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Energy Consumption Modeling of Data Center IT Room with Distributed Air Flow

Xiaojing Zhang[1], Therese Lindberg[2], Krister Svensson[2], Valeriy Vyatkin[3,4], Arash Mousavi[3]
[1]ABB Corporate Research, Västerås, Sweden
[2]Department of Engineering and Physics, Karlstad University, Sweden
[3]Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, Luleå, Sweden [4]Aalto University, Helsinki, Finland xiaojing.zhang@se.abb.com

Abstract **Modern data centers are characterized with large sizes, high energy consumption and complexity of involving IT, power supply, ventilation and cooling. Data center energy efficiency is a major concern for data center design and operation. To improve data center energy efficiency through efficient cooling, ventilation and advanced process control and optimization, process models to describe the process energy consumption are required. In this work, literature study was made to investigate available data center energy consumption models. Objective is to develop an improved comprehensive data center energy consumption models to describe IT room, computer room air handling (CRAH), ventilation and cooling energy characteristics as well as distributed air flow. The models are intended to be used for simulating various data center design and operation scenarios in our next phase of work.**

Keywords: server; rack; CRAH, model; energy efficiency

I. Introduction

The worldwide energy consumption of data centers increased 56% between 2005 and 2010, and reached 237 terawatt hours (TWh) in 2010, accounting for over 1% of the world's electricity usage [1]. It is estimated that the market was worth about $128 billion in 2012, and will grow by about 5 percent yearly to reach $152 billion in 2016 [2]. Meanwhile there is a trend to build mega-data centers with capacity over 20 MW. Energy efficiency becomes an important issue in these mega-data centers. We have made an investigation of 10 random data centers showed in Fig. 1, which revealed the energy consumption by cooling data center IT equipment is between 30% and 55% of total energy consumption. Cooling and ventilation system consumes on average 39% of the total energy consumption. Therefore, how to improve power utilization, reduce operation costs and increase energy efficiency must be taken into account before building up a data center. There are several approaches to increase the energy efficiency. One of them is through process modeling, simulation, control and optimization, which is used in this work. A modern data center has a large room with many rows of racks filled with servers and other IT equipment used for process, store and transmit digital information. Previous work from Grenoble Institute of Technology provided system models for IT system and data center cooling system including server modelling and power equipment losses [3]. The model was used to build a simulation tool to estimate and simulate the energy consumption of all equipment in the data center.

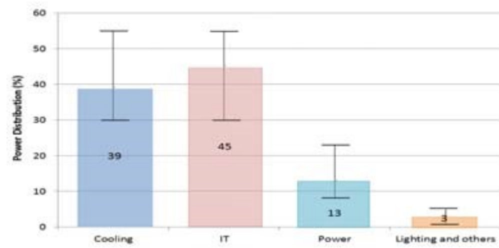

Fig. 1. Data center energy consumption distribution and variation.

Another approach is to combine computational fluid dynamics and heat transfer modelling was proposed by *Joshi* and *Kumar* [4], which gives a detailed description of the flow and the temperatures across the room. A limitation to this method is its complexity and high computationally intensive. The energy consumption model of the different cooling system components was developed by *Iyengar* and *Schmidt* [5][6]. They introduced a relationship between the flow rates of the CRAH units and the server racks *Pelley et al.* published data center model included an idle consumption of the CRAH units [7]. *Beitelmal et al.* further developed chiller and cooling tower model [8], while *Demetriou et al.* included hydraulic modelling of the pipe network in the model of the cooling system [9]. Recently published model from *Cupertino et al.* was main focused on workload modelling [10].

In the conventional data center with hot aisle/cold aisle, cold air generated by the cooling system is supplied through a plenum under the floor and perforated air flow panels. The cold air flows up entering the tiny spaces between the servers from one side of the servers and leaving from another side. Higher flow pressure drop, cold and warm air mixing on the up side of racks are main disadvantages. To solve these problems, data center racks with vertically placed servers are proposed [11] and shown in Fig. 2.

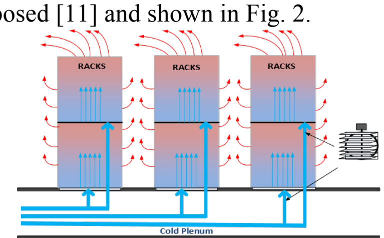

Fig. 2. Distributed ventilation for vertical placed server rack design.

II. DISTRIBUTED AIR FLOW

Many data centers operate under uneven IT load and cooling load over different racks. To meet the cooling needs of all servers and racks without local overcooling, distributed air flow control is required to divide a data center in different zones and controllable openings (showed in Fig. 2). With the distributed air flow control, different amounts of air flow are supplied to different zones across the data center based on local cooling load. In this way, overcooling can be reduced or even eliminated, which results in a significant energy saving. The size of these zones (the number of racks in each zone), is related to how we design the ventilation and air flow system. The distributed air flow control can be implemented in a traditional raised-floor data center or air flow control with vertically placed servers.

III. DATA CENTER MODELING

A data center consists of several complex systems comprising the IT equipment as the main heat source and cooling equipment, ventilation system as heat sink. A number of approximations and assumptions are made to simplify the modeling effort,

-Neglect change in the temperature between CRAH outlet temperature and rack inlet temperature

-Neglect the change in temperature over rack and CRAH fans

-All CRAH units supplying air to all zones with same server utilization and same heat load. CRAH inlet temperature is coupled to the rack outlet temperature of the zone where air is supplied

-The server fans are assumed to be able to, and operate on the principle of, keeping the outlet temperature constant. In the case of racks with vertical servers, all server fans operate on the principle of keeping the outlet temperature of the last row constant.

-The air flow rate through a rack is evenly distributed and all servers get the same flow rate.

-There is no recirculation, but a constant air bypass is included (except for distribution control with rack supply).

-The change in kinetic energy can be neglected in all energy balances

-Air is modelled as an ideal gas

Complete data center power consumption simulation model is under development. The models of server power, rack power, CRAH power, pressure drop over CRAH, flow rates of rack and CRAH are presented in this paper.

A. Server power

The server power consumption is assumed to be linear with the server work load and it can be calculated from Equation (1) [1]. Idle power is related to the maximum power consumption.

$$P_{server} = P_{server\_idle} + (P_{server\_peak} - P_{server\_idle})u_{zone\_y} \tag{1}$$

$$P_{server\_idle} = xP_{server\_peak} \tag{2}$$

where *Uzone_y* is the server utilization, a fraction of the maximum server work load. *Uzone_y* differs depending on the design and operation scenarios. The index *y* refers to the quantity belongs to racks with utilization of type *y*. It is defined as server utilization group which is related to scenarios, for example, *y* can refer to servers that are idle.

The rack heat load is simply the power consumption of all servers in a rack.

$$\dot{Q}_{rack} = N_{server\_rack}\dot{Q}_{server} = N_{server\_rack}P_{server} \tag{3}$$

B. Pressure drop over CRAH

CRAH power consumption is related to system pressure drop. For standard type of racks, the pressure drop over the CRAH units was developed [3][5]. The change in pressure over a rack consists of three parts, the drop over front doors, rear doors and servers, where the servers are stacked on top of each other in parallel. For the vertical placed server rack showed in Fig. 2, the pressure drop is further developed in this study. This setup consists of two separated compartments with individual air supply. Each compartment has three rows of racks. The main air stream flows up to top and the air can leave the rack between the rows as minor side flows and leakage. Since the air flow enters at the bottom of the compartments, the flow rate will be reduced for each row further up. Because of the change in flow rate, the pressure drop needs to be determined for each row. With three rows (1, 2 and 3) and two compartments (lower and upper in Fig. 2), this gives six pressure drop equations,

$$\Delta p_{lower,1} = C_{server}^2 \dot{V}_{server}^2 = C_{server}^2 \left(\frac{\dot{V}_1}{\frac{N_{server\_rack}}{N_{row\_rack}}} \right)^2$$
$$\Delta p_{lower,2} = C_{server}^2 \left(\frac{\dot{V}_2}{\frac{N_{server\_rack}}{N_{row\_rack}}} \right)^2$$
$$\Delta p_{lower,3} = C_{server}^2 \left(\frac{\dot{V}_3}{\frac{N_{server\_rack}}{N_{row\_rack}}} \right)^2 + C_{bend}^2 \dot{V}_3^2 \tag{4}$$

$$\Delta p_{upper,1} = C_{server}^2 \left(\frac{\dot{V}_1}{\frac{N_{server\_rack}}{N_{row\_rack}}} \right)^2 + C_{dist}^2 \dot{V}_1^2$$
$$\Delta p_{upper,2} = C_{server}^2 \left(\frac{\dot{V}_2}{\frac{N_{server\_rack}}{N_{row\_rack}}} \right)^2$$
$$\Delta p_{upper,3} = C_{server}^2 \left(\frac{\dot{V}_3}{\frac{N_{server\_rack}}{N_{row\_rack}}} \right)^2 \tag{5}$$

where $\dot{V}1$, $\dot{V}2$, $\dot{V}3$ are the flow rates through the first, second and third row of each $\dot{V}$compartment, respectively. *Cbend* is the pressure loss coefficient caused by the roof of the lower compartment, which forces the flow to bend off its path and leave through the sides. *Cdist* is the pressure loss coefficient of the distributor that distributes the air flow equally in the bottom of the upper compartment. N_{row_rack} is the number of rows in each rack.

C. CRAH flow rate with distributed air flow control

The flow rate supplied by the CRAH units is derived with assumption of all CRAH units supply the same amount of cooling air. There are two equations to be used depending on which side of the CRAH heat exchanger has the minimum heat capacity rate. For the case of air side, CRAH flow rate is calculated implicitly as,

$$1 - \exp\left(\frac{B^{0.22}\dot{V}_{BCW}}{D\dot{V}_{CRAH}^{1.22}}\left(e^{-DB^{0.78}\frac{\dot{V}_{CRAH}^{0.22}}{\dot{V}_{BCW}}} - 1\right)\right) = \\ = \frac{A'\dot{Q}_{rack\_max}}{(T_{rack\_out\_set} - T_{CRAH\_H_2O\_in})\dot{V}_{CRAH} - \delta_{bypass}A\dot{Q}_{rack\_max}} \quad (6)$$

Both racks and CRAH units are assumed to operate on the principle of keeping the outlet temperature of the top row in the rack constant. With the rack outlet temperature as set-point parameter, CRAH flow rate can be calculated as,

$$1 - \exp\left(\frac{B^{0.22}\dot{V}_{BCW}}{D\dot{V}_{CRAH\_y}^{1.22}}\left(e^{-DB^{0.78}\frac{\dot{V}_{CRAH\_y}^{0.22}}{\dot{V}_{BCW}}} - 1\right)\right) = \\ = \frac{H\dot{Q}_{rack\_y}}{(T_{rack\_out\_set} - T_{CRAH\_H_2O\_in})\dot{V}_{CRAH\_y} + (H - G)\dot{Q}_{rack\_y}} \quad (7)$$

$$A' = \frac{N_{rack}}{\rho_{air}c_{p,air}N_{CRAH}(1 - \delta_{leakage})}$$

$$B = \frac{(UA)_{CRAH}}{\rho_{air}c_{p,air}}$$

$$D = \frac{\rho_{air}c_{p,air}N_{CRAH}}{\rho_{H_2O}c_{p,H_2O}}$$

$$H = \frac{N_{rack}}{\rho_{air}C_{p,air}N_{CRAH}(1 - \delta_{leakage})}$$

D. CRAH power consumption

For complex data center operation with uneven IT load, the IT room can be divided into several zones with different various server utilization, total CRAH power consumption is sum of all rack zones.

$$P_{CRAH\_total} = \sum_y \delta_{zone\_y}N_{CRAH}\frac{(C_{CRAH\_int}(1 + \beta_{CRAH}))^2\dot{V}_{CRAH,zone\_y}^3}{\eta_{CRAH\_fan}} \quad (8)$$

where $\delta_{zone\ y}$ is the fraction of CRAH units belonging to utilization group *y*.

E. Rack flow rate

For traditional server racks the supplied flow from the CRAH units are based on the racks with the maximum heat load. For zones with lower utilization, the air bypass increases since the servers need less cooling. Rack fans will move a part of the air supplied by the CRAH units through the racks. T_{rack_in} or T_{rack_out} can be used as the set-point parameter, the mixed flow of rack flow and air bypass can be expressed as,

$$T_{rack\_in\_y} = \frac{I - J\dot{V}_{rack\_y}T_{rack\_out\_set}}{1 - J\dot{V}_{rack\_y} + K} \quad (9)$$

$$I = \frac{\epsilon_{CRAH\_HE}C_{min}T_{CRAH\_H_2O\_in}}{\epsilon_{CRAH\_HE}C_{min} - C_{air}}$$

$$J = \frac{N_{rack}}{N_{CRAH}(1 - \delta_{leakage})\dot{V}_{CRAH}}$$

$$K = \frac{C_{air}}{\epsilon_{CRAH\_HE}C_{min} - C_{air}}$$

The server fans are assumed to keep the rack outlet temperature constant at the set-point value.

$$\dot{V}_{rack} = \frac{\dot{Q}_{rack}}{\rho_{air}c_{p,air}(T_{rack\_out} - T_{rack\_in})} \quad (10)$$

The rack flow rate for vertical server racks can be determined directly from the CRAH flow rate since these supply just the amount of air needed by the racks.

$$\dot{V}_{CRAH\_y} = \frac{N_{rack}\dot{V}_{rack\_y}}{N_{CRAH}(1 - \delta_{leakage})} \quad (11)$$

F. Rack power

The rack power consumption can be calculated for each zone with different utilization

$$P_{rack\_total} = \sum_y \delta_{zone\_y}N_{rack}P_{rack,zone\_y} \quad (12)$$

where $\delta_{zone\ y}$ depends on different utilization in the operation scenarios (idle or non-idle scenario). For the even load scenario the sum can be dropped and $\delta_{zone\ y}$ is simply 1.

The power consumption of an individual rack can be calculated based on fan efficiency, where an expression for the flow rate was presented in a previous section.

$$P_{rack,zone\_y} = \frac{\dot{V}_{rack}\Delta p_{rack}}{\eta_{rack\_fan}} = \\ = \frac{\left(C_{rack\_front}^2 + \frac{C_{server}^2}{N_{server\_rack}^2} + C_{rack\_rear}^2\right)\dot{V}_{rack}^3}{\eta_{rack\_fan}} = \\ = \frac{C_{rack\_tot}^2\dot{V}_{rack}^3}{\eta_{rack\_fan}} \quad (13)$$

$$P_{rack,zone\_y} = \left(\frac{2C_{server}^2 N_{row\_rack}^2 \left(1 + (1-\delta_{rack\_12})^3 + \delta_{rack\_3}^3\right)}{N_{server\_rack}^2 \eta_{rack\_fan}} + \frac{C_{bend}^2 \delta_{rack\_3}^3 + C_{dist}^2}{\eta_{rack\_fan}} \right) \frac{1}{2^3} \dot{V}_{rack,zone\_y}^3 \tag{14}$$

where Equation (13) is for traditional server racks and (14) for the vertical server racks.

IV. Summary

Progress of data center power consumption models for distributed air flow control is reported in this paper. Power consumptions of servers, racks and CRAH have been modeled to cover traditional server rack and a new server rack design with modeling flexibility. The model is intended to be used for simulations for various data center design and operation scenarios in order to improve data center energy efficiency. For the future work, we will develop complete data center models including chiller, cooling tower and cooling system. The model will be validation with available data, and typical data center operation scenarios will be simulated.

V. Reference

[1] J. G. Koomey. Growth in data center electricity use 2005 to 2010. *Analytics Press*, Oakland, 2011.

[2] J. F. Kovar. The 2014 Data Center 100, *CRN*, 2014.

[3] T. Van Giang, D. Vincent, and B. Seddik. Data center energy consumption simulator from the servers to their cooling system. In *PowerTech (POW- ERTECH), 2013 IEEE Grenoble*. IEEE, June 2013.

[4] Y. Joshi and P. Kumar. Introduction to data center energy flow and thermal management. In Y. Joshi and P. Kumar, editors, Energy E_cient Thermal Management of Data Centers, chapter 1. Springer, New York, 2012.

[5] M. Iyengar and R. Schmidt. Analytical modeling for thermodynamic characterization of data center cooling systems. Journal of Electronic Packaging, 101, June 2009.

[6] R. Schmidt and M. Iyengar. Thermodynamics of information technology data centers. IBM Journal of Research and Development, 53(3), May 2009.

[7] S. Pelley, D. Meisner, T.F. Wenisch, and F.W. VanGilder. Understanding and abstracting total data center power. In Workshop on Energy Effcient Design, 2009.

[8] A.H. Beitelmal and C.D. Patel. A steady-state model for the design and optimization of a centralized cooling system. International journal of energy research, 34:1239{1248, 2010.

[9] D.W. Demetriou, H.E. Khalifa, M. Iyengar, and R.R. Schmidt. Development and experimental validation of a thermo-hydraulic model for data centers. HVAC&R Research, 17(4):540{555, 2011.

[10] L. Cupertino, G. Da Costa, A. Oleksiak, W. Pi_atek, J. Pierson, J. Salom, L. Sis_o, P. Stolf, H. Sun, and T. Zilio. Energy-e_cient, thermal-aware modeling and simulation of data centers: The coolemall approach and evaluationresults. Ad Hoc Networks, 25:535{553, 2015.

[11] Z. Song, X. Zhang, C. Eriksson. Data Center Energy and Cost Saving Evaluation, The 7th International Conference on Applied Energy, Energy Procedia, 2015.

VI. Nomenclature

β_{CRAH}	$(1+\beta_{CRAH})$ is a correction factor of C_{CRAH_int} for inclusion of plenum and tiles
δ_{bypass}	The fraction of the flow rate supplied by the tiles that pass by the racks
$\delta_{leakage}$	The fraction of the total data center flow rate attributed to leakage
δ_{rack_12}	The fraction of the rack compartment flow rate leaving the rack between row 1 and 2
δ_{rack_23}	The fraction of the rack compartment flow rate leaving the rack between row 2 and 3
δ_{rack_3}	The fraction of the rack compartment flow rate leaving the rack at the top
$\Delta p_{lower,1/2/3}$	Pressure drop over the first/second/third row in the lower rack compartment (Pa)
Δp_{rack}	Pressure drop over one rack (Pa)
$\Delta p_{upper,1/2/3}$	Pressure drop over the first/second/third row in the upper rack compartment (Pa)
ϵ_{CRAH_HE}	The CRAH heat exchanger efficiency
η_{CRAH_fan}	Efficiency of the CRAH fans
η_{rack_fan}	Rack fan efficiency
ρ_{air}	Density of air (kg/m^3)
ρ_{H_2O}	Density of water (kg/m^3)
C_{air}	The heat capacity rate on the air side of the CRAH heat exchanger (W/K)
C_{bend}	Pressure loss coefficient due to the roof in the rack lower compartment (rack supply) $(Pa^{0.5}s/m^3)$
C_{CRAH_int}	Pressure loss coefficient of only the CRAH $(Pa^{0.5}s/m^3)$
C_{dist}	Pressure loss coefficient due to the distributor in the rack upper compartment $(Pa^{0.5}s/m^3)$
C_{min}	The smallest heat capacity rate of the CRAH heat exchanger (W/K)
$c_{p,air}$	Specific heat at constant pressure of air $(J/kg{\cdot}K)$
c_{p,H_2O}	Specific heat at constant pressure of water $(J/kg{\cdot}K)$
C_{rack_front}	Rack front cover pressure loss coefficient $(Pa^{0.5}s/m^3)$
C_{rack_rear}	Rack rear cover pressure loss coefficient $(Pa^{0.5}s/m^3)$
C_{rack_tot}	A combined pressure loss coefficient for the rack doors and servers $(Pa^{0.5}s/m^3)$
C_{server}	Server pressure loss coefficient $(Pa^{0.5}s/m^3)$
N_{CRAH}	The number of CRAH units
N_{rack}	The total number of racks
N_{row_rack}	The number of rows per rack
N_{server_rack}	The number of servers per rack
P_{CRAH_total}	Total CRAH power consumption (W)
P_{rack_total}	Total rack power consumption (W)
$P_{rack,zone\_y}$	The power consumption of the fans in one rack in zone y (W)
P_{server}	Power consumption of one server (W)
P_{server_idle}	Power consumption of an idle server (W)
P_{server_peak}	Power consumption of a server at peak load (W)
$\dot{Q}_{rack}$	The heat dissipated from the IT equipment in one rack (W)
$\dot{Q}_{rack\_max}$	The maximum heat dissipated from the IT equipment in one rack (W)
$\dot{Q}_{server}$	The heat dissipated from one server (W)
$T_{CRAH\_H_2O\_in}$	The temperature of the BCW entering the CRAH heat exchanger (K)
T_{rack_in}	The temperature of the air entering the racks (K)
T_{rack_out}	The temperature of the air leaving the racks (K)
u_{zone_y}	Server utilization in group y (for example idle)
$(UA)_{CRAH}$	Overall heat transfer coefficient times area of the CRAH heat exchanger (W/K)
$\dot{V}_{1/2/3}$	Air flow rate of the first/second/third row of one rack compartment (m^3/s)
$\dot{V}_{BCW}$	Water flow rate in the BCW loop (m^3/s)
$\dot{V}_{CRAH}$	Volumetric air flow rate in one CRAH (m^3/s)
$\dot{V}_{rack}$	Air flow rate of one rack (m^3/s)
$\dot{V}_{server}$	Air flow rates of one server (m^3/s)
x	The fraction of P_{server_idle} to P_{server_peak}