Experimental Investigation of CRAH Bypass for Enclosed Aisle Data Centers

Hamza Salih Erden [a], Mehmet Turgay Yildirim [b], Mustafa Koz [b], H. Ezzat Khalifa [b]

[a] Istanbul Technical Universiy, Informatics Institute, Istanbul, Turkey 34469
Email: erdenh@itu.edu.tr
[b] Syracuse University, Mechanical and Aerospace Engineering Department, Syracuse, NY, USA 13244

ABSTRACT

Aisle containments in data centers help provide uniform server inlet air temperatures. This allows the cooling system to run at a higher evaporator temperature and more efficiently. On the other hand, CRAH units run at higher speeds to ascertain that racks receive sufficient air flow. Since CRAH fan power already constitutes an important component of data center power use, such increases in the fan power can overshadow the energy savings due to more efficient chiller operation. CRAH bypass configuration is proposed to achieve optimum operating condition for enclosed aisle data centers. This configuration utilizes fan-assisted perforated floor tiles to induce a fraction of tile flow from the room through bypass ports or leakage paths and help decreasing the amount of air flow passing through the large flow resistances of CRAH units. Experimental results show that there is an optimum operating condition for the specific data center test cell that is designed to represent an enclosed aisle data center utilizing the proposed CRAH bypass configuration. Here, the flow characteristics of major system components and experimental measurements have been used to calibrate a flow network model (FNM) for the design optimization and trade-off analysis of the proposed system. Calibrated FNM along with a thermodynamic model (TM) of the cooling infrastructure provides an estimate of the energy use at various fractions of CRAH bypass air and chilled water temperatures. This study introduces the design of the experimental setup for testing CRAH bypass configuration for enclosed aisles and for calibrating models to predict the cooling infrastructure energy saving potential of the proposed technique.

KEY WORDS: Aisle Containment, CRAC/CRAH Bypass, Fan Assisted Tiles, Experiments, Flow Network Model, Cooling Infrastructure Power

NOMENCLATURE

A	flow area, m^2
CFD	computational fluid dynamics
COP	coefficient of performance
CRAH	computer room air handling
DP	differential pressure
EA	enclosed aisle
EXP	experimental
FNM	flow network model
IT	information technologies
K	loss coefficient, -
NTU	number of transfer unit
OA	open aisle
P	pressure, Pa
T_{chw}	chilled water temperature, °C
TM	thermodynamic model
V	velocity, m/s

Greek symbols

Δ	difference
ε	effectiveness
ρ	density, kg/m^3

INTRODUCTION

Data centers consume about 2% of the electricity consumption in U.S. [1]. Cooling infrastructure is typically responsible for almost half of the total power use in data centers [2]. Hence, energy efficiency of cooling equipment is as important as that of Information Technology (IT) equipment. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) published envelopes of recommended and allowable environmental conditions for IT equipment [3]. According to these recommendations maximum inlet air temperature of typical IT equipment needs to be below 27°C for continuous operation [3]. In a traditional air cooled open aisle (OA) data center, racks are placed front-to-front and back-to-back to form hot and cold aisles as shown in Figure 1 [4]. In this configuration, servers are subject to non-uniform inlet air temperatures due to the recirculation and mixing of hot air in the cold aisle. Due to the resulting temperature non-uniformity in the cold aisle most of the servers are over-cooled so that the server with the highest inlet air temperature is below the 27°C threshold recommended by ASHRAE [3]. Therefore, the higher the non-uniformity, the less energy efficient is the data center since the cooling infrastructure has to operate at lower and inefficient evaporator temperatures.

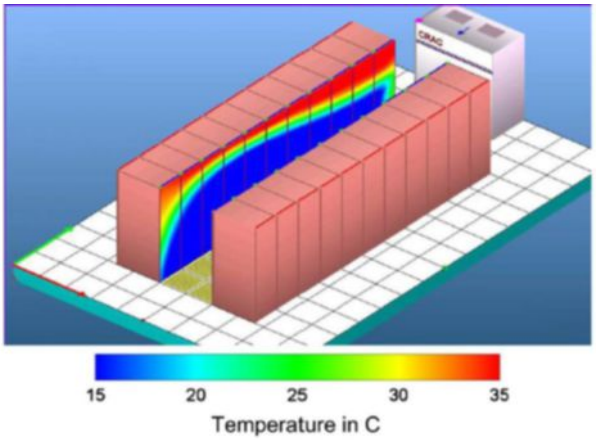

Fig. 1 Temperature non-uniformity in the cold aisle of an air cooled OA data center [4].

978-1-4673-8121-5/$31.00 ©2016 IEEE

In conventional OA data centers, chillers maintain chilled water temperature at around 7°C so that Computer Room Air Handling (CRAH) unit air supply temperature is around 15°C [5]. CRAHs typically provide around 85% of the rack flow rate through the perforated tiles. For the cold air supply fraction of about 85% Computational Fluid Dynamics (CFD) modeling results by Alkharabsheh et al. [6] and Demetriou and Khalifa [7] also confirm that server inlet air temperatures at critical locations remain below the redline temperature for similar operating conditions. Aisle containment is a solution to reduce temperature non-uniformities inside the hot and cold aisles and improve the energy efficiency of air cooled data center cooling infrastructure [8]. Containments separate the volumes of hot and cold air and allow higher supply air temperatures in a data center, which not only increases the efficiency of the cooling infrastructure but also the number of hours for economizer operation. However, in enclosed aisle data centers CRAH units need to supply the entire air flow demand of server racks through the perforated floor tiles in the containment so that servers receive sufficient amount of air flow for cooling. Therefore, in a contained data center CRAH unit fans ramp up. CRAH fans typically consume less power than chillers but their contributions are comparable [2]. Since the fan power is proportional to the cube of the fan speed, increases in the fan energy consumption may reduce and in some cases eliminate energy savings achieved through more efficient operation of cooling systems.

Khalifa and Demetriou proposed a novel approach to address energy efficiency concerns of the enclosed aisle data centers and increase the energy saving potential of enclosed aisle data centers via CRAH bypass fans [9]. CRAH units constitute the major flow resistances in the air flow path in traditional data center setting due to filters and heat exchangers. The proposed approach suggests bypassing a fraction of air supply through leakage ports or dedicated openings that will have significantly lower flow resistances compared to those in CRAH units, while ramping down the CRAH fans. Bypass flow can be introduced either by inducing room air into the plenum via fan assisted floor tiles in the cold aisle containment or by forcing warm room air into the plenum via low-lift fans mounted on the floor in the hot aisle. Figure 2 shows schematics of the flow diagrams for the proposed configurations describing both of the options. In the induced configuration, the entire rack air flow passes through the fan assisted floor tiles. In a fan assisted floor tile, a single fan or multiple parallel fans are mounted underneath each perforated tile in the cold aisle. These fans operate across the tile flow resistance to supplement CRAH flow rate and maintain the required rack air flow rate. One advantage of the induced configuration is that, fans lead to slightly depressed pressure in the plenum eliminating leakage into the data center white space. In the forced configuration, the bypass fans cooperate with CRAH fans to pressurize the plenum. Unlike induced configuration, forced configuration fans only supply a fraction of the rack air flow rate across a smaller pressure resistance compared to that of the CRAH units. However, a fraction of both bypassed and CRAH air flow is expected to leak back into the room since the plenum is pressurized.

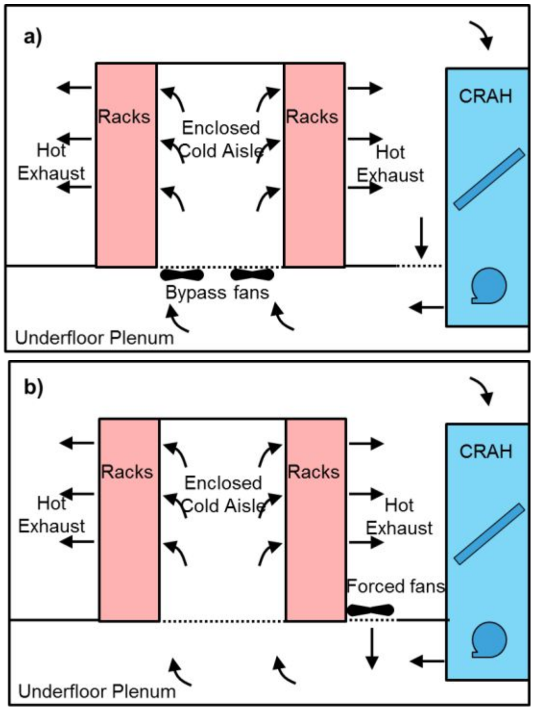

Fig. 2 CRAH Bypass configurations: (a) induced, (b) forced

In a previous study, Khalifa and Demetriou indicated an energy saving potential of up to 50% in the cooling infrastructure power relative to the enclosed aisle (EA) configuration via CRAH bypass method using a simplified model of assumed resistances and leakage rates [10]. Here we present an experimental study to verify a model for the air flow network of the data center test cell and use this information to develop more detailed models for air cooled data centers with enclosed aisle configurations with and without bypass fan configurations. The FNM is experimentally verified in EA configuration and can be used to determine optimum design and operation of CRAH bypass for various data center settings.

AIR FLOW NETWORK MODEL (FNM)

As containment systems are becoming more popular, researchers conduct both experimental and computational studies to investigate the flow and thermal implications of aisle containments on the air flow in data centers. Arghode et al. [11] verified the performance of various tile modeling techniques for CFD through thermal characterization and modeling of open and enclosed aisle data centers. Their experimental results confirm considerable impact of aisle containment on the flow and pressure field as well as temperature distribution both in the under- and over-provisioned cases. FNM is a useful tool for conceptual design studies and helps in testing what-if scenarios and deciding if more detailed simulation tools are needed for thermal management studies at various scales [12]. Steinbrecher et al. [13] exemplified the server level use of FNM when they studied air flow paths inside an air cooled server package. At higher level, earlier studies include Kang et al. [14] and Schmidt et al. [15] using CFD to verify different versions of a simplified FNM to predict tile flow rates for specific cases.

Shrivastava and VanGilder [16] used FNM at the room level to predict tile airflows for data centers with containment architectures and row-based cooling systems. Alkharabsheh et al. [17] validated a CFD model based on pressure and flow measurements conducted in a data center test cell with a cold aisle containment system by utilizing flow resistances and fan curves for key components. This paper presents a FNM model verified in a data center test cell with cold aisle containment as well as CRAH bypass fans utilizing flow characteristics of key components in the associated flow circuit.

Fundamentally, FNM stems from the analogy between the fluid and electric circuits. The air flow path in a data center can be represented by a collection of flow resistances in addition to the fans that create pressure difference to overcome various resistances. Flow resistances in a data center can be listed as CRAH internal components such as heat exchangers, filters; server flow resistance, perforated tiles and other losses due to contractions, expansions, bends etc. Even though head loss in key components such as CRAH units, racks and tiles are defined as minor losses in fluid mechanics, they constitute the vast majority of losses in a data center air flow network, which has a relatively short air flow path with no or limited conventional ducting. Here, we assume that the flow resistances of CRAH units, racks, tiles and leakage paths are major components for practical characterization purposes. Experimental results confirm that other losses are negligible for the system tested here.

The pressure loss due to each flow resistance is represented by the following equation,

$$\Delta P = K \frac{1}{2} \rho V^2 ,$$

where K is the loss coefficient for the specific flow resistance, ρ is the density of air and V is the velocity of the air.

The fan curves of various fans in the system (e.g. CRAH unit, servers, CRAH bypass) along with the system resistances determine the amount of flow passing through each flow path described in Figure 3. It is important to identify operating conditions of the fans in the proposed system to meet the air flow requirements of servers. Meanwhile, another role of the air FNM is to provide the fan power at various conditions to be fed into the thermodynamic model (TM) of the cooling infrastructure so that the optimum operating condition for the proposed CRAH bypass configuration can be determined.

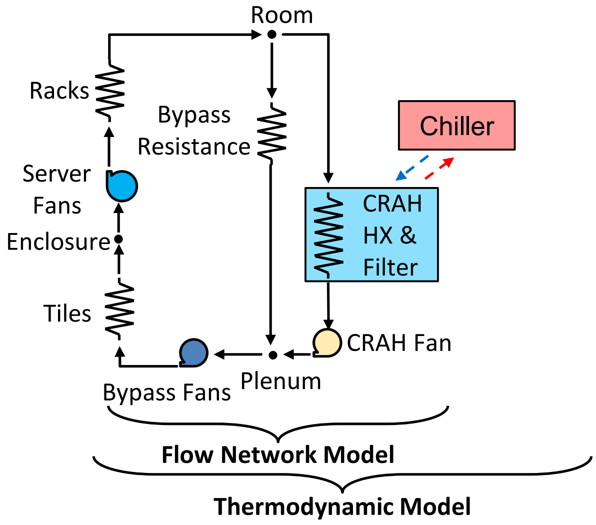

Fig. 3 FNM and TM (Solid black arrows: Air flow paths; Dashed colored arrows: supply/return chilled water flow paths)

THERMODYNAMIC MODEL

CRAH unit needs to provide colder air as the CRAH bypass fraction increases and CRAH air flow rate decreases (i.e. CRAH air supply fraction decreases). This leads to inefficient chiller operation due to the lower evaporator temperatures. In other words, while the CRAH fan power is decreasing chiller power is increasing, which poses an optimization problem to be solved. The search for the optimum operating condition with the CRAH bypass configuration requires an adequate TM for the cooling infrastructure. FNM provides key information regarding the air flow rates and fan power for a specific configuration. TM constitutes key components of the cooling infrastructure such as chiller and CRAH heat exchanger to utilize FNM-provided information to compute the total power use by the entire cooling infrastructure for optimization.

The experimental facility to be discussed next does not allow independent control on the chilled water temperature. Hence, the TM provides the tools to estimate the power use by the system at various operating conditions. The CRAH supply air temperature is determined based on the perfect mixing of various air streams at different temperatures provided that the server inlet air temperature in an enclosed aisle data center is as close to the recommended 27°C as possible. Heat exchanger performance of the CRAH unit is governed by ε-NTU relations for a cross-flow heat exchanger [18] along with the thermal characteristics determined based on the available technical specifications of the unit. The chiller model runs on the performance data file provided by the vendor to compute the change in the Coefficient of Performance (COP) and the chiller power at various chilled water set point temperatures based on normalized performance map of the chiller.

EXPERIMENTAL SETUP

The test cell for the experimental verification of the air flow network model has characteristic features of typical air cooled data centers. As shown in Figure 4 and Figure 5, there are three simulated server racks placed in the middle of the white space. There are six perforated tiles in front of the racks representing the cold aisle. Two perforated tiles in the hot aisle represent leakage paths in a conventional enclosed aisle data center setting with leakage air flow rate of about 25% of the CRAH air flow rate. Three racks have a heat dissipating capacity of about 100 kW and constant air flow rate of about 3.964 m^3/s (8400 CFM) in total. Server racks receive cold air through the perforated tiles in front of them and the air heats up as it passes through the simulated servers before it gets into the hot aisle and then CRAH units to reject the heat to the chilled water supplied by the cooling plant. There are two CRAH units on both sides of the room and each of them is capable of handling the maximum cooling load by the racks. CRAH units receive chilled water from the chiller of the neighboring data center cooling infrastructure. The cold air exiting the CRAH heat exchanger is supplied into the pressurized plenum via centrifugal fans to provide the cold air through the perforated tiles into the cold aisle. The maximum air flow rate a CRAH unit can supply in this configuration is also around 3.964 m^3/s (8400 CFM).

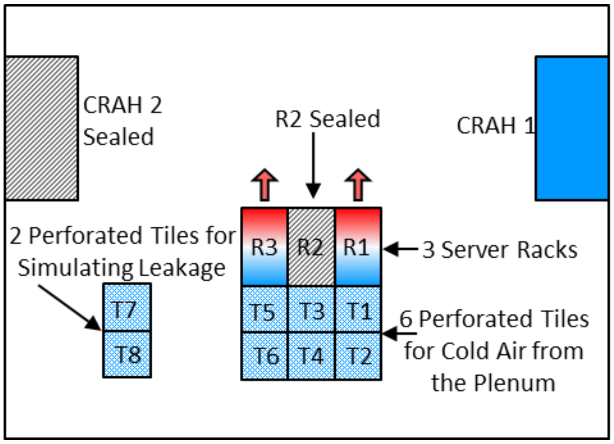

Fig. 4 Experimental facility layout.

A modular containment structure is designed and built on-site, which is made of steel shelving posts and riveted supporting structure sealed by aluminum foil covered rigid insulation material (Figure 5 (b)). The structure provides the flexibility to test enclosed aisle data center configuration in the test cell. Figure 5 (c) shows 1 of 6 commercially available fans in the test cell to be mounted underneath the tiles to test the induced CRAH bypass configuration. Similar fans are commercially available and they are typically used to boost the air flow rate at locations where hotspots emerge due to insufficient air flow. This study also provides a demonstration of a different use of these fans to optimize the cooling infrastructure of the enclosed aisle data centers.

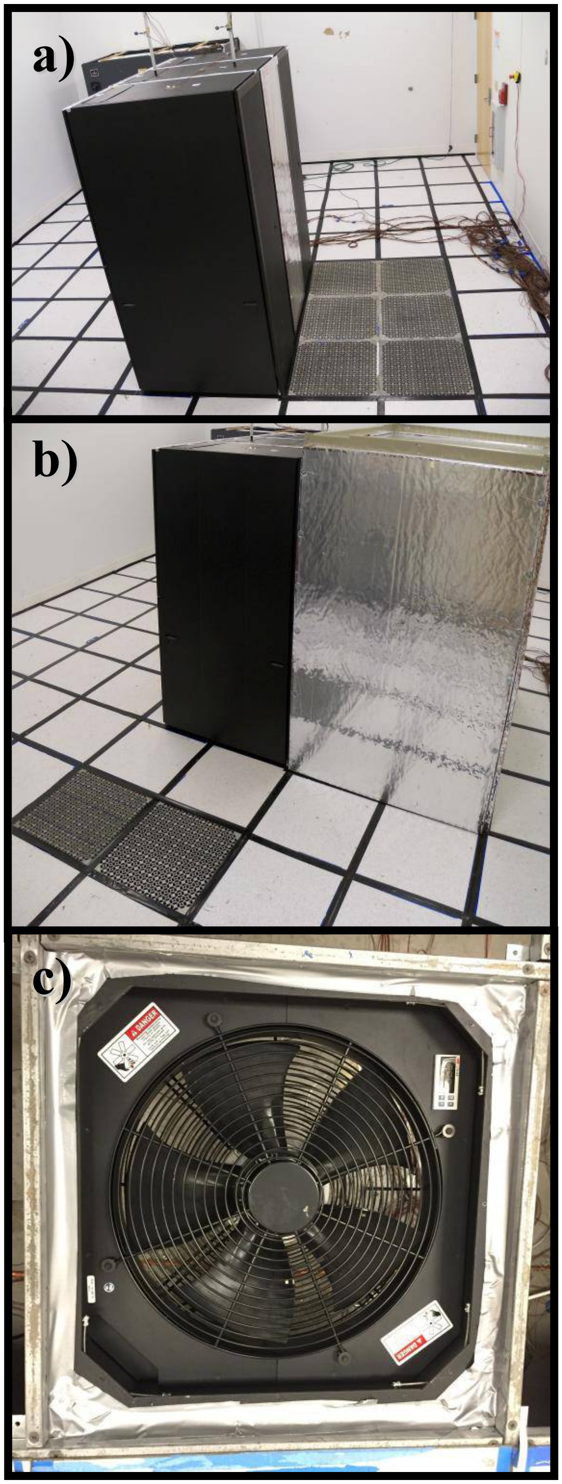

Fig. 5 (a) Cold aisle without containment and three racks (middle rack sealed, CRAH 1 behind the racks),
(b) Cold aisle with containment and perforated tiles for leakage on the side of the racks.
(c) CRAH bypass fan installed for demonstration.

The air flow network model verification requires a series of air flow, pressure and power measurements. CRAH 2 is sealed for all of the tests performed as part of this study. Since the test cell floor leakage is no more than *2%* of the CRAH air flow rate based on a leakage test [19], the air flow rate of

CRAH 1 in the test cell is assumed to be approximately the same as the total air flow rate through the perforated floor tiles. In legacy data centers, unmanaged leakage can be up to 50% of the CRAH air flow rate [20, 21]. Hence, intentional leakage ports via perforated tiles in the hot aisle provide realistic scenarios if needed. Since the maximum air flow rate by single CRAH unit is barely sufficient to provide the constant air flow rate of three racks, Rack 2 among the three racks is sealed to allow single CRAH operation. All air flow rate measurements in the test cell are conducted via a flow hood device with an accuracy of ±4%.

Pressure difference measurements are conducted via differential pressure (DP) transducers. One of the DP transducers has a range of 0-1250 Pa and it provides DP measurements between the room and the inlet of the CRAH fans with an accuracy of ±5 Pa. The other one has a range of 0-250 Pa and provides DP measurements between the room and the cold aisle with an accuracy of ±2 Pa. The DP measurement between the CRAH fan inlet and the room leads to the combined flow resistance coefficient for the CRAH heat exchanger and filters. The latter DP measurement between the containment and the room confirms the air flow provisioning of the containment system. The flow characteristics of the simulated servers and perforated tiles; the characteristic curves of the servers, CRAH and CRAH bypass fans are already available through the manufacturer's data.

Verification of the air flow network does not necessarily require simulated servers to generate heat. Since the test cell is already dependent on the cooling infrastructure of the existing data center facility, changing the chilled water supply temperature is not within the capabilities of the research lab. Hence, all of the tests to be discussed here are performed without additional server heating beyond the dissipated heat by the server fans. However, for a holistic analysis of the cooling infrastructure, CRAH and bypass fan power results will be implemented into TM.

Variable frequency drive unit provides the power use by the CRAH fans through a RS485 USB communications cable and the commissioning software, which also allows the lab operators to adjust the speed of the fans. Power provided by the software was also calibrated through a power meter with an accuracy of 1.5% of the reading. Similarly, fan speed data provided by the software are calibrated by readings via tachometer with an accuracy of 0.05% of the reading.

CRAH bypass fans utilized in this study as shown in Figure 5(b) are mounted underneath the perforated tiles in the cold aisle. These fans can be controlled via variable DC power supplied to the controller. The fan and efficiency curves determine the fan performance at various operating conditions, which are available through manufacturer specification sheets (EBM EC axial fan - W3G450-CC38-42).

FNM MODEL VERIFICATION

As briefly mentioned above, flow characteristics of key components in the flow network are based on either manufacturer's data or experimental measurements. Abdelmaksoud [22] provides details about the flow resistance experiments regarding the simulated servers, which are designed based on typical flow characteristics of blade type servers. Fan curve data for both simulated server fans and the CRAH fans are available through manufacturers. The initial step for FNM model is the verification of the system resistance based on the major flow resistances in the test cell. Accordingly, tests at various CRAH fan speed levels were conducted in the test cell with an active CRAH unit but without rack flow. The operating points on the fan curves were determined based on the fan head reading at the intersection of the measured air flow rate and specific fan curve at measured fan speed. Measured points show good agreement with the system curve for the test cell considering contributions of various resistances (i.e. Tiles, CRAH HX and filter) and the dynamic head loss within the system. Here pressure difference (DP) measurements across the CRAH filter and heat exchanger (HX) provide the pressure loss coefficient (K Value) for the specific unit in the test cell. The loss coefficient due to the perforated tiles is computed based on data provided by the vendor. Table 1 summarizes K values and associated air flow areas (A) for the key components used for the FNM model verification.

Table 1 Model parameters of key system components for FNM model verification

	K (-)	A (m^2)	Notes
CRAH	144	1.445	(a)
Racks	163	1.442	(a) (c)
Tiles	21	2.230	(b) (c)

(a) K determined experimentally.
(b) K determined based on manufacturer's data.
(c) Total air flow area (8 servers & 6 perforated tiles)

Associated system model in the FNM, which runs on the available system resistances and fan curves, confirmed the rack, CRAH and leakage air flow rates with errors of 0.4%, 4.5% and 15% respectively. Considering the relative weights of the respected flow rates, average error for the system is less than 4.5%. Additionally, CRAH fan model of the FNM was calibrated based on the actual CRAH fan power measurements so that losses that are not available on the fan curve such as motor and drive inefficiencies are taken into consideration.

Based on the above-mentioned calibration of the CRAH model, FNM verification was conducted for the conventional enclosed aisle configuration. Calibrated model was used to find the anticipated fan speeds for the CRAH (and bypass fans for the CRAH bypass configurations) that will satisfy a zero DP between the room and the containment so that the rack air flow rate is maintained. The test cell was operated at the conditions provided by FNM and the experimental measurements were compared against FNM results.

RESULTS and DISCUSSIONS

For the verification cases, the air flow rate through 2 perforated floor tiles in the hot aisle represents leakage air flow rate, which is approximately 25% of the total air flow supplied by the CRAH unit. Measured air flow rate through perforated tiles in the hot aisle (i.e. leakage air flow rate) as well as at the exhaust of simulated servers (i.e. equal to the tile flow rate) were compared against the FNM model results.

Additional confirmation for the model is the air DP measurement between the containment interior and the room. If the pressure in the containment is higher than the room pressure that means the CRAH is over-provisioned (e.g. providing more flow rate than the racks need). Otherwise, the system is under-provisioned leading to reduced rack air flow rate. Here CRAH fan speed is controlled to keep the pressure in the containment as close to that in the hot aisle as possible so that rack air flow is maintained at the original levels as if they operate in an OA configuration.

FNM simulation provides the CRAH fan speed required in the EA configuration to maintain original rack air flow rate. The experimental results were obtained at the FNM-provided CRAH fan speed. Table 2 shows the comparison of experimental and FNM results. As shown, key flow rates of the conventional enclosed aisle case obtained via FNM are in reasonable agreement with the experimental measurements. FNM predicted CRAH fan power as 3.77 kW which is only 4% percent off compared to the measured fan power of 3.94 kW. The measured pressure difference between the room and the plenum is 3 Pa which is acceptable within the accuracy of the pressure transducer, ±2 Pa.

Table 2 Comparison of air flow rates (m^3/s), (EXP vs. FNM)

	Rack	CRAH	Leakage	Leakage Ratio
EXP	2.509	3.473	0.964	27.8%
FNM	2.498	3.317	0.819	24.7%

There is a reasonable agreement between the FNM and experimental measurements. Since the test facility does not allow for independent control of the CRAH chilled water temperature, experimentally verified FNM model was exercised to make predictions for enclosed aisle configurations with the CRAH bypass fans. FNM provides power and flow estimations for CRAH and bypass fans, which are inputs for the TM to estimate the required chilled water temperature to keep the rack inlet air temperature at 27°C. Server heat load is assumed to cause 10°C air temperature rise across the servers. Heat transfer characteristics of the CRAH heat exchanger is based on the manufacturer data provided for the existing unit. Thermal conductance of the CRAH heat exchanger is computed to be 7,000 W/K based on the available technical specifications of the unit (Liebert CW051DCVA2). Heat exchanger is coupled with a chiller that has a constant condenser inlet water temperature of 30°C and runs on the normalized performance data of a centrifugal chiller [23]. Chiller model is set to have a design COP of 4.0.

Figure 6 presents the predicted trends by experimentally verified FNM along with TM to estimate optimum operating regime of the enclosed aisle configuration with bypass fans placed underneath each of the perforated tiles in the cold aisle. Cooling power is the summation of the chiller (blue line) and fan power (green line). Fan power includes both CRAH and bypass fans. The corresponding values of the baseline enclosed aisle configuration without CRAH bypass are represented by single point values (i.e. EA-Cooling, EA-Chiller, EA-Fan, EA-T_{chw}) at the CRAH air supply fraction of 1.0. Simulations of FNM and TM provide the performance at lower CRAH Air Supply Fractions assisted by the bypass fans placed underneath perforated tiles in the cold aisle. An initial reduction of 23% can be achieved in cooling power just by introducing bypass fans at CRAH air supply fraction of 1.0 and hence, preventing leakages from the plenum to the room. An additional 12% percentage points reduction in cooling power can be achieved with the optimum operation of the system (CRAH air supply fraction=0.62). These results confirm the energy saving potential of using CRAH bypass configuration as earlier studies [9-10] indicated. However, the fact that induced CRAH bypass configuration causes a depressed pressure in the plenum eliminating leakage from the plenum into the room, was overlooked. This phenomenon causes the majority of savings at high CRAH air supply air fractions. The results are conservative considering the fact that the chiller is assumed to be relatively inefficient with a design COP of 4.0. The percent reduction in cooling power is expected to be greater than 35% with a more efficient chiller.

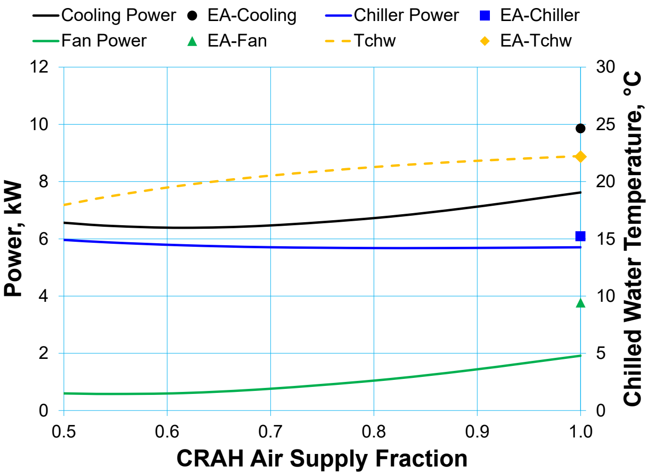

Fig. 6 Predicted performance of the induced CRAH bypass configuration for the test cell via experimentally verified FNM and TM.

This assessment is based on the perfect mixing assumption of the warm bypass air and the cold CRAH supply air in the plenum until they reach the enclosed aisle. Demetriou and Khalifa [10] investigated forced bypass configuration, which requires additional bypass ports, through CFD simulations. They recommended that these ports to be placed near CRAH units for better mixing. Future work should verify the validity of the perfect mixing assumption through computational and experimental effort.

CONCLUSIONS

Enclosed aisle data centers have less non-uniformity in server inlet air temperature and increase the potential of higher temperature and more energy efficient operation with more free cooling hours. However, enclosing the aisle does not guarantee optimum operating condition in a data center. CRAH bypass configuration relies on diverting a fraction of the CRAH air flow through leakage paths via fans attached underneath perforated tiles in the cold aisle and avoiding the high flow resistance of the CRAH units. This study presents an experimental verification of the airflow network model (FNM) of the data center test cell with enclosed aisle configuration. Accordingly, FNM predicts key air flow rates with a flow weighted average error of less than 5% for an enclosed aisle configuration. Integrating the fan and efficiency curves obtained for commercially available fans compatible with tile installation, FNM predicts the performance of various CRAH bypass fractions of the proposed configuration. The predictions provide sufficient information to run a thermodynamic model (TM) of the cooling infrastructure. The resulting trade-off analysis for the test cell indicates 35% reduction in the data center cooling power confirming the energy saving potential of the proposed approach.

Acknowledgments

This research is supported by The New York State Energy Research and Development Authority (NYSERDA) through Award Number 41202. We acknowledge additional support by Tate Access Floors, Inc. through lending CRAH bypass fans for the duration of this research.

References

[1] Koomey, J, 2011, “Growth in Data Center Electricity Use 2005 to 2010,” A Report by Analytical Press, completed at the request of The New York Times.

[2] Salim, M. and Tozer, R., 2010, “Data Centers’ Energy Auditing and Benchmarking- Progress Update,” ASHRAE Transactions, Vol. 116(1), pp. 109 - 117.

[3] ASHRAE, 2012, Thermal Guidelines for Data Processing Environments, 3rd Edition, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

[4] S.V. Patankar, Airflow and cooling in a data center, J. Heat Transfer 132 (2010). 73001-1-73001-17.

[5] ASHRAE, 2009, Best Practices for Datacom Facility Energy Efficiency, 2nd ed., Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

[6] Alkharabsheh, S., Sammakia, B., Shrivastava, S., and Schmidt, R., 2013, “A Numerical Study for Contained Cold Aisle Data Center Using CRAC and Server Calibrated Fan Curves,” ASME Paper No. IMECE2013-65145.

[7] Demetriou, D. W., and Khalifa, H. E., 2011, “Evaluation of a Data Center Recirculation Non-Uniformity Metric Using Computational Fluid Dynamics,” ASME Paper No. IPACK2011-52005.

[8] Joshi, Y., and Kumar, P., 2012, Energy Efficient Thermal Management of Data Centers, Springer, New York.

[9] Khalifa, H.E. and Demetriou, D.W., 2010, “Enclosed Aisle Data Center Cooling System,” U.S. Provisional Patent Application No 61/367,931.

[10] Demetriou, D.W., Khalifa, H.E., 2012a. "Optimization of Enclosed Aisle Data Centers Using Bypass Recirculation," Journal of Electronic Packaging, 134(2).

[11] Arghode, V. K., Sundaralingam, V., Joshi, Y., Phelps, W., Thermal Characteristics of Open and Contained Data Center Cold Aisle, ASME Journal of Heat Transfer, 2013, v 135, p 061901-1-11.

[12] Belady C., Kelkar, K.M., and Patankar, S.V., 1999, Improving Productivity in Electronic Packaging with Flow Network Modeling (FNM), Electronics Cooling, Vol. 5, No. 1, pp. 36-40

[13] R. Steinbrecher, A. Radmehr, K. M. Kelkar, and S. V. Patankar, “Use of flow network modeling (FNM) for the design of air-cooled servers,” in Proc. Adv. Electron. Packag., Pacific RIM/ASME Intersoc. Electron. Photon. Packag. Conf., vol. II, 1999, pp. 1999–2008.

[14] Kang S, Schmidt RR, Kelkar KM, Radmehr A, Patankar SV (2000) A methodology for the design of perforated tiles in a raised floor data center using computational flow analysis. Presented at ITHERM 2000 - Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, Las Vegas

[15] Schmidt, R., Karki, K., Kelkar, K., Radmehr, A., and Patankar, S., 2001, “Measurements and Predictions of the Flow Distribution Through Perforated Tiles in Raised Floor Data Centers,” in "Proceedings of IPACK ’01, The Pacific Rim/ASME International Electronic Packaging Technical Conference and Exhibition", Kauii, Hawaii.

[16] Shrivastava, S. and J. VanGilder. 2009. A Flow-Network Model for Predicting Rack Cooling in Containment Systems. Proceedings of the 2009 InterPACK Conference. San Francisco, California, July 19-23.

[17] Alkharabsheh, S., Sammakia, B., and Shrivastava, S., 2015, “Experimentally Validated CFD Model for a Data Center With Cold Aisle Containment,” ASME J. Electron. Packag., 137(2), p. 021010.

[18] Incropera, F. and DeWitt D. et al., 2007, “Fundamentals of Heat and Mass Transfer”, John Wiley & Sons.

[19] Smith, J. F., Abdelmaksoud, W., Erden, H., Dannenhoffer, J. F., Dang, T.Q., Khalifa, H.E., Schmidt, R., and Iyengar, M., 2011. “Design of Simulated Server Racks for Data Center Research”, Proceedings of ASME InterPACK, Portland, OR, July 6 – 8.

[20] Seymour, M. , 2015, Computational fluid dynamics applications in data centers. In: H. Geng (ed.) Data Center Handbook. Wiley. pp.313-341.

[21] ASHRAE, 2009, Design Considerations for Datacom Equipment Centers. 2nd ed. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; pp.35-46.

[22] Abdelmaksoud, W., 2012, Experimental and Numerical Investigations of the Thermal Environment in Air-cooled Data Centers, PhD Dissertation, Syracuse University, NY.

[23] Demetriou, D.W., 2012, Thermally aware, energy-based techniques for improving data center energy efficiency, PhD Dissertation, Syracuse University, NY.