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Determining wasted energy in the airside of a perimeter-cooled data center via direct computation of the Exergy Destruction

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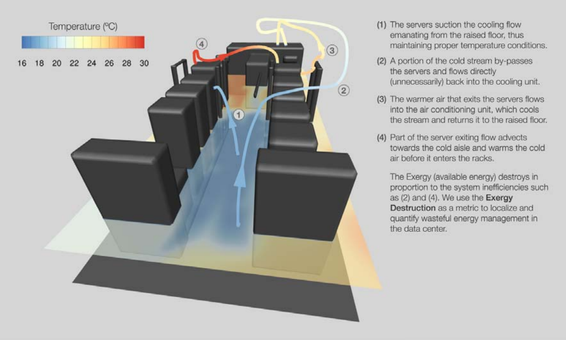
HIGHLIGHTS

- We located and quantified areas of significant airside Exergy Destruction.
- Raised floor pressure drop represented a third of the airside Exergy Destruction.
- The airside encompassed a significant proportion of the overall system losses.

GRAPHICAL ABSTRACT



(1) The servers suction the cooling flow emanating from the raised floor, thus maintaining proper temperature conditions.

(2) A portion of the cold stream by-passes the servers and flows directly (unnecessarily) back into the cooling unit.

(3) The warmer air that exits the servers flows into the air conditioning unit, which cools the stream and returns it to the raised floor.

(4) Part of the server exiting flow advects towards the cold aisle and warms the cold air before it enters the racks.

The Exergy (available energy) destroys in proportion to the system inefficiencies such as (2) and (4). We use the **Exergy Destruction** as a metric to localize and quantify wasteful energy management in the data center.

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ABSTRACT

To keep pace with the growing energy demand, legacy air-cooled data centers begun implementing energy efficiency strategies: Perfecting air flow management, enhancing cooling air delivery and collecting (re-using) waste heat. However, one may wonder: What is the magnitude of these energy savings? Is it worth the effort? The second law of Thermodynamics offers unique insights about energy wasteful practices by estimating the Exergy Destruction in a system. Exergy is equivalent to the "available energy", hence the presence of inefficiencies "Destroys Exergy". In this work, we numerically modeled the behavior of the airside in an existing data center laboratory (CEETHERM) using the commercial Finite Volume software 6SigmaDCX^{TM}. The collected numerical data were used to post-process two Exergy Destruction approaches (Direct and Indirect method), whose behavior was tested against: (1) A simplified study case and (2) Actual data center flow. Both approaches worked well against the study case, although for case (2) the Indirect Method–which neglects turbulence effects–predicted zones of artificial negative Exergy Destruction. The Direct Method permitted associating large inefficiencies in the airflow to hot–cold airstream pre-mixing and important pressure drops in the raised floor. The airside Exergy Destruction encompassed a significant amount of the total irreversibilities in the system, suggesting that mitigating (or eliminating) it, can substantially improve energy saving efforts, especially in legacy data centers.

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Nomenclature

Symbols

k	turbulence kinetic energy
Pr_t	turbulent Prandtl number
$\dot{Q}_{\mathrm{CRAC}}$	CRAC absorbed heat
$\dot{Q}_s$	server dissipating heat
s	specific entropy
$\dot{S}_{gen}$	entropy generation rate
T_0	dead state temperature
T_c	coolant temperature
T_s	server temperature
Tu	turbulence intensity

Greek letters

α_t	turbulent thermal difussivity
ε	turbulence dissipation rate
ν_t	turbulence eddy viscosity
ψ	specific exergy ($\dot{\Psi}/\dot{m}$)
$\dot{\Psi}$	exergy rate
$\dot{\Psi}_d$	Exergy Destruction rate
$\dot{\Psi}_d'''$	Exergy Destruction rate per unit volume
$\dot{\Psi}_{\dot{Q}_t}$	exergy associated with turbulent flux

Subscripts

d	destruction
gen	generation
in	inlet condition
out	outlet condition
ref	reference state

1. Introduction

Between 2007 and 2012, the worldwide data center energy consumption grew at a 4.4% yearly rate [1]; in contrast, the global electricity consumption grew by 3% in the same period. In their study, Van Heddeghem et al. claimed that in 2012 data centers consumed 270 TW h, with the infrastructure electricity such as cooling and power supply losses being the principal consumer at 60% of the total. As opposed to other similar studies, their calculations include servers that draw power but deliver no service, called “orphaned servers”. In terms of absolute electricity use, data centers, communication networks and personal computing each consume roughly the same power; the authors mentioned this to recommend energy-efficiency research throughout those three categories.

Most traditionally designed data centers utilize underfloor air cooling in which the conditioned air emanates from the main CRAC/CRAH unit via the underfloor space then through perforated tiles into a so-called “cold aisle” between two rows of racks, Fig. 1. The server fans suction this cooling air and reject it at an elevated temperature into the “hot aisle”. The flow returns via the overhead space to the CRAC unit.

The large power consumption associated with HVAC in data centers, renders thermal management as key towards efficient operation. Several studies have presented a variety of energy saving techniques, such as: Cooling and IT equipment redistribution, liquid cooling, localized cooling, aisle containment, airside economization [2–17]. Rambo and Joshi [16] analyzed different cooling configurations, recommending what they called the “OH-RR” (overhead supply and room return) scheme with the CRAC units opposing each other in the room. The Rack Cooling Index (RCI), introduced by Herrlin [17], improves the cooling effectiveness assessment in data center design. The author highlighted the shortcomings of solely using the temperature distribution to rank different designs.

Computational Fluid Dynamics (CFD) in data centers appears as a convenient tool for rapid design and diagnosis [3,7,10,13,16,18–30]. Compared to empirical investigations, CFD allows studying the data center airside cooling flow in great detail and, when done accurately, it leads to more intelligent decision making. Previous studies favored the Finite Volume Method as their numerical approach and the k-ε model to represent the turbulence [3,7,10,16,18,20,21,23–25,27–30].

A portion of data center thermodynamic analyses made use of the Exergy Destruction as a way to quantify inefficiencies [2,24,31–35]. In general, those studies followed a clasical thermodynamic approach by assuming the cooling components in mechanical and thermal equilibrium (uniform velocity and temperature distributions), including the complex air flow inside the server room. One exception, Shah et al. [24], simulated and quantified the pre-mixing of cold air with leaking air from the hot aisle in terms of Exergy loss, although they neglected pressure drop and turbulence effects. The study expanded to the rest of the data center components, where they compared individual to overall inefficiencies.

2. Motivation and objectives

Prior studies demonstrated that nearly a third of the Exergy supplied to the data center vanishes due to unoptimized thermal management [24]. Estimating the Exergy Destruction in the data center airspace appears as a practical metric to localize and quantify inefficiencies due to inadequate server cooling.

Common practice in Exergy Destruction computations establishes the Exergy balance and estimates the Exergy Destruction as the imbalance in that equation. Kock and Herwig [36] coined the term “Indirect Method” to define this approach, as the Exergy Destruction is calculated indirectly from other quantities such as entropy and heat fluxes. Kock and Herwig [37] proposed a second method to measure the Exergy Destruction by directly computing it from the velocity and temperature fields, the “Direct Method”. They demonstrated the superiority of the Direct Method and recommended its use in complex flow scenarios.

This study aims to identify and accurately quantify wasteful cooling in a perimeter-cooled data center airspace, including an examination of the role of viscous dissipation (pressure drop) which heretofore has always been assumed to be negligibly small in data center airflows. Furthermore, we directly compute the detrimental effect that turbulence exerts over the system efficiency; also neglected in prior studies. We also perform a side by side comparison of the Direct and Indirect

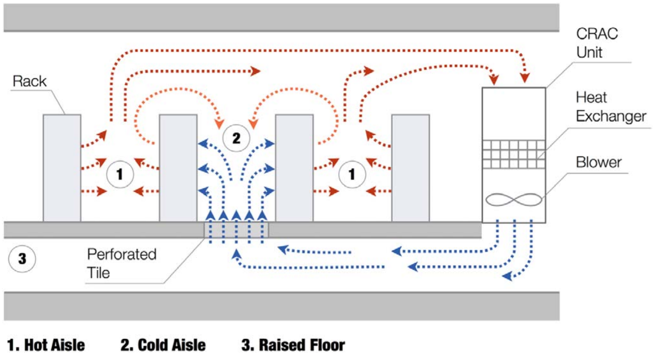

Fig. 1. Fluid flow schematic in a perimeter cooled data center.