SIMULATION OF A DATA CENTER COOLING SYSTEM IN AN EMERGENCY SITUATION

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ABSTRACT

The paper deals with keeping server rooms at reasonable air temperature in the case of an electrical power failure in a data center and with building performance simulations used to support emergency power planning. An existing data center was analyzed in detail with respect to the possibilities of emergency cooling. Based on the assumption that the thermal capacity of already chilled water can be used to prolong functionality of the cooling system when the roof chillers are out of operation, a backup power supply was designed for Computer Room Air-Conditioning and even for the cooling liquid circuit pumps (i.e. not for the roof chillers).

Special models representing the data center indoor environment and cooling system, including a detailed model of the Computer Room Air Conditioning (CRAC) units, were developed in order to estimate the time period during which the internal air temperatures in the server room will not exceed the limit. The numerical model of the server room and the cooling system was built in the TRNSYS software and calibrated by measured data acquired from a real power outage situation. The results and conclusions obtained from the performed analyses and simulations helped to improve the emergency power plan of the data center. The study also forms the basis for the development of an emergency decision algorithm that will included in the novel supervisory control platform: GENiC[1]

Keywords: Data Centre, Cooling System, Emergency situation, Building Energy Simulation, GENIC control platform

SIMULACE CHLADICÍHO SYSTÉMU DATACENTRA V HAVARIJNÍM STAVU

Článek pojednává o udržení vnitřní teploty vzduchu v prostorách data centra v případě havarijní situace a o použití nástrojů pro simulaci energetického chování budov pro vyhodnocení efektivního využití nouzového zdroje elektrické energie. Byla provedena analýza skutečného data centra zejména v souvislosti s chlazením při havarijním stavu. Na základě předpokladu, že tepelná kapacita vodního chladícího okruhu může být použita k prodloužení funkce chladicího systému v době, kdy je venkovní kompresorová chladicí jednotka mimo provoz, byla záloha elektrické energie navrhnuta jak pro vnitřní chladicí jednotku data centra, tak i pro čerpadla okruhu chladicí kapaliny (ne pro venkovní kompresorovou jednotku).

Byl vyvinut speciálně navržený model pro vnitřní prostředí data centra a chladicího systému, včetně detailního modelu výměníku vnitřní chladicí jednotky za účelem odhadu doby, při které vnitřní teplota prostředí data centra nepřekročí kritickou hodnotu. Numerický model data centra a chladicího systému byl vytvořen v programu TRNSYS a kalibrován na základě dat naměřených při skutečné havárii. Výsledky získané v provedených analýzách a simulacích pomohly k lepšímu rozvržení dodávky elektrické energie ze záložního zdroje data centra. Tato studie také slouží jako podklad pro vývoj algoritmu pro automatický zásah v nouzové situaci, která bude součástí nově vyvíjené dohlížecí řídící platformy GENiC[1]

Klíčová slova: data centra, Havarijní situace, Simulace energetického chování budov, GENiC řídící platforma

INTRODUCTION

Usage of Internet became an integral part of our lives. The following numbers illustrate the huge utilization of this service. The number of Internet users exceeded 2 billion people in 2010 and the amount of transferred data was estimated at 667 billion gigabyte for year the 2013, while these numbers are expected to increase rapidly in the near future [1],[2].

Since users expect non-stop access to their applications, there is a high requirement for uninterrupted processing of data in data centers. IT management standards require operators of data centers to have a minimum of 99.671% expected availability of their IT infrastructure per year [3]. Any interruption of processing, even in case of maintenance, is very complicated and causes significant financial losses, so backup systems for electricity supply for data centers and its systems are absolutely necessary. However, the capacity of uninterrupted power systems (UPS) is usually limited for technical or economic reasons, and most of the time, energy demand cannot be fully covered in emergency situations. The operator or an advanced fault detection and diagnostics (FDD) control system

[1] more information available http://projectgenic.eu

has to decide very carefully which component should be backed up.

This paper investigates the performance of back up plans for the breakdown of data center's cooling system using building energy simulation tools. Individual components of the cooling system during the breakdown were studied in detail with respect to their influence to data center indoor environment. In particular, the influence of the chilled-water circuit thermal capacity was assessed. A complex numerical model was developed in the simulation environment TRNSYS 16 to predict energy flows and air temperatures in the data center environment. The simulation model describes in detail the cooling system including control elements and it also takes the heat accumulation in room constructions into account. Model geometry and parameters of the cooling system were set up based on descriptions from a real data center. Furthermore the model was calibrated by using measured data from a real emergency situation.

CASE STUDY DESCRIPTION

The case study deals with a server room placed in the ground floor of an administration building. The server room, with floor area 231 m^2 and layout dimension 16x14m, belongs to a category of small data centers. Wall constructions are built from standardized bricks with a thin layer of plaster, while the ceiling and floor consist of concrete. Interior concrete columns and cabling in a raised floor were considered for calculating the efficient thermal capacity of the room.

The sever room is equipped with eight rows of racks with hot and cold aisle arrangement without any separation of the data center environment (white space). The maximum internal heat gain from IT devices was estimated at 80 kW. The backup system contains only batteries for short-period electricity outage. Diesel generators are not available.

Since the server room is included in a wider complex of utility rooms and an underground garage, the ambient air temperature around the case study server room is very stable at about 18 to 20 ˚C during the whole year. This assumption was confirmed by measurements.

The indoor climate of the server room during regular operation is kept in range of 18 to 27˚C, with a relative humidity range of 30 to 60% (recommended by ASHRAE TC 9.9 Committee [4]). The limit for the inlet air temperature for IT equipment, as defined by the ASHRAE guideline, is 35 ˚C. When this limit is exceeded, automatic disconnection may occur or in the worst case IT equipment may be damaged.

The required indoor climate is ensured by 4 internal CRAC units, which are placed on one side of the room. The supply air is distributed via an under floor air distribution (UFAD) system, so supply air goes through perforated floor tiles to front side of IT devices, where is air inlet. Used hot air is taken under the ceiling from the top of CRAC units. Circulating air is adjusted in a heat exchanger, where heat is removed by cooling water. Then cooling water is transported to an air-cooled chiller on the roof. The design water temperature difference is 7/12 ˚C.

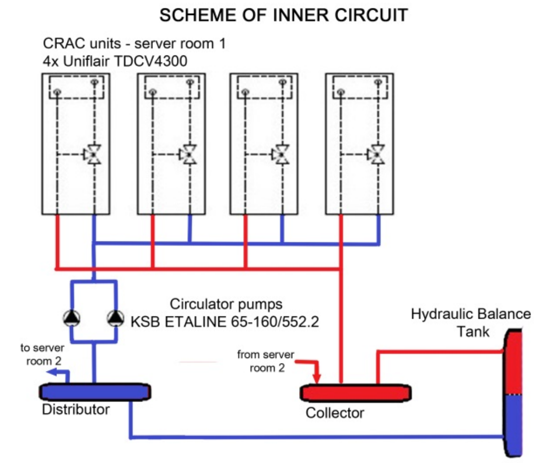

Fig. 1 - Scheme of cooling system, inner circuit

The cooling system is divided into an inner (fig.1) and outer circuit (fig.2) by an hydraulic balance tank in order to fulfill different pressure requirements of internal CRAC units and external roof chillers. Redundant backup is applied for each component of the cooling system.

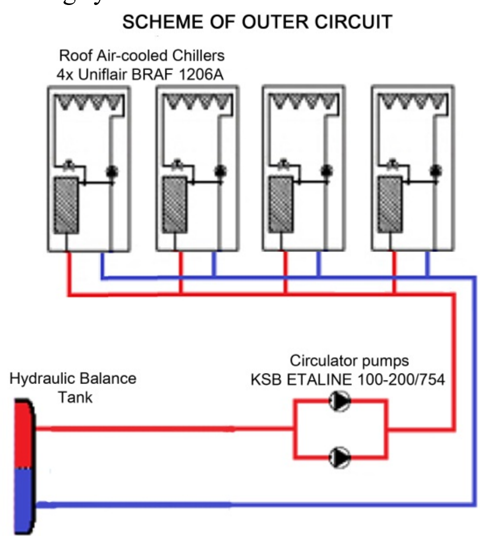

Fig. 2 - Scheme of Cooling System, Outer Circuit

Estimation of the total water volume inside the cooling system was based on technical documentation [5](see below in tab. 1). The potential thermal energy of the filling and a rough estimate of prolonging of operation can be calculated with the following assumptions:

- Potential energy is calculated for maximum water temperature difference during breakdown, where the low value is the mean water temperature during regular operation at 10 ˚C and the high value is the temperature limit of 35˚C considering ideal heat exchange.

- Water properties are: density 998 kg m^{-3} and specific heat capacity 4.18 kJ kg^{-1} K^{-1}.
- Heat dissipation of IT equipment is constant. Internal heat gain 80 kW is used for calculation of potential prolonging of operation.

The calometry formula is used to estimate potential energy of cooling system filling.

Tab. 1- Initial Estimation of Potential Energy of Cooling System Filling and Prolonging of Operation

	V (m^3)	C (kJ K^{-1})	E_{pot} (kWh)	τ_{pot} (hour)
Inner C.	1.61	6716	46.63	0.58
Outer C.	3.22	13432	93.27	1.16
Total	5.52	23027	159.90	1.99

CALIBRATION DATA

A real emergency situation in the case study server room happened in August 2011. Both pumps of the inner circuit were broken down due to a water leakage to its electronics. IT devices were still processing and the FDD system increased the CRAC airflow to its maximum value in order to ensure intensive air change in the server room. The whole situation was recorded by a monitoring system. Fig.3 shows measured data from 4 sensors placed in the white space of the data center.

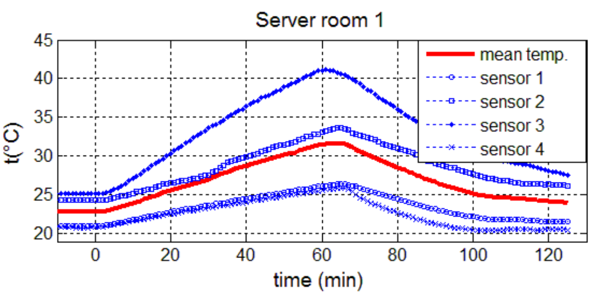

Fig. 3 – Calibration Data

Due to inhomogeneous heat dissipation distribution across the server room, the measured temperature field varies with the position in the room. Since the spatial resolution of building energy simulation techniques is limited, the temperature field of the white space is represented only by one temperature node. In further work, the mean value is used for calibration of the numerical model.

NUMERICAL MODEL

A complex numerical model was developed in software TRNSYS 16 in order to assess transient behavior of the data center during an emergency situation. The user interface of TRNSYS allows connection of individual components (called *type*) such as model of fan, pump, heat exchanger or controller which are available in a program library. By combining these types, TRNSYS allows the creation of a complex model of the whole system. A brief description of the main part of the model is mentioned below. Name of *type* is referred to be able to find detailed mathematical description in TRNSYS manuals [6] [7]

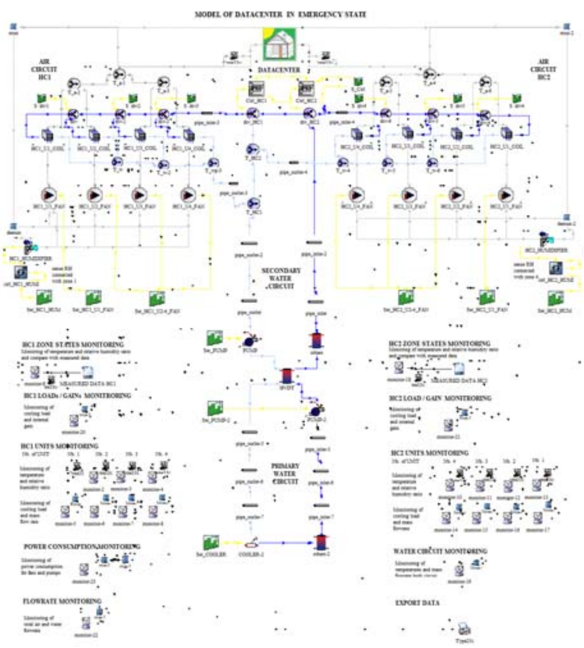

Fig. 4 – Numerical Model in TRNSYS software

Fig. 4 illustrates the complexity of the model, where a detail model of CRAC heat exchangers and an individual model for each unit, PI control of water flow of a CRAC unit, humidification, transport delay and physical properties of coolant, and also simplified building model using the multi-zone component (*type56*) are taken into account. Among other things, all variables can be monitored and exported for post-processing.

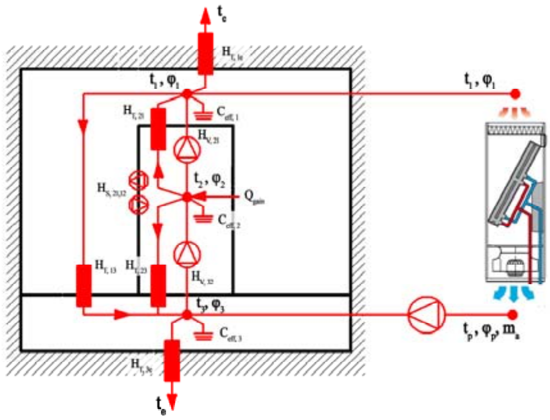

Fig. 5 - Scheme of Server Room Model

Simplified Building Model

A simplified 3-zone model of the server room was created in subprogram TRNbuild which is interfaced with TRNSYS via *type56*. Fig. 5 shows a schematic model of the server room, where the underfloor zone, rack zone and white-space zone are defined. Zones interact with each other as well as with the cooling system and the ambient environment. The mode of heat transfer interaction is indicated by the symbols in the scheme. A rectangular symbol means mainly conductive heat transfer; the fan symbol indicates convective heat transfer.

An effective thermal capacity was specified for each zone (grounding symbol). It is worth mentioning that the setting of this parameter has a major influence on the transient behavior of temperature in the zone. Internal heat gain is applied for the rack zone.

Detailed Heat Exchanger Model

Detailed parameters of a CRAC unit placed in server rooms are investigated in a previous study [7] and there is possibility to use Braun's Effectiveness – NTU calculation method (*type52*) [8]. Tab.2 shows all parameters which are necessary for calculation of the detailed cooling coil model.

Tab. 2 – Cooling coil parameters

Parameter	Value	Unit
Outside tube diameter	0.012	m
Inside tube diameter	0.01	m
Tube thermal conductivity	380	$W\ m^{-1}\ K^{-1}$
Fin thickness	0.1	mm
Fin spacing	1.5	mm
Number of fins	1438	-
Fin thermal conductivity	200	$W\ m^{-1}\ K^{-1}$
Center to center distance	11.2	mm
Tube spacing	36	mm

The Model was calibrated using a report with technical data from the manufacturer.

PI controller settings

Control of CRAC units is based on constant airflow and variable water flow. This means that a change of water flow rate keeps supply air temperature at the required set points value. A PI controller (*type23*) is applied in the numerical model. In order to be able to set appropriate gains and integral time constants, initialization of a surrogate model needed to be done. The surrogate model was initialized as a Laplace domain time-invariant model expressed by the following transfer function.

$$G(s) = \frac{-11{,}8}{2550s + 1} \qquad (1)$$

The transfer function was validated and evaluated based on a step response of supply air temperature with respect to a water flow change from 0 to 100% (valve control signal). A comparison between the step response predicted by TRNSYS and the surrogate model is presented in fig. 6.

After initialization of the surrogate model, the surrogate system sensitivity -11.8 (-) and time constant 2550 (sec) was read, and the method by Fruehauf et al. [9] was used to estimate PI controller parameters such as proportional gain -0.48 (-) and integral time constant 1250 (sec).

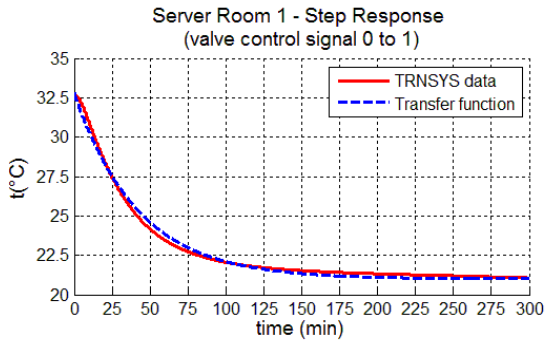

Fig. 6- Step Response of Supply Air Temperature

Transport Delay and Coolant Properties

A numerical model is primarily created for prediction of thermal utilization of energy potential of the coolant. Transport delay has to be taken into account because it is crucial to assess states during the emergency situation. Therefore, a model of the distribution system has to contain many pipe components (*type 31*) which calculate not only transport delay but also heat transfer losses during transport. Parameters of the distribution model were estimated based on technical documentation [10].

In the initial estimate of potential energy of the filling (tab.1), we assumed that the coolant is pure water. Technical documentation shows that actual coolant is a mixture of water with antifreeze in ratio 3 to 1, so physical properties of coolant are slightly changed. This change is expressed by equation 2 [11]

$$P_x = A_1 + A_2\xi + A_3\left(\frac{273{,}15}{T}\right) + A_4\xi\left(\frac{273{,}15}{T}\right) + $$

$$+ A_5\left(\frac{273{,}15}{T}\right)^2 \qquad (2)$$

Where A_i are coefficients which define calculated parameter P_x. The formula is validated for density, specific heat capacity, and thermal conductivity. ξ is the concentration of the mixture and T is thermodynamic temperature.

The changes of physical properties are demonstrated in tab. 3

Tab. 3 – Physical properties differences for temperature 10 °C

Type of Coolant	ρ ($kg\ m^{-3}$)	c ($kJ\ kg^{-1}\ K^{-1}$)	λ ($kW\ m^{-1}\ K^{-1}$)
Water	999.70	4.20	0.58
Mixture	1050.42	3.65	0.62

The main parts of the numerical model were briefly described. In addition to these components there are models of fans, pumps, humidifiers or ON/OFF controllers. Its meaning is not so significant. Also, the model of the roof chiller was simplified (*type92*) because operation of this unit during emergency situation is not considered.

RESULTS

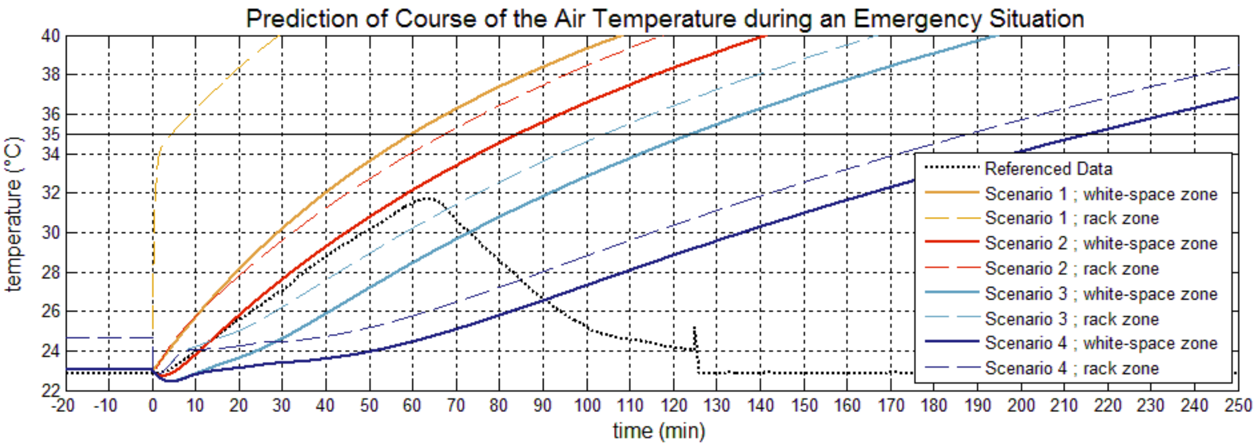

Fig. 7- Prediction of Course of the Air Temperature during an Emergency Situation

The main result of this study is shown in fig. 7. Four scenarios for four different levels of cooling system failure were investigated. For each scenario, two lines for zone air temperatures are shown: a dashed line for the rack zone and a solid line for the white-space zone. Calculation is with consideration of constant heat dissipation from IT devices.

Scenario 1 (orange) is the scenario that describes total cooling system failure. In this scenario a significant difference between courses of zone air temperature can be observed. Whereas the white space zone temperature rises slowly, as influenced by the thermal capacity of indoor constructions, the rack zone temperature shows a sharp increase. This step change may be very dangerous and can cause large damage to IT equipment.

Scenario 2 (red) is the scenario that describes failure of the roof chiller unit and its distribution system. In this case, the CRAC unit can provide only intensive air change of the white-space without any cooling. This scenario may also be understood as the situation of only backing up CRAC unit fans during an electricity outage. Conditions of scenario 2 were set in such a way that they meet the conditions of a real emergency situation. The results of this scenario are considered comparable with the referenced data.

Scenario 3 (light blue) is the scenario that describes failure of the roof chiller unit and outer circuit of a distribution system, or backing up of CRAC units and pumps of the inner circuit during an electricity outage.

Finally, scenario 4 (dark blue) is the scenario that describes failure of the roof chiller or backing up of CRAC units and all distribution systems during the electricity outage.

Tab. 4- numerical comparison

	Scenario 2	Scenario 3	Scenario 4
τ_p (min)	84	128	216
P_{el} (kW)	28.8	31.6	35.4
E_{el} (kWh)	40.32	67.41	127.44
$E_{coolant}$ (kWh)	-	64.57	204.16

Numerical results are presented in tab. 5. In order to compare the results in an easy way, the prolonging period of operation τ_p was defined as the period from the start of failure, until the time when the white-space temperature reaches the limit of 35 ˚C. Other indicators are mentioned such as required peak power and electric energy consumption during prolonging period as input information for back up devices and also heat removed from the space to the circulating coolant, which is output from the detailed heat exchanger model.

Fig. 8 shows the transient behavior of energy flows through the heat exchanger for scenarios 3 and 4 (blue lines). The assumption of constant internal heat gain (red line) is not very realistic. However, it may be interpreted as the worst case scenario, when the server room utilization is 100% during the whole outage period. On the other hand, a constant energy consumption (green lines) of backed up cooling system is very likely with respect to common practice, in which backed up components of cooling systems tend to be set to full power during emergency situations (e.g. fans of CRAC units due to intensive air change.). The influence of the step control action is most visible in initial course of energy flows through the heat exchanger (blue lines)

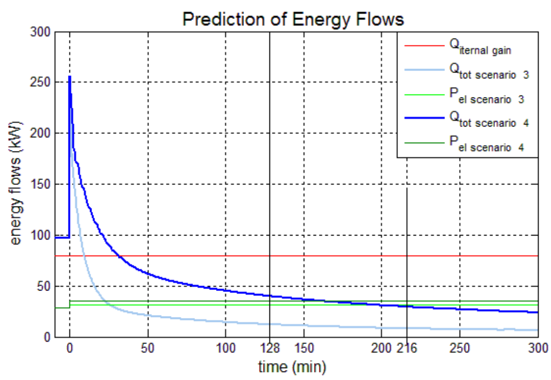

Fig. 8 Prediction of energy flows

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DISCUSSION

A numerical model based on a case study and calibrated by using measured data of a real emergency situation proved the significant influence of usage of coolant thermal capacity during emergency situation in data centers. This influence is even greater than our initial expectation. The reason for this difference is probably the additional thermal capacity of constructions which helps to keep temperatures in the recommended range. For a target group of small or medium sized data centers with water based cooling, which are mostly integrated in office buildings with long distance distribution systems, we recommended a back-up distribution system to be used during electricity outage. In addition, we recommend that additional water thermal storage tanks are included in the distribution systems in case the thermal capacity of the distribution system is not enough.

For the case study, the prolonging period of operation is around 2 hours, considering backing up of inner circuit with volume of filling of 1.6 m^3. For backing up of the whole distribution system with volume of filling of 5.5 m^3, the emergency operation period can be prolonged by more than 3 hours. This solution provides more time for operators to manage troubleshooting of failure of roof chiller units or launching of emergency electricity generators (if available) in case of long-term electricity outage. In case of short-term electricity outage, the thermal capacity of coolant contained in the distribution system is enough to cool the data center with minor additional requirements of batteries included in the UPS because fans of CRAC unit, which are already taken into account, are major consumers in comparison with consumption of circulation pumps.

Unfortunately, detailed data about utilization of IT devices or workload distribution were not available, so heat dissipation had to be estimated by only catalogue values of IT devices and internal heat gain was considered as constant. However, the value of internal heat gain represents the worst case, when the data center is fully utilized during the period of emergency situation and thus the influence of thermal capacity of distribution system might be even more significant.

Another limitation of this study is the level of resolution of temperature field calculation in the white-space, which could be higher. Using a methodology with a three-zone model offers only limited information and this issue should be investigated in future work.

In general, using building energy simulation is feasible for data center case and provides detailed information about the transient behavior and prediction of operation states of data center and its systems especially. With building energy simulations, many types of analyses can done which are not possible with conventional methods. Of course, the development of numerical models using advanced simulation methods is time consuming, however, this model does not have to be used only for design purposes but also may be included in an advanced model-based control platform.

CONCLUSION

The modeling of transient behavior of data center and its systems is a multidisciplinary task, where most of a conventional tools are failing. The use of dynamic building energy simulation methods such as TRNSYS seems feasible for this purpose. There already exist many models of HVAC, electrical and control components and by combining these components, the program allows the creation of a complex model. However some limitations were found in modeling of the data center environment. The methodology with a three-zone model offers only limited information.

The simulation results prove that backing up of the pumps of distribution systems has a positive influence during emergency situations in data centers. For the target group of small and medium size data centers with long distance water distribution systems, backing up of the distribution system offers alternative short-term energy back up for cooling of the data center with minimal efforts and additional investments. Usage of an additional storage tank added to the distribution system as alternative energy back up is also recommended with assumption that backing up of distribution system is applied

The results provide valuable information to data center operators and may also be used as theoretical basis for FDD decision algorithms, such as the supervisory control platform GENiC, which is currently being developed.

ACKNOWLEDGEMENT

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