for this Review

[1] Uptime Institute Professional Services, "Data Center Site Infrastructure Tier Standard: Topology", Uptime Institute, 2009.

[2] Patterson, M.K., Costello, D., Grimm P, Loeffler, M., "Data Center TCO; A Comparison of High-density and Low-density Spaces," THERMES 2007, Santa Fe, NM, 2007

[3] Ibrahim, M.; Gondipalli, S.; Bhopte, S.; Sammakia, B.; Murray, B.; Ghose, K.; Iyengar, M.K.; Schmidt, R.; , "Numerical Modeling Approach to Dynamic Data Center Cooling," Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 2010 12th IEEE Intersociety Conference on, pp.1-7, 2-5 June 2010

[4a] Breen, T.J.; Walsh, E.J.; Punch, J.; Shah, A.J.; Bash, C.E.; , "From Chip to Cooling Tower Data Center Modeling: Part I Influence of Server Inlet Temperature and Temperature Rise Across Cabinet," Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 2010 12th IEEE Intersociety Conference on, pp.1-10, 2-5 June 2010

[4b] Walsh, E.J.; Breen, T.J.; Punch, J.; Shah, A.J.; Bash, C.E.; , " From Chip to Cooling Tower Data Center Modeling: Part II Influence of Chip Temperature Control Philosophy," Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 2010 12th IEEE Intersociety Conference on, pp.1-10, 2-5 June 2010

[5] Zhikui Wang; Bash, C.; Hoover, C.; McReynolds, A.; Felix, C.; Shih, R.; , "Integrated Management of Cooling Resources in Air-cooled Data Centers," Automation Science and Engineering (CASE), 2010 IEEE Conference on, pp.762-767, 21-24 August 2010

[6] S. Greenberg, E. Mills, B. Tschudi, P. Rumsey, B. Myatt, "Best Practices for Data Centers: Results from Benchmarking 22 Data Centers", In Proc. of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings

[7] Ranganathan, P.; Leech, P.; Irwin, D.; Chase, J., "Ensemble-level Power Management for Dense Blade Servers," Computer Architecture, 2006. ISCA '06, 33rd International Symposium on, pp.66-77

[8] Sharma et al., "On Building Next Generation Data Centers – Energy Flow in the Information Stack," Proc. ACM Compute, Bangalore, India, January 2008.