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## Dimensionless parameter for evaluation of thermo-fluids performance of Air Conditioning and Ventilation Systems

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### **ABSTRACT**

Evaluation of effectiveness of air handling systems for cooling and ventilation is either non-existent or based on thumb rules. There is lack of quantifiable metrics to assess the performance of these systems vis-à-vis the environment. With the advent of high density, mission-critical datacenters and high energy demands it is necessary to develop metrics to evaluate the effectiveness and efficiency of thermal management provided by these systems. Hosting business and mission-critical applications at high power levels demand a high degree of reliability and flexibility in air conditioning systems. Energy consumptions of air handling equipment has also severely increased by over-designed fan systems, plenum designs and room layouts that allow the hot and cold air streams to mix. Lack of monitoring sensor network has added to this problem.

In this paper, we formulate non-dimensional parameters to evaluate the thermal performance of air conditioning systems within a conditioned space. The parameters, based on temperature, reflect the convective heat transfer and fluid flow within the space and can be applied to commercial or non-commercial buildings as well. The self-similar parameters can be scaled from one unit to several units operating in the same room. Measurements from an experimental system are used to validate and correlate with monitored data from other sources. Dimensionless parameters in the form of Utilization Index (UI) are calculated, based on space temperature, outlet and inlet temperatures, for validation purposes. Experimental data show that UI provides a simple and powerful tool to understand the convective heat transfer and fluid flow in around the air conditioning system. Analysis based on Utilization index is carried out to understand air flow distribution among units.

### **1. INTRODUCTION**

Energy consumption of the heating, ventilation and refrigeration equipment is on the rise (eia.doe.gov). This is partly due to increase in install base and rise in energy consumption of existing units. Energy use in buildings is also growing in all sectors – residential to commercial and industrial. More than 45% of this energy budget can be attributed to operation of HVAC equipment.

Rising compute needs is also one of the key drivers for increase in energy consumption (Kawamoto et al, 2001). Data centers are the computational (Friedrich et al., 2001) and energy consumption hub of the next generation. Hosting business and mission-critical applications demand a high degree of reliability and flexibility. Deployment of large number of high powered computer systems in very dense configurations in racks in data centers will result in very high power densities at room level (Schmidt, 2002). Managing high power levels in data centers with cost effective reliable cooling solutions is essential for reliability and uptime. Energy consumption of data centers can also be severely increased by over-designed air handling systems and rack layouts that allow the hot and cold air streams to mix.

One of the techniques used to cut down on over-design is computational fluid dynamic (CFD) modeling. This is a key improvement to understand the air flow patterns and create thermal zones of control (Patel et al, 2001). Yet another research effort, often used with CFD modeling, has attempted to optimize air flow patterns in buildings through second law techniques (Shah et al, 2003).

Energy efficient policy-based operation with flexible cooling infrastructure and dense sensor network is, also key to reducing energy consumption (Patel et al, 2002). Evaluation of raw data to extract metrics for optimization is crucial for such policy-driven control systems (Bash et al, 2003). In the past such metrics have been derived for heat dissipating devices like server racks (Sharma et al, 2002). Several others have been proposed for datacenter-related energy management applications (Schmidt et al., 2005)

## 2. Air Handling Infrastructure

Air handling infrastructures can be broadly divided into VAV boxes and AHUs. VAV boxes are primarily used for office space and local zone cooling while AHUs are for cooling large spaces, datacenters and high heat load zones.

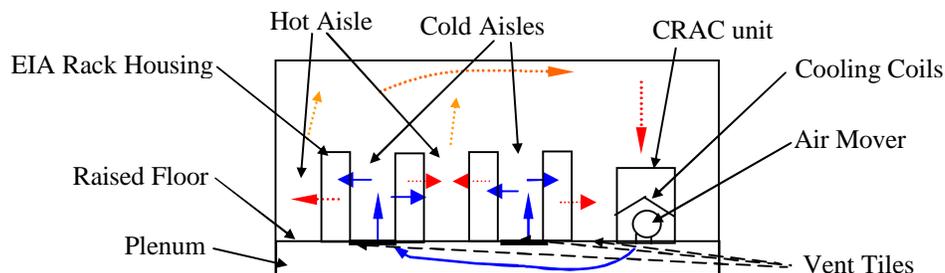
### 2.1 Dampers (VAV Boxes)

Variable air volume (VAV) systems for heating, air conditioning and ventilation provide many zones of control at relatively low initial and operating cost. In its simplest and most common form a central air handler delivers primary air (a mixture of first-pass outdoor and re-circulated return air) to the VAV boxes through a single duct. Then each VAV box regulates the flow of primary air into the space to maintain the desired sensible temperature.

### 2.1 Air Handling Units

Air handling systems comprise of chilled water coils, blowers and associated controls. Hot air is pulled in through the chilled water coils and discharged into a plenum or duct providing air to the conditioned space. Temperature sensing and control allows the unit to maintain a prescribed air temperature at the supply or return by manipulation of a mixing valve in the chilled water bypass line. Dampers or variable frequency drives may also be tied into the controls to manipulate the air flow as well.

Figure 1. displays a typical data center air-conditioning environment with under-floor cool air distribution (Patel et al., 2002). The air handling units (also called CRAC units) cool the re-circulated exhaust hot air from the computer racks. A refrigerated or chilled water cooling coil inside the unit extracts the heat from the air and cools it within a range of 10 °C to 17 °C. The cool air is recirculated back to the racks through vented tiles in the raised under-floor plenum. CRAC units are used to cool hot air from the data center and deliver conditioned air to the racks using a pressurized floor plenum and perforated vent tiles. Typically, volumetric delivery of the CRAC units is 5.7 m<sup>3</sup>/sec. Vent tiles with adjustable flow resistance allow for controllable conditioned air delivered to each rack. CRAC unit cooling flexibility is achieved through variable-speed blowers and the ability to control the flow rate of chilled water to the CRAC unit. In addition to the more common raised floor approach, there is a broad variety of non-raised floor infrastructures.



**Figure 1.** Typical Under Floor Air Cooling Data Center Configuration with Room Return

## 3. Hypothesis

Commercial and industrial infrastructures can differ in methods of cooling and air handling. In datacenters, computer equipment in racks can be deployed in a number of different ways. Other commercial and non-commercial buildings use VAV boxes to cool zones. But the basic thermo-physical processes that provide cooling and the cold air to servers is essentially the same. Successful room design involves complex optimization of flow work to distribute air judiciously around the room consuming minimum energy with the least irreversibility. Irreversibilities

in flow ( $\dot{f}_f$ ) can occur due to mixing of hot and cold air streams or due to flow expansion and contraction through vent tiles and aisles. Irreversibilities in thermodynamic work ( $\dot{f}_w$ ) can occur due to low isentropic efficiency in the compressor or high friction losses in the cooling cycle (Reynolds and Perkins, 1977). Irreversibilities in heat transfer ( $\dot{f}_T$ ) can occur due to un-optimized heat exchanger design (Kays and London, 1998). A conservative flow work design also reduces the overall COP of the cooling system by operating at lower evaporator temperatures and higher pressure drops. Thermodynamic and heat transfer irreversibilities within the air handler are beyond the scope of this paper.

The incremental irreversibilities associated with each flow and heat transfer processes are given by (Ozisik, 1985)

$$d\dot{f}_f = -mRT_o \ln(P_{out}/P_{in}) \quad (1)$$

$$d\dot{f}_T = mC_pT_o \ln(T_{out}/T_{in}) \quad (2)$$

where  $T_o$  is a reference temperature, in some cases, the lowest temperature of heat rejection. Since irreversibility is a path variable, total irreversibility is a summation of all the combined values for every significant process in the data center. Processes are identified based on control volumes created around each key region of transport. A typical process could be heat extraction in a AHU or flow of hot air from the exhaust of a device to AHU inlet.

We hypothesize that there exist key non-dimensional parameters that can be used to determine a scalable, temperature based “index of performance” for the any device that exchanges heat with it surroundings (Sharma et al, 2002). This index of performance would reflect the losses associated with the irreversibilities caused by the processes in the room. Figure 2 shows the flow model of such a device with an inlet region at the air intake. The inlet region is a mixing region for the desired input air stream before it enters the device. The mixing of air streams is driven by the flow characteristics and geometry of the device and the external flow patterns in the vicinity of the device. In the event of fully ducted flow, no such region would exist around the device. In such case,  $T_{in}$  and  $T_{ref}$  would be identical. In a non-ducted environment, however, air entering the device  $T_{in}$  is higher than the  $T_{ref}$  due to convective and diffusive heat transfer from exhaust air streams. Desired heat transfer to or from the air stream occurs within the device before the air exhausts from the device at temperature  $T_{out}$ . For purpose of this paper, we will focus on air handling systems which are, primarily cooling devices. A similar study on heat generation devices like racks has been carried out before (Sharma et al., 2002).

Flow and Heat Transfer irreversibilities occur in the region (Control Volume 1)

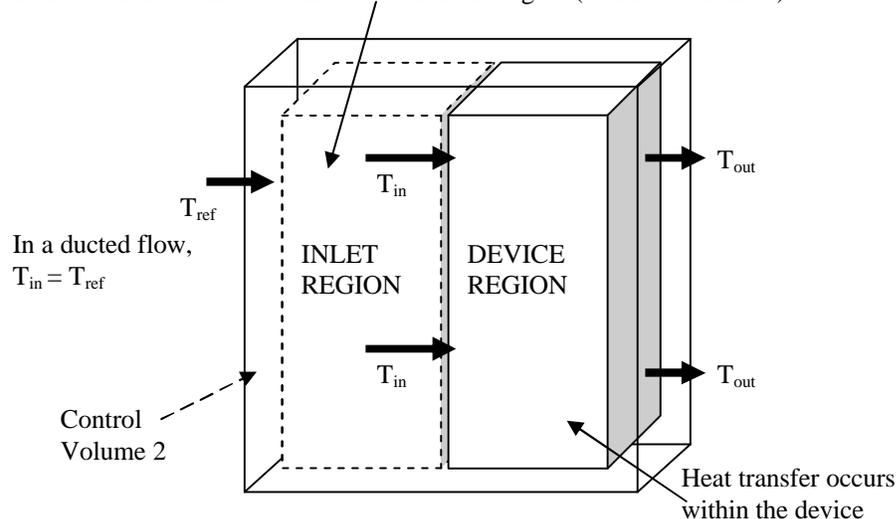


Figure 2: Control Volume Analysis for air flow in Air Handling Units

The key measure of a conditioned space is temperature. The performance of air distribution system in conditioned space can be characterized by inlet and outlet temperature. Thus, we will base the index of performance, on inlet and outlet temperature and a reference temperature. The key temperature measure, at the inlet of the device, is a function

of the geometrical layout of the room. Ideally, to minimize energy consumption, the temperature at the inlet of the air handling devices should be equivalent to the maximum temperature in the room, henceforth referred to as  $T_{ref}$ . However, mixing of hot and cold air streams reduces the temperature of the air before it returns to the units. In datacenters, the hot exhaust air temperature from the racks, and the hot aisles, would be equal to the AHU return air temperature e.g. if a duct was provided that picked up all the hot air from the hot aisle and returned it back to the AHU inlet. However, due to infiltration of cool air from the vent tiles and the cold aisles the return air temperature to the AHU is not equal to the exhaust air temperature from the rack.

Yet another phenomenon is the “short circuiting” of the airflow back to the AHU return and the degradation of capacity of the AHU. Increased mixing in the inlet region reduces  $T_{in}$ . Consequently,  $T_{out}$  has to be reduced to extract the same amount of heat, thus impacting the cooling capacity of the unit and the coefficient of performance of the upstream chillers. To summarize, the key to maximizing the performance in the AHU would be to increase capacity utilization and indirectly, improve coefficient of performance of chillers by:

- A. Minimizing the short-circuiting of cold air to the AHU inlet.
- B. Minimizing the mixing of hot return air with cold air streams, prior to return to the AHUs.

## 4. Methodology

A first principle approach to optimize flow work would be to understand how temperatures vary at the inlet and outlet of the AHUs. Creating control volumes around AHUs, inlet and outlet temperatures can be used to characterize each element (see Fig.2). Indices based on these temperatures could be used to evaluate the recirculation load on each device. Thus, we can base the index of performance, on inlet and outlet temperature and a reference fixed temperature.

### 4.1 First Law Perspective

Consider  $Q$  as the total heat exchange from the device and  $\delta Q$  as the change in enthalpy of the air stream before entering the devices. Then:

$$Q_j = m_j C_p (T_{in,j} - T_{out,j}) \quad (3)$$

where  $m_j$  is the mass flow of air through  $j^{th}$  device,  $T_{in,j}$  and  $T_{out,j}$  are average inlet and outlet temperature of the  $j^{th}$  device. Similarly:

$$dQ_j = m_j C_p (T_{ref,j} - T_{in,j}) \quad (4)$$

where  $T_{ref}$  denotes the reference temperature. Reference temperature is defined as the temperature of an un-mixed air stream that would ideally enter the device in the absence of mixing from the surrounding region. It is akin to inlet temperature in a ducted flow device. In cases, where the device is an air handler, this region will be located in the mixed region within its thermal zone.

The Utilization Index (UI) of  $j^{th}$  device is given by:

$$UI_j = \frac{Q_j}{Q_j + dQ_j} = \frac{\text{Enthalpy drop in the device}}{\text{Combined Enthalpy drop in the device and inlet region}} \quad (5)$$

The numerator denotes the heat extracted from the air in the device while the denominator represents the total heat extracted from the air entering at a reference state and leaving the AHU. Since the mass flow rates at the inlet and outlet of each device are equal, UI can be rewritten as a function of device inlet, device outlet and reference temperatures. For the data center, this gives:

$$UI_j = \left( \frac{T_{in,j} - T_{out,j}}{T_{ref,j} - T_{out,j}} \right) \quad (6)$$

where  $j$  represent specific AHU. Ideally, Utilization Index varies from 0 to unity. A higher UI indicates that the enthalpy drop in the device is significant compared to the enthalpy drop in the inlet region. In other words, a well utilized AHU with reduced mixing at the entry region of the unit. As a result of reduced mixing; the unit does not need to sub-cool aggressively, to dissipate its design load. Chilled water supply temperatures to these units also do not need to be reduced, thus, maintaining or improving the coefficient of performance of the chillers. UI values can

be calculated for a cluster of air handling units in a room or datacenter to evaluate the impact of overall mixing on the coefficient of performance. If the conditioned space is shared by several AHUs, UI can also be negative for some AHUs indicating under-provisioning. Individual unit UIs can help in isolating areas susceptible to hot spots. In this manner the index is scalable and can give information about the room as a whole or any sub-section thereof down to VAV box (or AHU). Equations 5 and 6 indicate that higher  $\delta Q$  leads to lower  $T_{in}$  and hence, a lower UI. When the inlet temperature ( $T_{in}$ ) to the AHU drops, AHUs have to reduce  $T_{out}$  to dissipate the same heat load. Since chilled water temperatures remain unchanged, AHUs become more vulnerable to capacity limiting. Reduced  $T_{in}$  also signifies increased entropy generation (irreversibility) due to mixing and reduced energy efficiency for the data center.

#### 4.2 Second Law Perspective

Consider two control volumes, one including the intake region in front of the AHU and the other including the intake region and the AHU as shown in Fig. 2.  $\delta Q$  and  $Q$  represent the drop in temperature of the fluid due to mixing with adjacent cold air streams and equipment heat load respectively. From Eqns. (1) and (2), irreversibilities in heat transfer in the two control volume are given by

$$\frac{df_T^1}{mC_p T_o} = \ln(T_{in}/T_{ref}) \quad (7)$$

$$\frac{df_T^2}{mC_p T_o} = \ln(T_{out}/T_{ref}) \quad (8)$$

Since the RHS is of the order of  $10^{-2} \sim 10^{-3}$  for both equations, we can safely assume that

$$T_{in}/T_{ref} \approx 1 + \frac{df_T^1}{mC_p T_o} \quad (9)$$

$$T_{out}/T_{ref} \approx 1 + \frac{df_T^2}{mC_p T_o} \quad (10)$$

Calculating Utilization Index for the AHU from the LHS of Eqns. (9) and (10), we obtain UI as a ratio of the difference of irreversibility generated at the device inlet and exhaust to that generated at the device exhaust.

$$UI = \frac{T_{in} - T_{out}}{T_{ref} - T_{out}} = \frac{df_T^2 - df_T^1}{df_T^2} = 1 - \frac{df_T^1}{df_T^2} \quad (11)$$

This relationship clearly shows that the Utilization Index also reflects the second law (exergetic) efficiency of individual devices and complete data centers.

## 5. Results and Discussions

Utilization index was calculated for several air handling units operating with chilled water supply in Hewlett-Packard datacenter in Palo Alto. A low cost sensor network is used to monitor  $T_{in}$ ,  $T_{ref}$  and  $T_{out}$ .  $T_{ref}$  is the maximum temperature at the exhaust of heat dissipating device in the region of influence of the particular AHU (Bash et al, 2006). AHU data is monitored through a building management system (BMS). Key operating parameters like chilled water return temperature, chilled water mixing valve opening were monitored and recorded for a series of steady state experiments. As in typical datacenters, several AHUs share heat loads from server racks. Although the results correspond to chilled water AHUs, such applications and correlation of UI are valid for direct compression units as well.

Figure 3 shows a plot of the UI index and the chilled water return temperature for an Air handling unit. The chilled water control valve of the AHU was completely open during the experiment. This implied that the capacity of the unit is fixed, for constant water-side and air – side temperatures. Chilled water temperatures change with temperature perturbations and load sharing among the other units. For a constant chilled water supply temperature and flow rate, increase in return water temperature indicates a rise in utilization. The utilization index is calculated from equation 6. The average UI value of 0.55 indicates that close to half of the temperature reduction occurs due to

mixing in the inlet region of the AHU. The balance temperature reduction occurs within the AHU. The chilled water supply temperature to the unit was maintained at 7.2C (45F) during this experiment. The AHU was rated for a chilled water flow rate of 2.5 liters per second (40 gpm).

A time series plot of Utilization Index and chilled water control valve position for a different AHU is shown in figure 4. The control valve alters the flow rate of chilled water to the unit to match the cooling demand. The chilled water through put in the coils determines the cooling potential of the AHU for a given air flow rate and temperature.

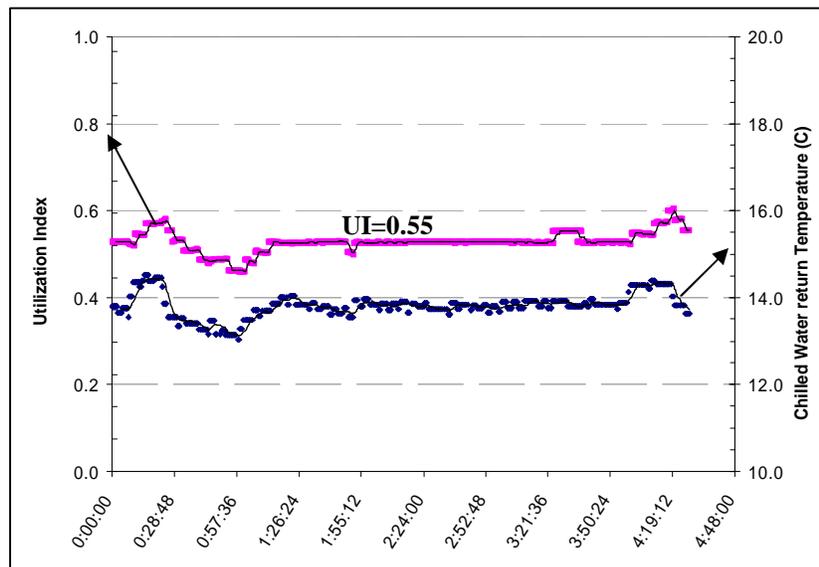


Figure 3: Utilization Index and Chilled Water return temperatures

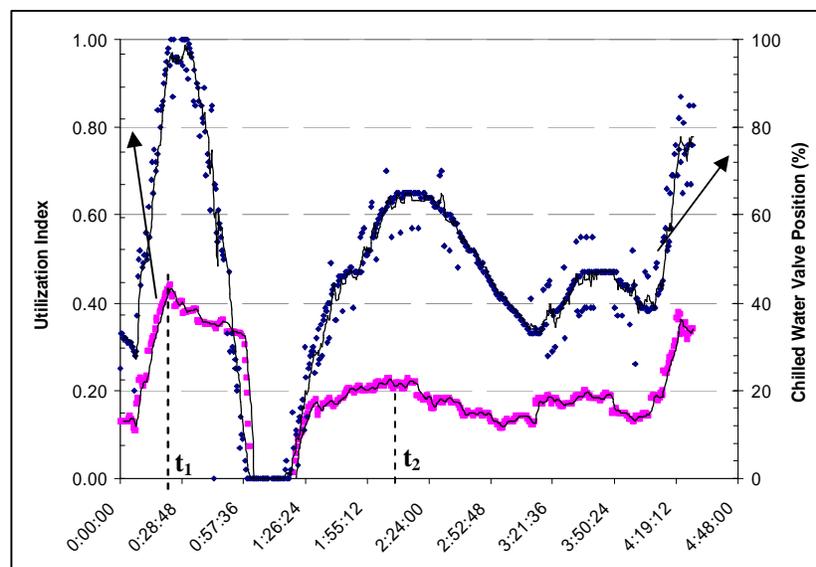


Figure 4: Utilization Index and Chilled Water control valve position

Unlike the case shown in fig. 3, valve position changed during the course of the experiment while the AHU return air temperature was steady at 23.8C (75F). During the course of this experiment, the utilization index becomes zero, indicating no temperature reduction occurred in the unit during that period. At time  $t_1$ , UI is 0.4. Although the valve position is high, only 40% of the temperature reduction actually occurs at position A. At time  $t_2$  the valve position is high but about 80% of the total temperature reduction occurs in the mixing region at the inlet of the AHU. Nevertheless, UI tracks the change in valve position and acts as a proxy for changes in the real AHU capacity. The

lag between the control valve position and utilization index results from the air flow dynamics in the conditioned space.

As is conventional, all the units in the present study are controlled based on the return-side air temperatures. Supply temperatures vary based on the load shared among the units. Short circuiting of these air streams affects the load on the units and long term reliability. These variations are captured by utilization index. Such variations are responsible for the results shown in fig.4. Variations in fig.3 relate to temperature perturbations in the room like AHU shutdown or increase in heat load etc.

In the cases where AHUs have variable frequency drives, it is often difficult to track changes in AHU cooling load with varying speeds in the absence of a building management system. UI can provide information on changes in loading when VFDs change speed or any perturbations occur in air flow.

For ventilation systems, UI can be calculated using the ambient air intake conditions to the AHU.  $T_{ref}$  should include a contribution from the ambient temperature conditions.

## 6. CONCLUSIONS

Use of dimensionless parameters allows development of scalable solutions for thermal and energy management of AHUs. Operation of multiple AHUs can be complicated with load sharing imbalances and complex air flow patterns. In case of AHUs with VFDs, keeping track of loading with varying air flow rates from AHUs can also be expensive, if not difficult.

The utilization index utilizes simple temperature measurement to provide information about the air flow pattern around AHUs. Within its definition, UI also provides a framework to quantify the irreversibilities associated with mixing of hot and cold air streams.

Further research is needed to expand on the long term usage of the utilization index for operation of AHUs.

## NOMENCLATURE

<i>AHU</i>	Air Handling Unit
<i>BMS</i>	Building Management System
$C_p$	Specific heat of air at constant pressure
<i>CRAC</i>	Computer Room Air Conditioning unit
<i>f</i>	Irreversibilities
<i>l</i>	Rack depth
<i>m</i>	Mass flow rate of air through a rack
<i>M</i>	Mass flow rate of air through a AHU
<i>Q</i>	Cooling load on air handling unit
<i>UI</i>	Utilization Index
<i>VFD</i>	Variable Frequency drive
<i>T</i>	Temperature
<u>Superscripts</u>	
<i>1,2</i>	control volumes
<u>Subscripts</u>	
<i>in</i>	inlet
<i>out</i>	outlet
<i>ref</i>	reference
<i>w</i>	work
<i>f</i>	flow
<i>T</i>	heat transfer

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