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# Thermal Management of Electronic Equipment Using Closed and Open Loop Cooling Systems

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## ABSTRACT

There is a strong need to improve our current capabilities in thermal management and electronic cooling, since estimates indicate that IC power density level could reach 50 W/cm$^2$ in near future. This paper presents several possible closed and open loop cooling schemes for thermal management of electronic equipment in data centers. Additionally, analytical modeling of two kinds of direct expansion refrigeration cooling evaporator and a secondary liquid cooling fan coil heat exchanger is incorporated with a computational fluid dynamics (CFD) model to analyze a refrigeration cooled high heat density electronic and computer data center installed on a raised floor. Both models incorporate an accurate tube-by-tube thermal hydraulic modeling of the heat exchanger. The refrigeration coil analysis incorporates a multi region heat exchanger analysis for a more precise modeling of two phase refrigerant flow in the evaporator. The single phase secondary loop fan coil heat exchanger modeling uses an effectiveness method for regional modeling of the spot-cooling coil. Using an iterative method, results of the heat exchanger modeling is simultaneously incorporated in the CFD model and an optimal design of spot cooling heat exchanger is developed.

## NOMENCLATURE

| | |
|---|---|
| Q | Heat transfer rate (W) |
| T | Temperature ($^o$C) |
| U | Overall heat transfer coefficient (W/m$^2$ $^o$C) |
| NTU | Number of transfer units |
| h | Heat transfer coefficient (W/m$^2$ $^o$C) |
| m | Mass flow rate (kg/hr) |
| $C_p$ | Specific heat at constant pressure (kJ/kg $^o$C) |
| w | Tube thickness (m) |
| A | Flow cross sectional area (m$^2$) |
| d | Tube diameter (m) |
| K | Tube thermal conductivity (W/m $^o$C) |
| t | Air temperature ($^o$C) |
| ANNUL | Length fraction of the tube with quality up to 0.85 |
| XDRY | Length fraction of the tube with quality within the range of 0.85 to 1.0 |

## GREEK SYMBOLS

| | |
|---|---|
| ε | Heat exchanger effectiveness |
| η | Fin efficiency |
| ρ | Density (kg/ m$^3$) |

## SUBSCRIPTS

| | |
|---|---|
| o | exiting |
| a | air side properties |
| o | outside |
| i | tube inlet |
| v | gas phase |
| l | liquid phase |
| f | fin |
| c | contact, related to contact resistance |
| a | air |
| r | refrigerant |
| p | pipe |
| m | mean |

## INTRODUCTION

Removal of heat has become one of the most important challenging issues facing computer system designers today. The combination of increased power dissipation and increased packaging density have led to substantial increases in chip and module heat flux over the past 50 years. With this trend towards miniaturization, heat removal has become the major bottleneck in microsystems development.

As the rate of power dissipations from electronics components continue to increase, standard forced-air convection cooling techniques no longer provide adequate cooling for sophisticated electronic systems. The reliability of the electronic system will suffer if high temperatures are permitted to exit. Conventional thermal control schemes in data centers have either reached their practical application limit or are soon to become impractical. Recent advances in information technology and demand for higher performance density have increased the power density of electronic devices significantly (Fig.1) [1]. With the increased population density comes increasing power and thermal concerns as data center managers struggle with the ability to thermally manage these highly dense rack servers.

In the open literature different techniques, such as raised floor cooling [2], creation of alternating “hot aisles” and “cold aisles” [3], and spot cooling [4] have been reported for cooling of the high end thermally challenging data centers.

A general thermal description of rack cooling system in the data center is shown in Figure 2. The Figure shows the computer room air conditioning (CRAC) units cool the circulating exhaust hot air from the computer racks. The cool air is circulated back to the racks through the vented tiles in the raised under-floor plenums.

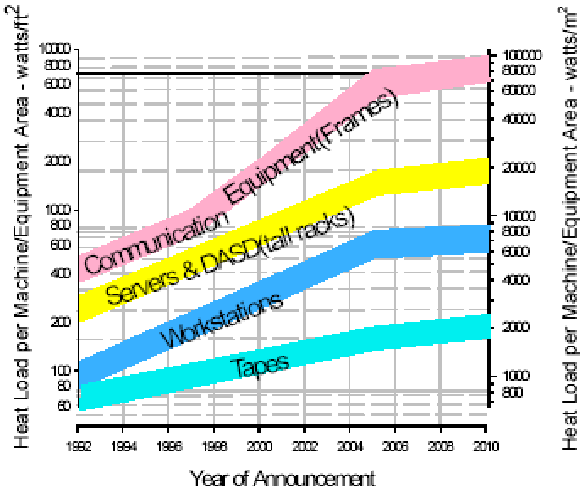

Fig.1: Heat Density Trends and Projections for IT Products [1]

The electronic equipment are typically arranged to form a hotaisle/cold-aisle configuration to maximize the delivery of cooled air to the intakes of the electronic equipment, and allow for the efficient extraction of the warm air discharged by the equipment. The cooling air is typically designed to be supplied at 15°C (58°F) and is expected to be heated up 20°C above the incoming air temperature by passing through the heat generating electronic equipment.

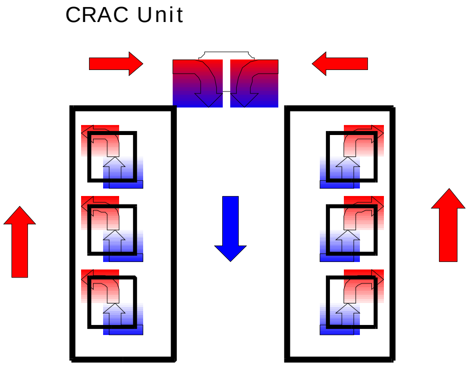

Fig 2: Schematic of Rack Cooling

## Air, Liquid and Refrigeration Cooling Systems

Computations at low temperatures has traditionally been considered a way to improve on computational speed and reliability of high end processors. Several commercial applications of refrigeration cooled high end central processor units have been developed jointly by computer server and air-conditioning and refrigeration industries, but there has always been a public stigma on widespread usage of liquid for cooling of electronics components. Utilization of below ambient temperature air-conditioning cooling and low or subzero refrigeration and cryogenic cooling have their respective advantages, but air has always been the favorite heat exchange medium and the industry persist on prolonging the life of air-cooling using traditional fan and heat sink assembly. There is also fundamental thermodynamic limits where the benefits of liquid or refrigeration cooling will out-weight their advantages, beyond which there is little gains in switching away from air cooling. A second law of thermodynamics exergy analysis can be used for gaining an inside into a design-based physical efficiency limits of various air, liquid and refrigeration cooling techniques. That level of analysis is beyond the scope of this paper, which will focus on detailing acceptable open and closed loop air, liquid and refrigeration cooling options with an introduction to a sample analysis technique.

When considering the issue of refrigeration in a computer cooling application, evaporator temperature distribution, temperature stability, and initial cool down time along with efficiency, reliability, size and cost have to be all considered to have an acceptable cooling solution. Furthermore, overall system availability is critical. To assure continuous system operation, some companies have incorporated a redundant design where two independent refrigerant loops pass through a single evaporator. Packing the refrigeration unit in the computer system is also important. The refrigeration system must be transparent to the end user (i.e., the end user should not have to know or care that refrigeration is taking place.) Refrigeration system heat must therefore be transferred to the ambient air in the same manner as do conventional computer cooling systems today. Condensation must also be prevented from forming on components within the computer as condensation on electronics components is detrimental to reliability and functionality.

The are a number of ways that a refrigeration loop can be incorporated in the thermal management scheme of a electronics components in a computer system [5]. Active cooling systems for computers must compete with passive alternatives such as air cooling and heat pipes. There are a number of refrigeration technologies and even more ways of incorporating each technology into the thermal management scheme of computers in a data center. Therefore, there is possibly no perfect solution and a compromise between proper implementation, reliability, efficiency and cost of ownership is what makes a refrigeration cooling system an option for thermal management of computers in data centers.

## Closed-Loop and Open-Loop Cooling Refrigeration and Air-Conditioning of Computers in Data Centers

Air conditioning and refrigeration cooling systems can provide below ambient temperature cooling and are especially important for enhancing the performance and improving the reliability of CMOS devices [5]. Many advantages can be obtained when properly choosing and designing either a closed or open-loop systems for cooling of densely packaged, high heat flux electronic computers. In this work, major components of few open and closed loop cooling systems are identified and a short description of the components and cooling schemes with their respective schematic diagrams are presented. The following are list and a short description of the major components of air-conditioning and refrigeration cooling systems:

**1- Fan**:

A device that produces pressure difference in air to make it move. It is an essential component of all cooling systems. Except for those cases where free convection exists, a fan is used to move air. The centrifugal fan is the most widely used. Besides centrifugal, vaneaxial and tubeaxial fans are other kinds of fans used in localized and central cooling of electronic components. To select a fan for a cooling system it is necessary to know the capacity and total pressure required for the system. In many cases, manufacturers present their fan performance data in the form of graphs of tables.

**2- Fan Coil Unit (FCU) and Air Cooled Condenser (ACC)**:

The FCU is a versatile room terminal that is applied to both air-water and water-only systems. The basic elements of FCU are a finned-tube and a coil and a fan section. The fan section recirculates air continuously from within the perimeter space through the coil, which is supplied with chilled water in the data center or the electronic enclosure. When hot refrigerant gas is condensed into liquid phase by passing it through a FCU, it is referred to as an air cooled condenser (ACC).

**3- Heat Sinks**:

The heat sink is the most commonly used thermal management hardware in the electronic industry. It is used to enhance heat transfer by directly attaching to the surface of an electronic component or package and removing the heat to the surrounding environment. Heat removal can be accomplished by either natural convection through buoyancy or by forced convection using a fan. Physically, the heat sink can be a solid block of material such as a heat spread, a solid block with fins, a cold plate, or a heat pipe (with or without wick). Other heat sinks include liquid cooled or chilled-liquid cooled heat sinks (LHS), and refrigerant cooled heat sinks (RHS) wherein the heat transport is by phase change of the refrigerant being circulated through the heat sink.

**4- Air Cooled Condensing Unit (ACCU)= ACC + Compressor + Throttling valve**:

A unitary air conditioner unit is a complete refrigeration system composed of an indoor (or an enclosure) FCU and an outdoor air cooled condensing unit (AACU). The ACCU is composed of the compressor, ACC and throttling device, and the FCU consists of an evaporator with a fan.

**5- Air Cooled Water Chiller (ACWC) = ACCU + Evaporator + Secondary Heat Exchanger**:

The ACWC is a complete refrigeration system composed of the following four major components; an air cooled condenser, a compressor, throttling device and an evaporator unit. A build-in secondary loop heat exchangers is used to chill inlet water to the desired temperature level using the cold refrigerant line. For computer cooling applications, the ACWC provides chilled-water that can be pumped to:

- the LHSs which are directly attached to the hot electronic devices, or
- the FCU which provide chilled-air within the computer enclosure.

**6- Unitary Air Conditioner (UAC)**:

A UAC (also known as a CRAC unit) consists of components (fan, coils, filters, etc.) for inclusion in air-conditioning systems that are field-designed to meet the electronic cooling needs. The many combinations of coil configurations, evaporator temperature, air handling arrangements, refrigerating capacities, and variations thereof that are available in central systems are seldom possible with unitary systems.

**7- Air Conditioner (AC) = FCU + Compressor + Throttling valve**:

An AC is an encased designed as a unit primarily for mounting through a wall, or as a console. The basic function of a AC is to provide cooling by passing air over a refrigeration-cooled evaporator in to the electronic enclosure.

**8- Single-packaged Air Conditioner (SAC) = FCU + ACCU**:

A SAC incorporates a complete air-cooled refrigeration (ACCU) and air-handling system (FCU) in an individual package. Each packaged terminal air conditioner has a self-contained, direct-expansion cooling system and packaged controls. No external piping is required for the single-package air cooling unit.

## Open-Loop Computer Cooling Systems

In open-loop cooling system all the heat generated by the computers and electronic equipment is transferred into the space surrounding the electronics hardware in the data center. The heat is then removed by the data center air conditioning and refrigeration system to outside environment.

**1. Air Cooled Data Center**:

The most common way of cooling of computers and electronics devices is by forcing cold air through the raised floor of the data center by using unitary air conditioners (UAC), which are commonly known as computer room air conditioners, or CRACs. Cold air is sucked into the computer enclosure from the cold aisles of the data center and heated air is cooled by passing through the cold evaporator coils of the data center UAC. Cooling of the electronic components can be enhanced using heat sinks. Heat absorbed by the data center UACs is rejected to the outside environment by UAC condensing coils (Fig. 4).

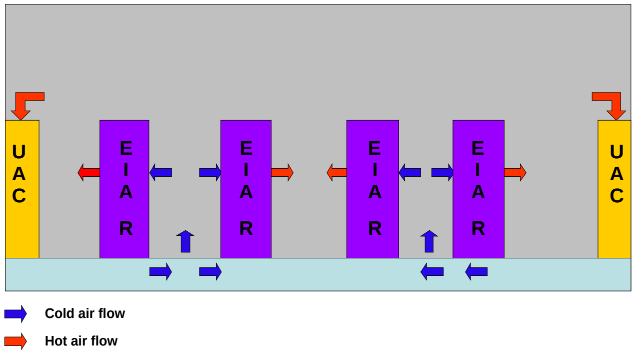

Fig (4): Air cooling of Electronics Devices

**2. Liquid-Cooled Closed-Loop Cooling of Computers in an Open-Loop Air Cooled Data Center**:

In this configuration cooling of microelectronics is achieved by passing cold liquid into a liquid heat sink (LHS) attached directly to electronic components in a server enclosure. A liquid cooling unit (LCU) made of a fan coil unit (FCU) and a pump is used to pump liquid into a liquid heat exchanger (LHS) attached to the electronics components. Forcing cold air of the data center over the FCU heat exchanger removes high heat of the coolant to the ambient outside of the server enclosures. As such, the liquid coolant's temperature is few degrees above data center temperature. Heat rejected from the FCU is finally removed to the outdoor environment by the data center CRAC unit (Fig. 5).

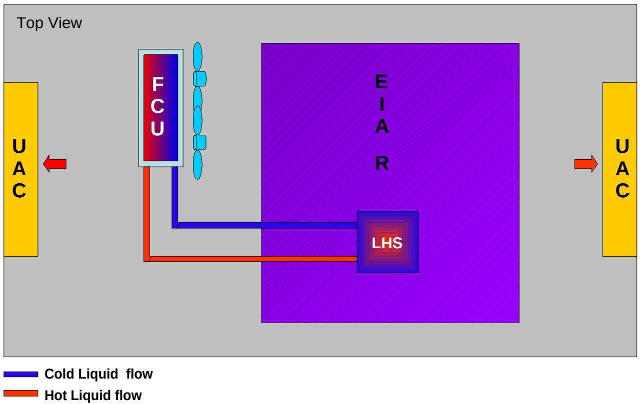

Fig (5): Liquid cooled utilizing LHS and LCU.

**3. Chilled-Air Closed-Loop Refrigeration Cooling of Computers in an Open-Loop Air-Cooled Data Center:**

In this configuration a more aggressive cooling of the entire enclosure of the server is achieved by placing a package air conditioner (PAC) for providing chilled air directly in to each of the servers in the data center. Heat generated by the components of the server is removed by below room air temperature chilled air of the PAC to the area adjacent to the server. Eventually, data center heat is removed by the action of the UAC units to outside of the data center. In this configuration lower junction temperature of the components may be achieved as the temperature of the cooling medium is below room air temperature (Fig. 6).

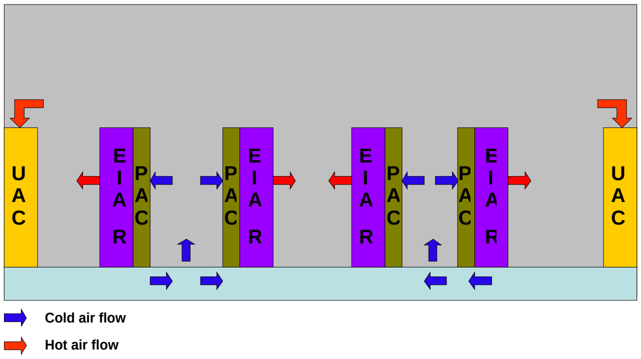

Fig (6): Chilled-air cooled racks using PAC and UACs

**4. Chilled-Liquid Cooled Refrigeration-Assisted Cooling of Computers in an Open-Loop Air-Cooled Data Center:**

In this configuration cooling is achieved by passing low temperature refrigerant fluid through a heat sink attached directly to the high heat flux electronic components. Refrigerant is pumped from an air cooled water chiller (ACWC) situated adjacent to servers into the liquid heat sinks of the servers. Similar to the previous 2 configurations, heat rejected by the server components is absorbed by the chiller unit and in turn is rejected to the ambient air of the data center. Heat of the ACWC units is rejected to outdoor ambient through the data center UAC units (Fig. 7).

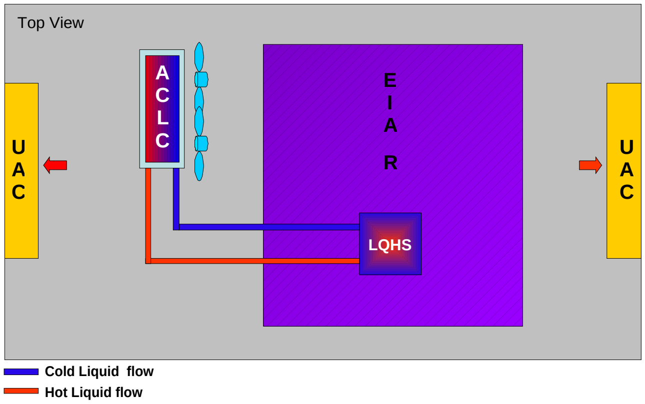

Fig (7): Chilled-air cooling using LCHS , ACWC, and UACs

## Closed-Loop Computer Cooling Systems

In closed-loop configurations, below air temperature is achieved for cooling of electronic components. Heat rejected by the heat generating electronic components is transferred to the outside of data center environment by pumping heat exchange liquid or refrigeration cooling fluids to a water chiller outside of the data center. Closed loop cooling systems has the advantage of minimizing recirculation losses of most open loop systems, minimizes acoustic noise by pumping cooling fluid through pipes which would eliminate the need for large fans of data center UACs, reduces total system cooling costs, to name a few. Though the total cooling system capital costs and need for special cooling system design may be considered as disadvantages of closed-loop cooling systems. The following are some examples of the closed-loop cooling system concepts.

### 1. Chilled-Air Closed-Loop Cooling of Computers Using a Closed-Loop Central Liquid Cooling System:

In this closed-loop cooling configuration a remote central water is chiller is used to pump low temperature liquid coolant to a FCU located adjacent or inside of the computer server. Passage of air forced over the liquid heat exchanger of the FCU drops the air temperature to the desired level for locally cooling of electronics components in the computer server. Heat absorbed by the cooling fluid in the heat exchanger of the FCU is pumped back to the building water chiller, where it is eventually released to the ambient through the condenser of the water chiller. To economize this configuration of the closed-loop cooling system, the same water chiller can be used for cooling of other areas of the building besides the data center (Fig. 8).

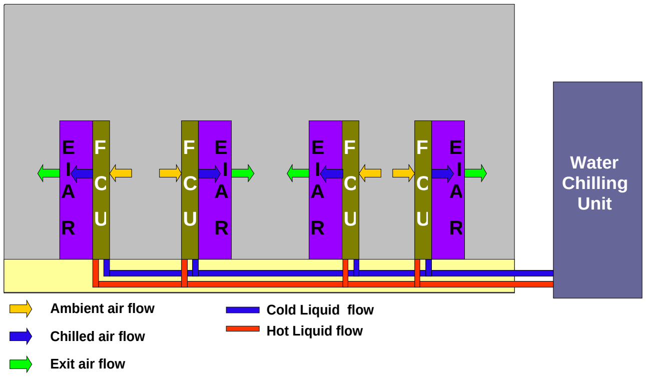

Fig (8): Chilled-air cooling using FCU and central water chiller unit

### 2. Chilled-Air Closed-Loop Cooling of Computers Using a Closed-Loop Distributed Liquid Cooling System:

A uniquely-sized air conditioner (AC) unit is located adjacent or within the space of the computer server, with each AC's condensing unit located outside of the data center's building. Cold refrigerant fluid is pumped out of the compressor of the condensing units into the evaporator of the AC unit, where air blown over the AC evaporator reduces its temperature much lower than the data center's air temperature (Fig. 9).

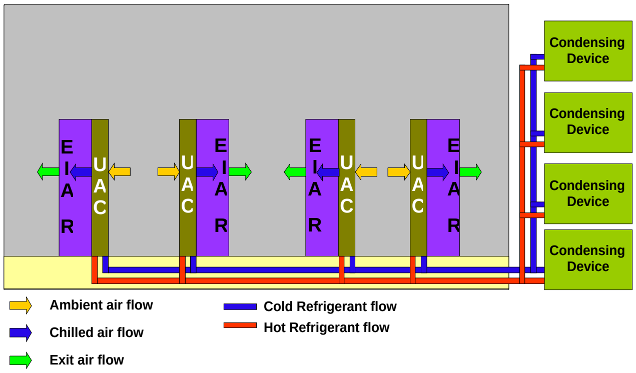

Fig (9): Chilled-air cooling using AC and remote condensing units

### 3. Chilled-Liquid Closed-Loop Cooling of Computers Using a Closed-Loop Central Liquid Cooling System:

A central water chiller unit located outside of the data center building is used to provide chilled water to a liquid to liquid heat exchanger (LLHX) located inside the computer server cabinet. Therefore, in a highly aggressive way, heat is locally removed from the electronic components through the LHS through a secondary cooling loop to the LLHX unit. In the LLHX, primary cooling liquid pumped from the external liquid chiller to each of the LLHX units situated for each of the server boxes removes local heat collected by the secondary fluid in LHS units and the overall data center heat load is removed to the outside environment in the water chilling unit (Fig. 10).

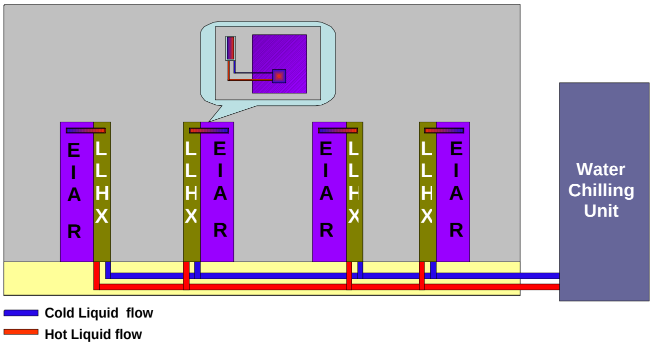

Fig (10): Chilled-liquid cooling using LLHX and central a water chiller

### 4. Refrigerated Closed-Loop Cooling of Computers Using a Closed-Loop Distributed Refrigeration Cooling System:

This configuration presents the most aggressive method for removing heat from the local electronic devices. Refrigeration heat sink (RHS) units located locally inside the server units are directly attached or are located in the proximity of high heat components in the server units. Liquid refrigerant flow in the RHS units provide low temperatures for cooling of high heat flux components. Heat absorbed by the cooling refrigerant is pumped out to the outside environment through the cooling action of the air cooled condensing units (ACCU) located outside of the data center for each one of the server units. Through a proper loading and piping design of the refrigeration system, one of the ACCU units can be used for removing the heat of more than one of the server unit RHS refrigeration evaporator units to the outside environment (Fig. 11).

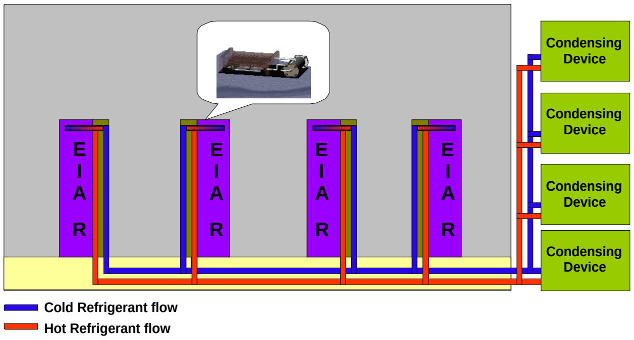

Fig (11): Refrigeration cooled cooling using RHS and ACCU

## PERFORMANCE MODELLING ANALYSIS

Performance analysis of a chilled-air closed-loop cooling of server and electronic enclosure data center using a closed-loop central liquid cooling system is conducted [7] using a commercial software package FLOVENT [8], a customized CFD package designed specifically for airflow distribution and thermal management of computer data centers. The mathematical model is based on simultaneous solution of conservation equations of continuity, momentum, and energy together with a k-ε turbulence modeling [9]. The k-ε model is the most appropriate for large, open spaces circumstances because of the way it calculates the turbulent viscosity and conductivity. The conservation equations are discritized by subdivision of the domain into a set of non-overlapping, contiguous finite volumes. A full description of the mathematical model and the algorithm is beyond the scope of this paper. Further details and equation and method of solution have been reported elsewhere. [10]

A high heat density data center consistent of 24” in height plenums, 2’x2’ perforated tiles utilizing 2 50 tons CRAC units with 5 spot cooled refrigeration units, each 6’ wide by 6’ long with water flow rate of 4.75 lit/sec is considered. Non-uniformly heat generating racks each 2.5 ft wide by 2 ft long and 6.5 ft high are placed in a typical fashion in the floor area of the data center.

Data center room is modeled as an adiabatic enclosure made of concrete walls. Air flow from the CRAC units (modeled as flow device with 5.7 $m^3/s$ (~12000CFM) air capacity and supply temperature of 15°C (58°F)) is modeled as an inflow source into the plenum. Air flow through the perforated tiles are modeled as collapsed resistance with 32% opening area and 1.7 loss coefficient based on the approach velocity, relates the pressure drop across the tile via the flow resistance. Cold intake air is then sucked into the racks by axial fans and the heated air will return through the return duct of the CRAC units. Racks have ventilated doors on both front and backsides, with 2 groups of sub-racks that are perforated on the front face with fans located on their rear face. A resistance is used to produce the appropriate pressure drop through the shelves.

Under floor cables are ignored in this analysis, however overall air flow rate through the server racks is decreased due to added cables flow resistance and as a result incoming air would not remove heat efficiently.

The Spot cool heat exchangers are modeled as counter flow heat exchangers. A Spot cool unit is where heat is absorbed directly from the data center interior and is rejected from the condenser of its primary (in case of direct expansion evaporator unit) or secondary (in case of liquid-cooled fan coil unit) refrigeration loop. Construction of Spot coolers involves space constraints since it is desired to have it placed over the hot spots inside the data center air-handling system. Therefore, there is a need for a precise tube-by-tube method for design of the evaporator coil. A model developed for refrigeration air-conditioner evaporator coil is based on a detailed geometrical model in which heat transfer and pressure drop resulting from flow of refrigerant through individual lines of flow is modeled. For a refrigeration evaporator coil, a multi-region flow model consisting of a two-phase and an all-vapor flow model, which considers existence of annular and dispersed two-phase flow regimes is used. In case of a liquid cooled secondary loop fan coil unit, heat and fluid flow of air passing in cross flow over the heat exchanger is theoretically modeled using an ε-NTU formulation.

Figure 12 shows a schematic diagram of a typical spot cool heat exchanger coil. The following presents analytical modeling of a direct expansion refrigeration evaporator and a secondary loop fan coil heat exchanger for a typical heat exchanger shown in Fig. 12.

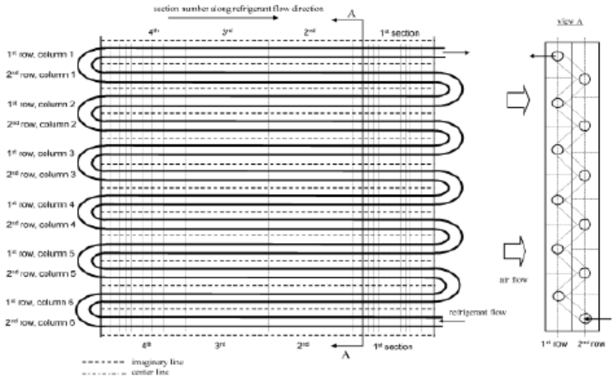

Fig (12): Schematic diagram of a spot cool heat exchanger

### Direct Expansion Refrigeration Evaporator;

The spot cool evaporator is part of a refrigeration system, composed of a compressor, condenser and a flow control thermostatic expansion valve. A typical working refrigerant in such a system is R-22 and R-407A.

Thermal hydraulic modeling of the evaporator spot cooler is accomplished by considering two flow regimes of annular and dispersed flows, distinguished by the quality of refrigerant in the evaporator coil. Refrigerant flow quality of up to 0.85 is considered to represent annular and refrigerant quality of between 0.85 and 1.0 is considered to represent dispersed flow regimes. Flow quality of greater than 1.0 constitutes superheated flow regime.

For annular flow regime, the cooling capacity of the evaporator is;

$$Q = m_a.C_{p,a}\left(t_i - T_i\right)\left(1 - \exp\left(-\frac{U.A_o}{m_a.C_{p,a}}\right)\right). \qquad (1)$$

For dispersed flow regime, the cooling capacity is;

$$Q = m_a.C_{p,a}\left(1 - ANNUL\right)\left(t_i - T_i\right)\left(1 - \exp\left(-\frac{U.A_o}{m_a.C_{p,a}}\right)\right) \qquad (2)$$

For single phase superheated flow of refrigerant in the evaporator coil,

$$Q = m_r.C_{p,r}\left(t_i - T_i\right)$$
$$\left(1 - \exp\left(-\frac{\left(1 - ANNUL - XDRY\right)m_a.C_{p,a}}{m_r.C_{p,r}}\right)\right)\left(1 - \exp\left(-\frac{U.A_o}{m_a.C_{p,a}}\right)\right) \qquad (3)$$

where, the fraction of coil in annular flow regime, ANNUL, is calculated as,

$$ANNUL = \frac{m_r\left(i_{r,0.85} - i_{r,i}\right)}{m_a.C_{p,a}\left(t_i - T_i\right)} \cdot \left(1 - \exp\left(-\frac{U.A_o}{m_a.C_{p,a}}\right)\right) \qquad (4)$$

The fraction of flow in dispersed regime, XDRY, is calculated as,

$$XDRY = \frac{m_r.\left(i_{r,v} - i_{r,i}\right)}{m_a.C_{p,a}\left(1 - ANNUL\right)\left(t_i - T_i\right)} \cdot \left(1 - \exp\left(-\frac{U.A_o}{m_a.C_{p,a}}\right)\right) \qquad (5)$$

The overall heat transfer coefficient, U, consists of different resistance terms for the flow of heat. Heat transfer calculations employ different inside tube heat transfer correlation for annular flow, dispersed flow, and single-phase superheated vapor flow available from literature. Consideration of dehumidification process over the evaporator coil may be considered by a proper formulation for the value of the overall heat transfer coefficient.

**Fan Coil Heat Exchanger;**

A water-cooled spot cooling system involves using a fan-coil system including a chiller in the central plant, water system supplying chilled water to the fan coils, and a space recirculation system. Chilled water is supplied to the fan coil through a two pipe water system. The fan coil units are installed horizontally over the hot spots of the data center. One large or two smaller fans are placed over the surface of the fan coil surface. Coils are usually made from copper tubes with aluminum fins. Coils may have two, three, or four rows of fins, depending on the coil's cooling capacity. The ε -NTU method is used to calculate cooling load of the fan coil Spot-cooling units. Cooling load of the fan coil unit is calculated as;

$$Q = m_a.C_{p,a}\left(t_i - T_i\right)\varepsilon \qquad (6)$$

where, the effectiveness of the fan coil unit is a function of the heat exchanger's number of transfer units (NTU). The ε–NTU relationship is governed by the physical design and specification of the fan coil heat exchanger. Typical values for ε as a function of NTU can be obtained in literature [11]. The NTU is defined as,

$$NTU = \frac{UA}{C_{P,a} m_a} \qquad (7)$$

The overall heat transfer coefficient, *U*, is calculated from sum of the individual resistances in the coil assembly, as;

$$U = \frac{A_o}{h_i A_{pi}} + \frac{A_o w_p}{k_p A_{pm}} + \frac{A_o}{h_c A_{po}} + \frac{1}{h_o\left(1 - \frac{A_f}{A_o}\left(1 - \eta\right)\right)} \qquad (8)$$

The first and last term refer to the inside and outside heat transfer resistances, respectively. The second term represents the conductive heat transfer resistance through the tube wall. The fourth term represents the contact resistance between the outside tube surface and the connecting fin.

## NUMERICAL RESULTS & DISCUSSIONS

Using an iterative procedure, the cooling load of evaporator or fan coil heat exchanger is integrated with the commercially available computational fluid dynamic simulation code, Flovent, for the data center specified above.

The results of the simulation of data center are reported to show the temperature contours at various locations. (Figures 13-16) From these figures it's apparent that Spot cooling is inevitable to prevent the effect of high temperatures at elevated heights of the high heat flux racks which dissipate most of the heat.

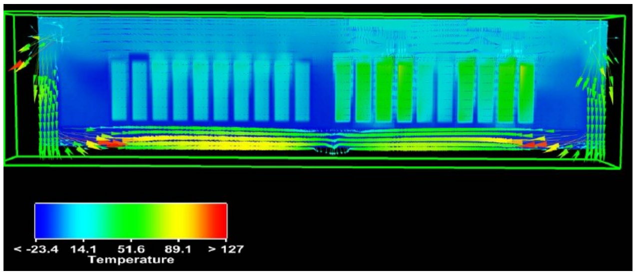

Fig (13): Temperature Distribution at X=18.6ft with spot-cool

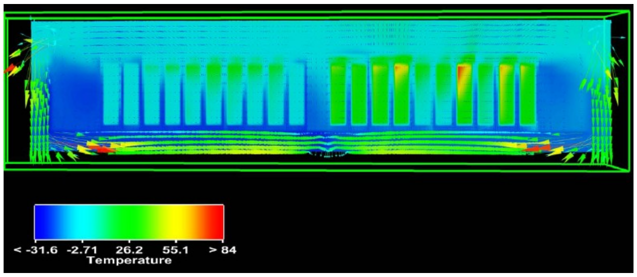

Fig (14): Temp Distribution at X=13.4' without Spot-cool

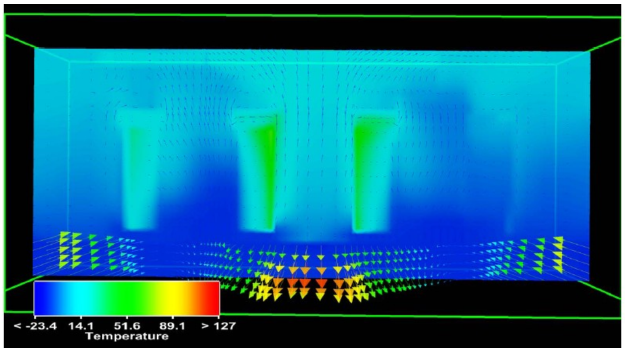

Fig (15): Temperature Distribution at Z=14ft with Spot-cool

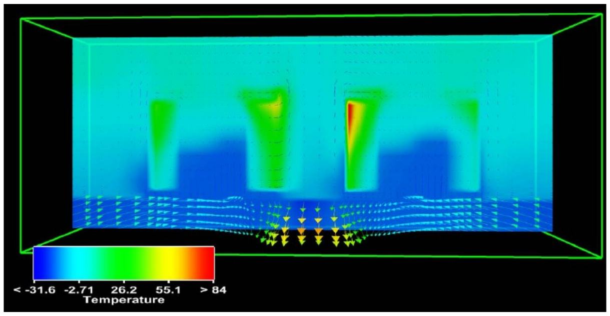

Fig (16): Temperature Distribution at Z=14ft without Spot-cool

In order to find the optimum condition of the spot cooling heat exchanger we set up temperature monitor points at highest height of the server racks. (Figures 17-19)

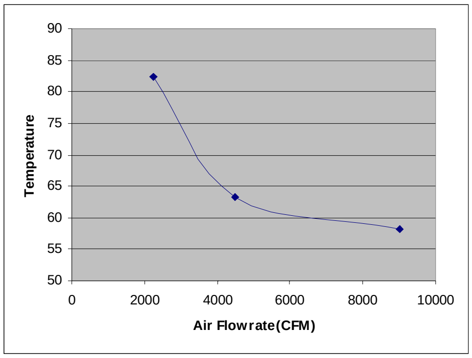

Fig (17): Effect of air flow rate on a typical rack temperature

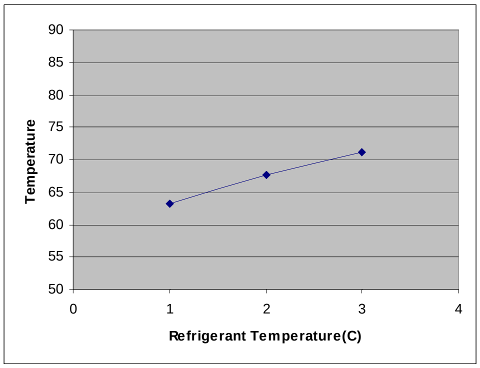

Fig (18): Effect of refrigerant temp. on typical rack temperature

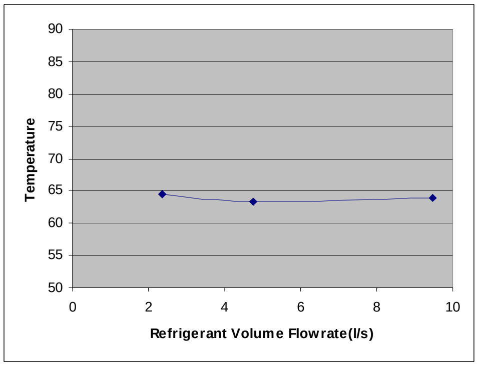

Fig (19): Effect of refrigerant flow rate on typical rack temperature

From Figure 17 it's apparent that air flow rate has a strong impact on the spot the spot cooling and monitoring air flow can significantly help to overcome spot points. Refrigerant temperature and volume flow rate however do not have a strong impact on spot cooling.

The resulting air temperature increase at any point in the server is inversely proportional to how fast the air is moving through the server. If the speed is cut in half, the increase in the air temperature doubles at any point within the server. For instance, if the air is heated up 1 degree as it passes the first component and is 5 degrees higher as it passes the last, it should heat up 2 degrees past the first and 10 degrees past the last component if the flow rate were halved. So, on a relative basis, the increase in the air temperature around the rear components is larger than around the front components for a server with a decreased flow rate.

## CONCLUSION

This paper presents details of components and few practical open and closed-loop air, liquid and refrigeration cooling schemes of electronic components and computer enclosures in data centers. Detailed description of each cooling scheme is provided and advantages and disadvantages of closed loop cooling schemes to open loops are discussed. To present analytical modeling techniques, liquid and refrigeration spot cooling of a high heat density data center is presented. A direct expansion refrigeration evaporator spot cooler with multiple refrigerant phase quality regions is analytically modeled. A tube-by-tube modeling of a secondary loop single phase fan coil heat exchanger is presented using an effectiveness-number of transfer units method. The results of the spot-cooler heat exchanger analysis are then incorporated in a commercial CFD model for a high heat density data center thermal design and analysis. The analysis on effects of such parameters as the air volume flow rate through the spot-cooler, refrigerant mean temperature, and the refrigerant flow rate on the temperature distribution of a rack in the data center is presented.

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