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An experimental and theoretical investigation of the extent of bypass air within data centres employing aisle containment, and its impact on power consumption

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HIGHLIGHTS

- Experimental investigation of bypass of cooling in data centres employing aisle containment systems.
- Effect of bypass on total power consumption investigated using a new system model.
- Practical measures for reducing bypass shown to reduce power consumption.
- Optimum level of aisle pressure investigated.

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ABSTRACT

A combination of laboratory experiments and a system model are used to carry out the first investigation into the potential for cold air to bypass IT equipment within data centres (DCs) employing aisle containment, and the effect of this bypass on DC electricity consumption. The laboratory experiments involved applying a differential pressure across commercially available server racks and aisle containment systems and measuring the resulting air flow. The potential to minimise bypass by sealing leakage paths and redesigning racks was investigated and quantified experimentally. A new system model is developed using a combination of manufacturer data, empirical relationships and experimental results to predict the impact of bypass on the power consumption of the various components of a DC's cooling infrastructure. The results show that, at typical cold aisle pressures, as much as 20% of the supplied air may bypass servers by finding alternate paths through the server rack itself. This increases the required flow rate from air conditioning units (ACUs). The system model predicts that: (i) practical measures undertaken to reduce this bypass could reduce total power consumption by up to 8.8% and (ii) excessive pressure differentials across the containment system could also increase power consumption, by up to 16%.

1. Introduction

Energy use in residential and commercial buildings reportedly accounted for over 24% of total global energy consumption in 2012 [1], with this figure ranging from 20% to 40% in individual, developed countries [2]. Energy consumption in buildings has recently been predicted to rise by 31% between 2012 and 2040 [1]. Accordingly, it has been a focus of political initiatives to limit energy consumption for the past four decades, and has received much attention from the research community [3,4]. Heating, ventilation and air conditioning accounts for around half of energy consumption in buildings [2], and air conditioning specifically is expected to contribute significantly to the expected growth to 2040 [1,2]. Efforts within the research community to improve the efficiency of air conditioning systems have focused primarily on improving the coefficient of performance (COP) of the cooling system under a given set of air supply and return temperatures and flow rates, with savings achievable through changes to the management of air flows having received relatively little attention [5]. However, investigations into the benefits of reducing the mixing of hot and cold air streams through intelligent positioning of supply and return vents have shown this approach to have great potential for reducing energy consumption. Specifically, investigations focusing on air conditioning for thermal comfort, industrial food refrigeration and cooling of manufacturing facilities have

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Nomenclature

Greek symbols

μ	dynamic viscosity (Pa s)
η	efficiency (no units)
ρ	density (kg m^{-3})

Symbols

a	width of channel (m)
b	height of channel (m)
c_p	specific heat capacity (J kg^{-1} K^{-1})
D_h	hydraulic diameter (m)
E	power consumption (kW h)
f	friction factor (no units)
k	loss coefficient (no units)
L	length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
p	pressure (Pa)
$\dot{Q}$	heat load/generation (W)
Re	Reynolds number (no units)
u	average velocity (m s^{-1})
$\dot{V}$	volumetric flow rate (m^3 s^{-1})

Acronyms

ACU	air conditioning unit
CFD	computational fluid dynamics
COP	coefficient of performance
CW	chilled water
DC	data centre
HACA	hot aisle/cold aisle
LMTD	logarithmic mean temperature difference
PA	process air

Subscripts

½	up/downstream
BP	bypass
CA	cold aisle
CH	between hot and cold aisle
con	contraction
eco	economiser
exp	expansion
HA	hot aisle
i/o	at entrance/exit
l	laminar
PA	process air
req	required
$slot$	slot
t	turbulent
T	relating to the whole data centre facility

predicted potential energy savings of 9–50% [6–9], 47% [10] and 63% [11], respectively, using this approach. The savings are accrued through reductions in the required conditioned air flow rate (which leads to savings in fan power) [6,7], and the potential to increase the supply air temperature, which increases the COP of chillers [6,7] and reduces their required operating hours (where free cooling is available) [7].

Data centres (DCs) are buildings which facilitate the operation of large quantities of computing equipment, and form the backbone of today's digital infrastructure [12]. They are energy-intensive facilities, with typical power densities of 540–2200 W/m^2, and extreme cases exceeding 10 kW/m^2 [13]. The DC industry has recently been estimated to account for 1.4% of global electricity consumption [14]. The compound annual growth rate (CAGR) of this electricity consumption from 2007 to 2012 has been estimated as 4.4% [14], much higher than the 2.1% projected for total global electricity demand from 2012 to 2040 [1]. Unchecked, this growth could have serious implications for efforts to reduce carbon emissions over the coming decades [15,16]. Governments have begun to take action to drive efficiency improvements in DCs, with the aim of reducing costs and environmental impact [17–19]. Energy consumption in the sector has also attracted the attention of the research community, as will be detailed in the remainder of this section.

Air conditioning is required in DCs in order to remove the heat generated by the servers, preventing them from overheating, and typically accounts for 20–50% of a DC's total electricity consumption, E_T [20]. Accordingly, the efficiency of cooling is a major focus of efforts to reduce DC electricity consumption, with good practice regarding air management, cooling equipment operating conditions and selection of efficient equipment forming the basis of academic and governmental studies and best practice guidelines [21,22]. This paper focuses on air management, since recent studies have highlighted the potential for energy savings through improvements in this area [23–33]. As with air conditioning for thermal comfort, efforts to minimise DC air conditioning energy consumption must be balanced against the need to maintain the desired thermal conditions. Poor air management can both increase energy consumption and compromise the thermal environment. Specifically, the potential for supplied cold air to bypass IT equipment, returning to the ACU without carrying out any useful cooling duties, is known to impair the efficiency of a DC's cooling system [26,34–36]. This "bypass" increases the rate at which cold air must be supplied in order to ensure that sufficient air is available to cool the servers. Efforts to minimise bypass must be balanced against the need to avoid 'recirculation', i.e. the transport of hot air from server outlets back into server inlets. This can cause servers to fail due to over-heating [37], leading to DC managers reducing the supply temperature of conditioned air, which reduces the COP of the cooling system [38]. The goal is thus to distribute the cold air in such a way as to minimise the supply flow rate of cold air which is required in order to achieve an acceptably small level of recirculation, keeping server inlet temperatures within AHRAE's recommended limits [39]. Improvements in air management have been highlighted both as a cause of recent improvements in DC cooling efficiency and as an area in which further efficiency improvements can be made [40].

In an effort to minimise both bypass and recirculation, most modern, purpose-built DCs are arranged in hot aisle/cold aisle (HACA) formation. Servers are housed in rows of racks, with racks in adjacent rows aligned in opposite orientations, such that server inlets face each other into aisles into which cold air is supplied (termed cold aisles). The servers contain fans which draw the cold air over the heat generating components. Server outlets then face each other in hot aisles, from which hot air returns to the ACUs [37]. Segregation of hot and cold air streams is increasingly being further enhanced through the introduction of solid barriers separating hot and cold aisles, commonly referred to as aisle containment systems [34,35,40]. Fig. 1 shows diagrammatical representations of DCs employing HACA formation and cold aisle