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A Novel Design of Rack Mount Server Thermal Simulator: Design, Assembly, and Experimental Verification

The practice of commissioning data centers (DCs) is necessary to confirm the compliance of the cooling system to the information technology equipment (ITE) load (design capacity). In a typical DC, there are different types of ITE, each having its physical characteristics. Considering these geometrical and internal differences among ITE, it is infeasible to use the actual ITE as a self-simulator. Hence, a separate device called load bank is employed for that purpose. Load banks create a dummy thermal load to analyze, test, and stress the cooling infrastructure. Available commercial load banks do not accurately replicate a server's airflow patterns and transient heat signatures which are governed by thermal inertia, energy dissipation, flow resistance, and fan system behavior. In this study, a novel prototype of the server called server simulator was designed and built with different components to be used as a server mockup. The server simulator accurately captured air resistance, heat dissipation, and the functionality of actual server behavior. Experimental data showed up to 93% improvement in ITE passive and active flow curves using the designed server simulator compared to the commercial load bank. Furthermore, the experimental results demonstrated a below 5% discrepancy on the critical back pressure and free delivery point between the actual ITE and the designed server simulator. In addition, experimental data indicated that the developed server simulator improved the actual ITE thermal mass by 27% compared to the commercial load bank. [DOI: 10.1115/1.4053643]

Keywords: server thermal simulator, thermal design, aerodynamic servers' behavior, servers' thermal inertia, servers' control system, dynamic data center

1 Introduction

Data centers (DCs) energy consumption is continuously increasing to satisfy the growing needs of E-commerce and other revolutionary technologies such as cloud computing and cryptocurrency mining. Subsequently, maintaining environmental conditions within the recommended and allowable envelopes by either IT vendors and ASHRAE guidelines [1] becomes crucial in the design deployment and operation of the next server's generations. During DCs life span, they end up with ITE heterogeneity including various types, models, and generations of ITE. Each server type accounts for different thermal and aerodynamic behavior. As the heat dissipation by computer hardware increases, special consideration for redundancy and carefully commissioning of ITE is required. Hence, accurately characterizing the cooling requirement and providing adequate airflow to the ITE play a critical role.

Numerous experimental and numerical thermal management techniques have been adopted to increase the energy efficiency and reliability of a modern DC [2–5]. One of these techniques is containment systems implementation. Both cold and hot aisle enclosures have been widely used as an energy saving strategy by preventing the mixing of hot and cold airstreams [6–12]. For active monitoring and real-time control, a variety of different methods are introduced to react to the environmental changes [13,14]. Mohsenian et al. [15–18] designed a fuzzy control system to ensure that just enough airflow is delivered to the aisles regardless of the model, generation, and workload of ITE. Furthermore, Zhang et al. [19] investigated the effect of rack modeling details on DC airflow and temperature predictions. Ibrahim et al. [20,21] showed the impact of server thermal mass on the cooling unit thermal characteristics in transient analysis. Moreover, they explained an experimental procedure to obtain a thermal mass which led to developing a compact server model [22]. In another study, VanGilder et al. [23,24] proposed a compact black-box

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model for characterizing the thermal response of servers for a transient DC. Another experimental procedure was introduced for measuring heat capacity and thermal effectiveness of a compact server model by Pardey et al. [25]. Ham et al. [26] developed a server model that effectively represented the server thermal characteristics. Moreover, the impact of the server model on the annual cooling energy consumption of a DC was analyzed. Song et al. [27] utilized a compact thermal model based on zonal method to analyze the design of a DC thermal management system.

To avoid additional costs and lost revenue, it is infeasible to use the actual ITE as a simulator. Therefore, the need to design a separate device that captures the thermal performance of actual ITE receives the attention of DC operators and cooling systems designers. The load banks are typically standalone units (i.e., not rack mounted) connected directly to a power source to test the adequacy of the data center's power system. The load banks place a load on the power system by using heating elements to convert electrical energy into heat. Typical load banks use fixed speed fans to move a fixed amount of air to help prevent the load bank's heating elements from overheating at maximum loading. Due to the constant fan speed and lack of thermal mass inside the commercial load banks, at lower load levels the air remains cool, and at high load levels, the air gets extremely hot. This behavior is unlike actual ITE that is commonly designed to raise the temperature of cooling air by only about 20–35 °F [28]. Alissa et al. [29] developed a methodology for ITE airflow characterization using a 4 U server simulator. The internal design of an existing commercial server simulator demonstrates lack of considerable amount of aerodynamic and transient characteristics of actual ITE. In addition, most commercial simulators are expensive, nondeterministic, have a large form factor, relatively fragile, and last but not least are difficult to calibrate with controllers. Al Kharabheh et al. [30] used a 9 U server simulator to explore the pressure drop impact in a server rack flow rate and hence on the available cold air entering the ITE. They reported a reduction of 45% of the total flow rate when a 9 U server simulator was used.

This paper introduced a novel and improved design of a less expensive, reliable, deterministic, and calibrated server simulator. What distinguished this design from commercially available load bank was that the new server simulator provided the aerodynamic and thermal characteristics substantially equal to the ITE under simulation. Moreover, the new design was capable of controlling the server temperature by changing the heat generation and the fan speed of the server remotely. Different parameters such as geometrical design, airflow behavior, thermal capacitance, and server fan and heaters control systems were taken into account during the design of the server simulator. Figure 1 shows the difference between the design of the commercial load bank, the new design of the server simulator, and the actual 4 U Dell server.

2 Load Bank Simulator

A load bank simulates an electrical load from a source and dissipates that electrical load. Load banks are either reactive or resistive. Reactive load banks can have either inductive or capacitive loads to supplement a resistive load. On the other hand, resistive load banks have an input of electrical energy and an output of heat. Load banks are used in many applications such as engine generators, battery systems, inverters, aircraft power generators, wind, and hydrogenerators, and server simulators.

2.1 Comparison Between the Commercial Load Banks and Actual Information Technology Equipment. The purpose of introducing a new server simulator is that the commercial load banks are not accurately simulating the actual ITE aerodynamic and thermal performance. There are several differences between a load bank and its corresponding piece of ITE: 1. passive flow behavior: due to the lack of internal components to capture the internal airflow characteristics, the airflow resistance of the load bank is significantly lower than the actual ITE. 2. Active flow behavior: The sensitivity of the load bank air system to external impedances based on the active flow curve analysis is significantly less than real ITE. 3. Thermal inertia: The thermal mass provided by the commercial load bank does not correspond to the real servers. Due to the lack of internal thermal mass, the transient thermal response of the load bank is much faster. Therefore, the hot surfaces are quickly cooled without proper time constant and thermal storage. This yields to inaccurate uptime results while simulating cooling failure.

3 Novel Design of Server Simulator

3.1 Geometrical Design. The server simulator is designed to fit into an ITE rack and conform to the geometry of the normal equipment in the rack. The chassis is designed to match the size of the actual 4 U server ($4\,\mathrm{U} = 4 \times 1.75'' = 7''$), as shown in Fig. 2(*a*). The simulator is typically installed specifically for a test (commissioning the thermal, cooling, and electric capacity of the DC infrastructure) and then removed. They need to satisfy special requirements such as light weight that gives additional flexibility to short installation time. In addition, ease of mobility reduces the risk of user injury during installation. Likewise, a single user can install the simulator even at the top of the rack without assistance by keeping the weight low. As a result, aluminum is used for chassis material due to its low density, high specific heat, and overall strength. The server simulator contains heaters and movable fan trays. Four fans (two sets of back to back) are installed in the front of the chassis to simulate the cooling of an actual server simulator. The fans' model is Nidec 12038 Ultra-Flo 12V/3A DC with 250 cubic feet per minute (CFM) maximum airflow and pulse width modulation speed control as well as a signal wire tachometer. Moreover, aluminum plates are inserted into a series of slots at the bottom and top of the box (Fig. 2(*b*)). The threaded rods are used to keep the plates screwed in with a nut and attached securely to the simulator. On the top of the threaded rods, springs are provided to keep the assembly pressed together and to account for any thermal expansion. The plates are separated by washers and can be set closer together or farther apart by using more or fewer washers. In addition, to properly duplicate the heat generated by computer servers, cartridge heaters are provided. The six FIREROD cartridge heaters were employed, and the output of these heaters is stepped by a voltage regulator. These cartridge heaters have a max power output of 1000 W each. Hence, the server simulator is able to provide up to 6 kW of power. The heat is remotely controllable, in increments of 500 W. The heaters arrangement is shown in Fig. 2(*c*). In addition, an liquid crystal display and overheat light are provided for user feedback. These are both situated on the outside of the front plate. The liquid crystal display screen indicates the current temperature, fan speed, and power level of the simulator. The overheat light is activated when the system goes into overheat mode. The detailed computer-aided design drawing of all the parts is shown in Fig. 3.

3.2 Aerodynamic Behavior. The novel design of the server simulator is able to accurately emulate ITE dynamic airflow properties and capture corresponding ITE air resistance. The simulator technology presented in this study employs removable perforated plates that can be incrementally installed (Fig. 2(*d*)). The perforated plates increase the pressure drop across the server simulator sufficiently. The server simulator airflow properties can be matched to the actual server using a correct number of perforated plates with a specific open area percentage, i.e., the free delivery (FD) point for them should be matched. These perforated plates also help to straighten the flow and remove flow vector none–uniformities.

3.3 Thermal Mass. The proposed simulator improves the thermal time constant (e.g., thermal inertia) with respect to

Fig. 1 (*a*) Side view of a commercial load bank, (*b*) top view of a commercial load bank, (*c*) front view of a designed server simulator, (*d*) back view of a designed server simulator, (*e*) top view of a designed server simulator, and (*f*) top view of an actual Dell server

changes in heat dissipation. The novel design of the server simulator is provided with aluminum plates, which contain heat within themselves. These plates are built with holes cut into them to fit around one set of heaters and two threaded rods. A thermal paste is typically used to ensure consistent and reliable heat transfer from the heaters to the thermal mass. The server simulator thermal mass can be changed by incrementally adding or removing the aluminum plates. According to Eq. (1), the server simulator is designed to have 60–70% of the heat capacity of a server, which ranges from 500 to 800 $\frac{J}{K}$. The arrangement of the thermal mass plates is shown in Fig. 2(*b*)

$$M_{\text{total}}[\text{Kg}] = M_{\text{chassis}} + (N_{\text{perforated plates}} \times V_{\text{Al}} \times \rho_{\text{Al}}) + M_{\text{Al plates}}$$

$$\text{Total heat capacity of server}\left[\frac{J}{K}\right] = M_{\text{total}}\,[\text{Kg}] \times C_P\left[\frac{J}{\text{Kg K}}\right] \quad (1)$$

3.4 Control System. The current commercial load banks are not conducive to run multiple sets of experiments. They are typically used to obtain a single set of manually initiated measurements and then removed from the rack. The designed server simulator is remotely controllable through a communication link or network and employs an embedded intelligent processor named a Raspberry Pi device. As a result, a user can change different parameters such as server's fan speed or heater's power using the Raspberry Pi controller and run a series of experiments without removing the server simulator from the rack. The Raspberry Pi is used as a controller and interface between the user and the system. The Raspberry Pi is programed to send the signals when commands are received and when feedback is received from the system itself. Namely, when a command comes in for a new power level, the Raspberry Pi controls the correct voltage regulators in the power stepping system. If the system reaches a temperature higher than a defined threshold, the Raspberry Pi sends a signal to the heaters and turns them off. The Raspberry Pi internal timer is

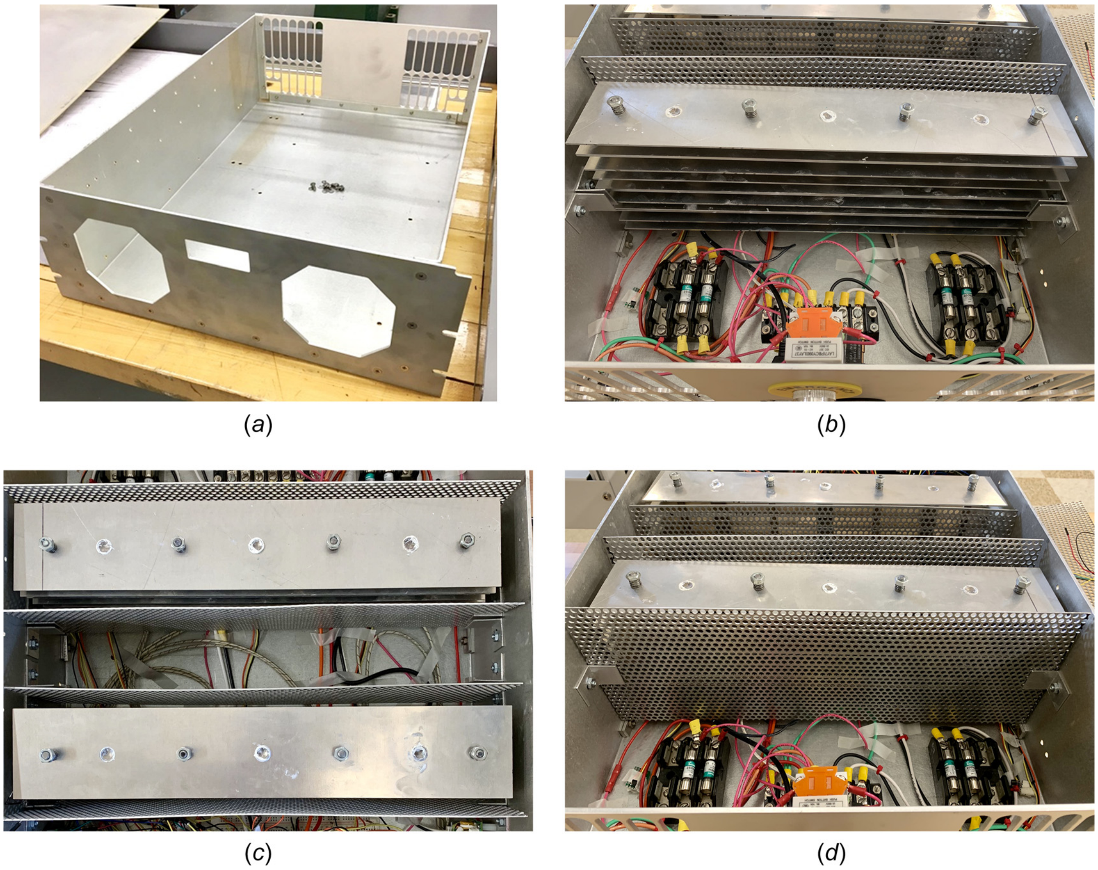


Fig. 2 (*a*) Server simulator chassis, (*b*) thermal mass plates, (*c*) heaters top view, and (*d*) perforated plates

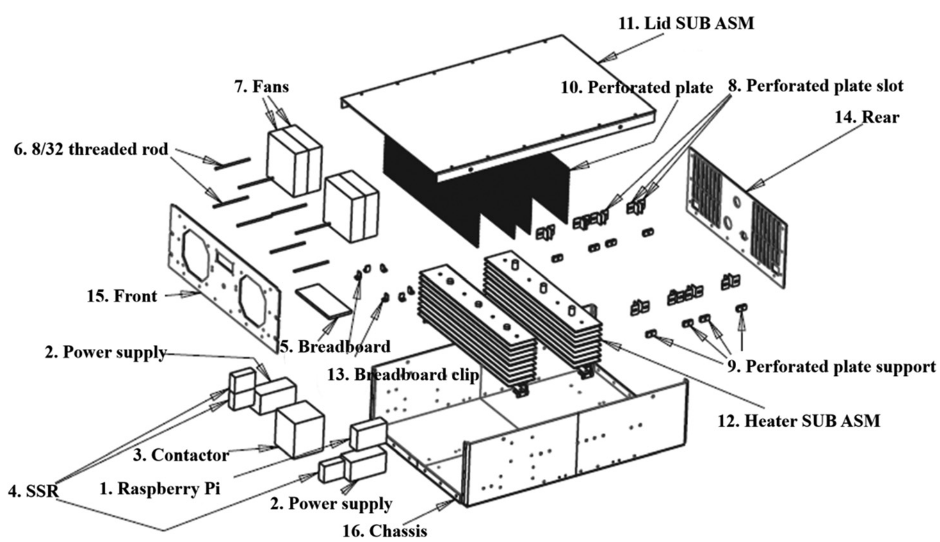


Fig. 3 Computer-aided design drawing of different parts

used to shut the fans off at a predefined time. The Raspberry Pi also takes measurements from temperature sensors in the simulator and can cooperate with other server simulators. The Raspberry Pi controller acquires data from the temperature sensors while controlling the heaters and fans. Afterward, it passes the temperature data to a server which can be added to a Microsoft Excel spreadsheet for processing, analyzing, or transferring to other software. A Linux OS is installed on the Raspberry Pi which allows for easy implementation of the secure socket shell protocol. This interface enables experiments to be run over a long period of time and also to record accurate data. The data collected indicates the amount of cold air needed from the DC cooling system. Moreover, an override system is provided to ensure that the simulator is not damaged in the event of an overheat scenario. The override system involves a contactor, a relay, three solid state relay (SSRs), and eight digital temperature sensors, all connected to the Raspberry Pi. The contactor lies between the AC inputs and the rest of the system. The relay controls power flow to the contactor and the SSRs control power flow to the heaters. Once any of the temperature sensors shows a temperature higher than 70 °C, the

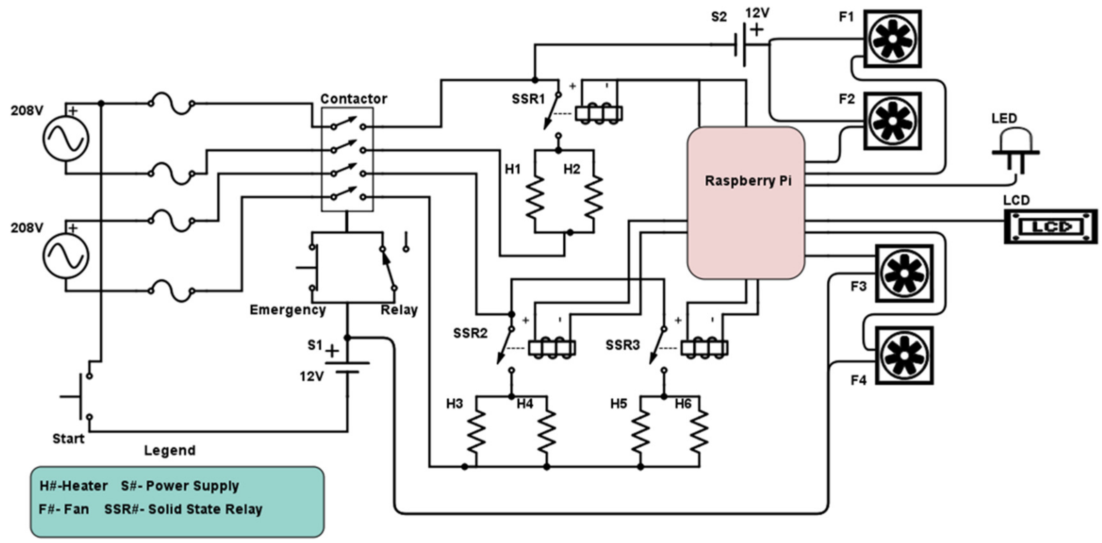
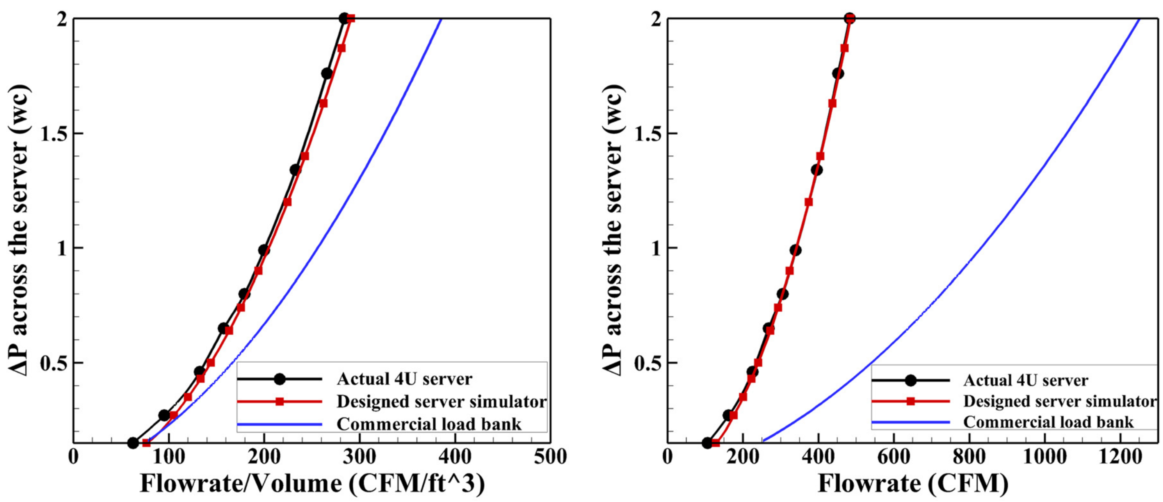


Fig. 4 Designed server simulator's control system schematic



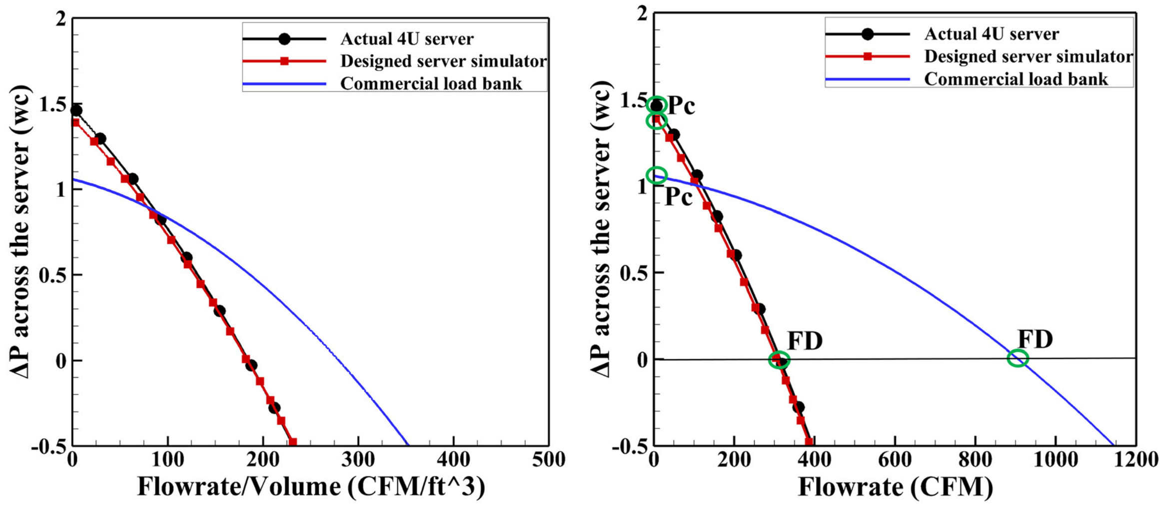
(*a*) (*b*)

Fig. 5 (*a*) Normalized PFCs (impedance curves) and (*b*) actual values of PFCs

Rasberry Pi sends a signal to the SSRs to open the circuit and activate the overheat light on the display. This cuts the power to all heaters and causes them to shut down. Additionally, this triggers a 2-min timer in the microcontroller. When the timer completes, the relay going to the contactor is triggered, and contactor power is turned off. As the contactor opens, it cuts off the power flow from the outlet to both power supplies, and therefore the fans. This override system allows the fans to stay turned on longer than the heaters and cool down the system which leads to a faster recovery time. The power stepping system uses SSRs and temperature sensors to throttle the available power for the six heaters. This requires 3 SSRs and temperature sensors. Each SSR has two heaters attached to it. Temperature readings are used as a part of the control loop to verify heaters power level. The server simulator control system schematic is shown in Fig. 4.

4 Experimental Verification and Discussion

4.1 Airflow Characterization. This section compares the airflow behavior of the introduced novel server simulator and commercial load bank with an actual 4 U server. As the first step, the correlation between airflow and pressure differential across the ITE is characterized using the methodology developed in Ref. [29]. In order to find the desired passive and active flow curves, servers are attached to a test chamber (flow bench) designed in accordance with AMCA 210-99/ASHRAE 51-1999. Initially, passive flow curves (PFCs) are developed which present the relationship between airflow and the differential pressure across the ITE while the fans are turned off. The PFCs (also known as impedance curves) show the servers' air resistance. It is worth mentioning that to compare three different designs with a common scale, the flow rate data is normalized. As shown in Figs. 5(*a*) and 6(*a*), the ΔP is demonstrated based on the flow rate divided by the volume of each ITE. As shown in Fig. 5(*a*), the maximum flow rate discrepancy between the actual 4 U server and the designed server simulator is 14 [CFM] at 0.15 [wc] pressure. However, the maximum flow rate difference between the actual 4 U server and commercial load bank is 108 [CFM] at 2 [wc]. Hence, the PFC of the designed server simulator has a good agreement with an actual 4 U Dell server. Nevertheless, the commercial load bank indicates much lower air resistance than the actual server (Table 1). This implies that adding perforated plates to the designed server simulator caused sufficient airflow resistance to match the flow curve of real servers.



(*a*)

(*b*)

Fig. 6 (*a*) Normalized AFCs and (*b*) actual values of AFCs

Table 1 Normalized PFCs of different designs

PFC	Actual 4 U server [flow rate / volume]	Commercial load bank [flow rate / volume]	Difference [flow rate / volume]
$\Delta P = 2$ [wc]	284	392	108
	Actual 4 U server [flow rate / volume]	Designed server simulator [flow rate / volume]	Difference [flow rate / volume]
$\Delta P = 0.15$ [wc]	63	77	14

Table 2 Normalized AFCs of different designs

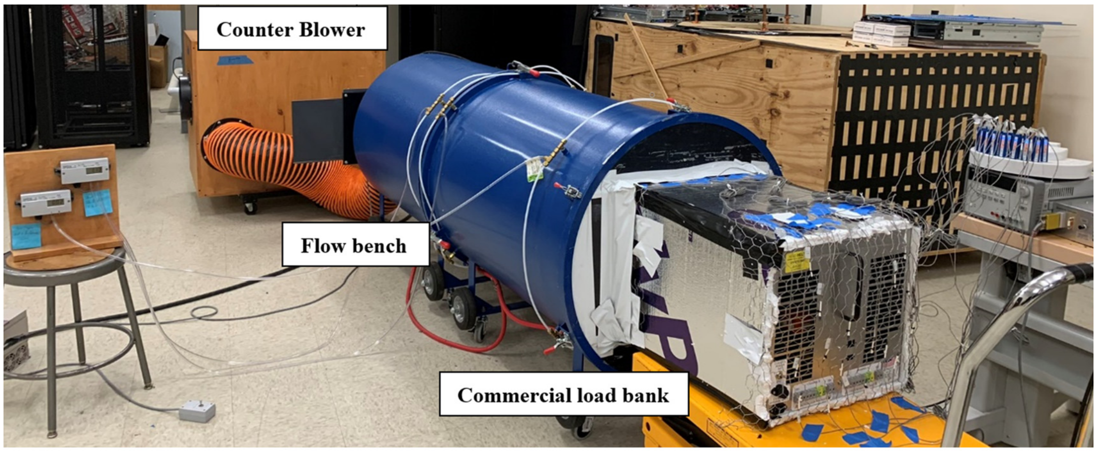
AFC	Actual 4 U server [flow rate / volume]	Commercial load bank [flow rate / volume]	Difference [flow rate / volume]
$\Delta P = -0.5$ [wc]	232	356	124
	Actual 4 U server [flow rate / volume]	Designed server simulator [flow rate / volume]	Difference [flow rate / volume]
$\Delta P = 1.24$ [wc]	37	28	9

Table 3 Critical back pressure and FD point of different designs

	Actual 4 U server	Commercial load bank	Designed server simulator
Critical back pressure (Pc) [wc]	1.47	1.05	1.41
Error		28%	4%
FD airflow (design) [CFM]	314	904	305
Error		187%	2%

In addition, servers' active flow curves (AFCs) which is the flow rate based on the differential pressure across the ITE when the fans are turned on is demonstrated in Fig. 6(*b*). The maximum normalized AFCs discrepancy between the actual ITE and the designed server simulator is 9 [CFM], which shows 93% improvement compared to the commercial load bank (Table 2). As airflow increases for all servers during characterization, static pressure drops. This pressure drop is a characteristic of each server. Table 3 shows that the designed server simulator improves emulation of the critical back pressure (Pc) and FD point of the actual 4 U Dell server by 24% and 185%, respectively, compared to the commercial load bank.

4.2 Thermal Capacitance. To measure the ITE thermal capacitance, servers are mounted to the flow bench. Then, a foam board insulator is used to reduce the airflow leakage through the servers' chassis as Pardey et al. explained in Ref. [25]. The airflow leakage to the lab environment reduces the servers exhaust temperature in which the inlet air is heated. An external heat source is used to ramp up the servers' inlet temperature. The °C UAS 1000



(*a*)

(*b*)

(*c*)

Fig. 7 (*a*) Commercial load bank attached to the flow bench, (*b*) designed server simulator mounted to the flow bench, and (*c*) actual 4 U Dell server attached to the flow bench

sensors with an accuracy of ±3% are used to measure the inlet and outlet temperature of the servers. All sensors are attached to the data acquisition hub via USB (ATM 2400 Hub). The experimental setup is shown in Fig. 7. Initially, server inlet and outlet temperatures are at the laboratory ambient temperature (approximately 23 °C). After 6 min, heating of the inlet airstream begins and server inlet temperature rises more rapidly than outlet temperate as the thermal mass of the server absorbs heat from the airstream. After approximately 70 min, the system reaches a steady-state and due to the energy balance, the inlet and outlet server's temperatures are about 36 °C. Figure 8 depicts the temperature profile of the actual 4 U server, designed server simulator, commercial load bank, and the temperature comparison between them. As shown in Fig. 8(*d*), the designed server simulator and actual server temperature profile are almost identical. However, due to the lack of thermal mass in the commercial load bank, its transient response time is much faster than the actual server. The data shows a 27% improvement in server simulator thermal mass compared to the commercial load bank (Table 4).

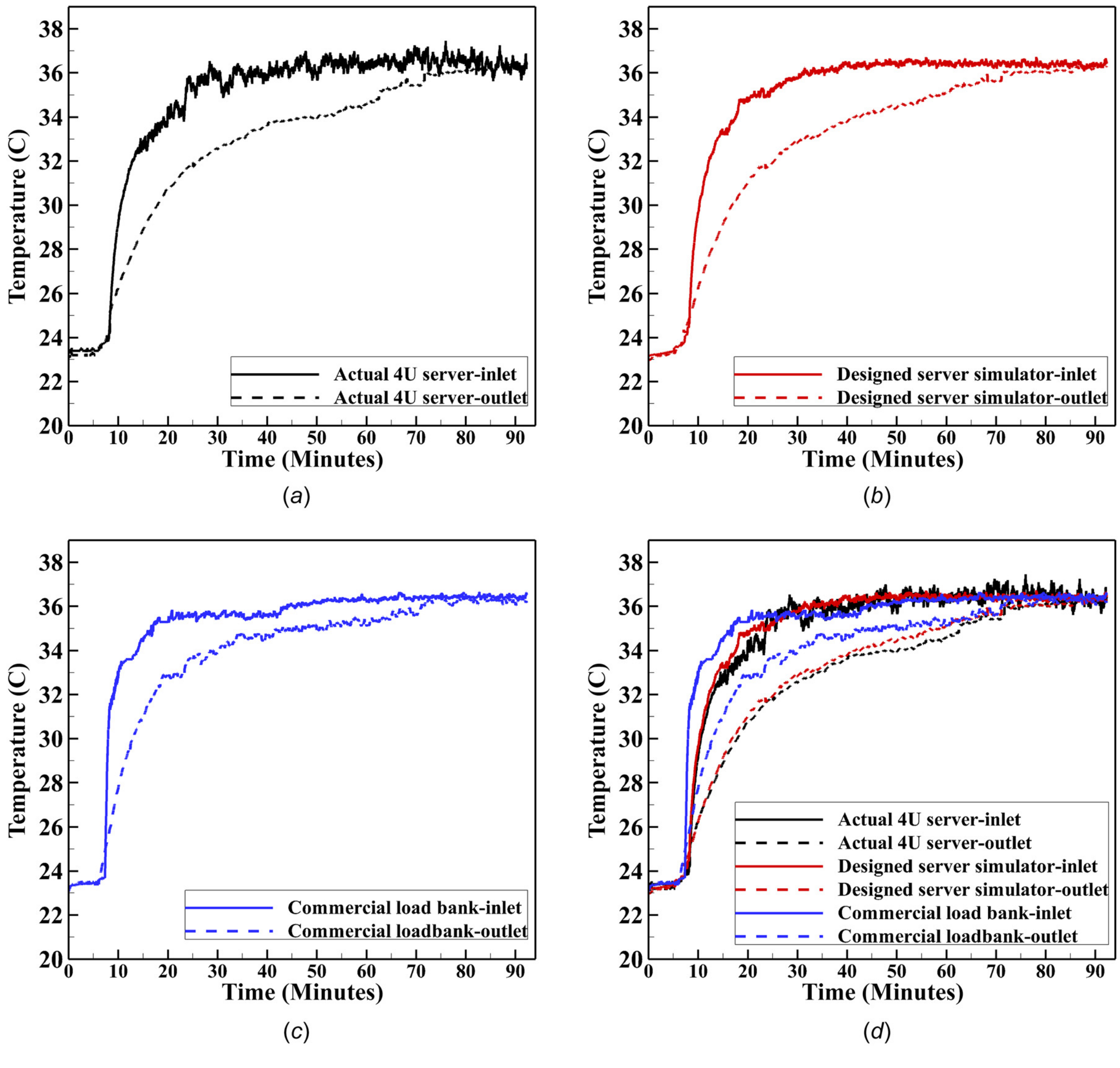


Fig. 8 (*a*) Temperature profile of the actual 4 U server, (*b*) temperature profile of the designed server simulator, (*c*) temperature profile of the commercial load bank, and (*d*) comparison between different temperature profiles

Table 4 Temperature discrepancy between different designs

	Actual 4 U server	Commercial load bank	Designed server simulator
Max $\Delta T_{Tin-Tout}$ (°C)	4.4	5.7	4.5
Error		29%	2%

5 Conclusions and Next Steps

The existing commercial load banks lack a considerable amount of the aerodynamic and transient characteristics of real ITE. In this study, a novel design of a server simulator was introduced. The designed server simulator was able to mechanically and aerodynamically mimic the actual ITE with much greater accuracy than commercially available load banks. Based on the results of the experiments, unlike the commercial load bank, the designed server simulator improved the airflow characteristics up to 93% compared to the commercial load banks. The discrepancy between actual ITE and novel server simulator back pressure and the free delivery point is below 5%. In comparison, the commercial load bank error is up to 187% in emulating the actual ITE free delivery point. Moreover, the thermal capacitance of a designed server simulator had a good agreement with the actual server and improved the thermal mass by 27% compared to the commercial load banks.

In addition, the developed server simulator had various adjustable features which can be modified to test multiple types of servers and use multiple simulators to perform DC wide experiments. The number and arrangement of fans, the amount of thermal mass, and the air resistance can be easily modified to address specific system features and characteristics. The shape of heaters and plates can be different depending on the application. The density and spacing of thermal mass plates can vary to mimic different heat sinks, form factors, and processor architectures. Additional heaters and thermal mass can be added locally to imitate secondary internal hot spots. Temperature sensors mounted on the thermal mass may be used to indicate internal heating while simulating the failure of cooling blowers for opened or contained solutions. Also, a surface temperature alarm can be added for the thermal mass, e.g., a thermostatic alarm or an alarm triggered by the thermal rise rate. Internal sensors at the inlet may be provided to mimic intelligent platform management interface (IPMI) data for a simulated server. To compensate for the accurate momentum throw, adjustable size vents may be mounted at the outlet of the chassis. A fan control algorithm could be implemented based on internal inlet sensor reading, thermal mass surface temperature, and temperature difference across the unit. This adjustability allows various kinds of experiments to be run with one basic server simulator kit. For future studies, computational modeling of the developed design can be investigated which helps for design optimization of air-cooled servers.

Nomenclature

AFC = active flow curve
Al = aluminum
ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFM = cubic feet per minute
Cp = specific heat capacity
DC = data center
FD = free delivery (design airflow)
IPMI = intelligent platform management interface
ITE = information technology equipment
M = mass
N = number
Pc = critical backpressure
PFC = passive flow curve
SSR = solid state relay
V = volume
ρ = density

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