Existing Air-Cooled System

Lawrencium is Berkeley Lab’s institutional computational resource. LR5 is the latest consisting of 144 Broadwell Dell C6320 nodes. LR4 has 108 Haswell nodes. They are cooled by an existing cooling tower, chiller and computer room air handler system. The PUE is 1.55. The total average power is 47KW with a CPU load of 41-44%. The CPU power per node is 50.4 watts and the server power per node is 161 watts. See http://scs.lbl.gov/Systems

Chilldyne Conversion

Chilldyne’s direct-to-chip Cool-Flo® system is optimized for data centers and offers all the benefits of liquid cooling plus no leaks and extra air cooling through the fins on the cold plate. The system utilizes hybrid air-and-liquid cooled heat sinks and negative pressure to deliver a zero-downtime, leak-proof, low cost solution. The conversion is simple, because the connections from our CDU are under negative pressure so IT-techs can hook-up the liquid cooled racks instead of plumbers.

Chilldyne Converted Dell C6320 Node

Expected Performance with Chilldyne Conversion

- Power Savings of 30% from air to liquid
- PUE Reduced from 1.55 to 1.17
- CPU power reduction of 6% (3.4 watts) due to lower leakage current
- Fan power reduction of 75% (8.6 watts)
- HVAC power reduction of 76% (65.3 watt)
- The liquid cooling system requires 2 watts of power per server including cooling tower

The liquid cooled server power is 149 watts instead of 161 watts and 23 watts of heat is removed from the server internal air by the fins on the cold plate in addition to the CPU heat removal.

*Chilldyne Liquid cooling removes 77% of the server heat with our cold plate heat sink.*

Expected Power Savings

The total power per server is 249.6 watts including air cooling, and 174.9 watts liquid cooled, a 30% savings and the PUE is 1.17 instead of 1.55, a reduction of 25%. For this system, the annual savings is 638 KWHR per server or $21K per year for the system at $.11 per KWHR, the California industrial average.
Childdyne liquid cooling system power savings analysis for LBNL data center using Xeon processors
Steve Harrington 5-4-2018

Model Inputs

Server Room Air temperature
\[ T_a := 31 \cdot \text{C} \quad F(T_a) = 87.8 \] assumed warm for liquid cooled system

Outdoor Wet Bulb Temperature
\[ T_{wb} := 17 \cdot \text{C} \quad F(T_{wb}) = 62.6 \] Mean wet bulb temp, Berkeley CA

Cooling tower water temperature:
\[ T_w := T_{wb} + 5 \cdot \text{C} \] Typical cooling tower approach

Processor power reduction with temperature
\[ P_{vsT_cpu} := 0.09 \% / \text{C} \] Based on LRZ data for E5-2697 v3

Processor Power/load from LBNL
\[ P_{cpu} := 120 \text{watt} \quad \text{E5-2670 v3} \]

number of CPUs per server
\[ N_{cpu} := 2 \]

Total CPU power
\[ P_{cpu} N_{cpu} = 100.8 \text{watt} \]

Server Power, air cooled from LBNL
\[ P_{server_air} := 161 \text{watt} \]

Percent of server power to CPUS
\[ \frac{P_{cpu} N_{cpu}}{P_{server_air}} = 63 \% \]

Water in/out Temperature Difference across processor
\[ \Delta T := 6 \cdot \text{C} \]

Estimated Flow per CPU based on target DeltaT
\[ Q_{CPU} := \frac{P_{cpu}}{\rho \cdot C_p \cdot \Delta T} \quad Q_{CPU} = 120.69 \frac{\text{cm}^3}{\text{min}} \]

Thermal resistance
\[ \theta_{HS_L} := \left[ 2 \times 10^{-7} \left( \frac{Q_{CPU}}{\text{cm}^3/\text{min}} \right)^2 + 3 \times 10^{-4} \left( Q_{CPU} \right) + 0.05 \right] \frac{\text{C}}{\text{watt}} \]

Note: Curve from 1U heat sink test.xls
\[ \theta_{HS_L} = 0.09 \frac{\text{C}}{\text{watt}} \]
Chilldyne
Matches data from LBNL

PUE 1.55 = PUE 1

FractionServer = 64.5 %

FractionServer = 1 - FractionOther - FractionHVAC - FractionUPS

FractionHVAC = 34%
FractionUPS = 0%
FractionOther = 1.5%  Efficient lighting

PUE := \frac{1}{\text{FractionServer}}

PUE = 1.55

Server Fan Power air cooled

P_{fan} := 11.5\text{-watt}

Server Fan Power savings liquid cooled

Savings_{fan} := P_{fan} 75\% \quad \text{Savings}_{fan} = 8.63\text{ watt}

Server Fan Power liquid cooled

P_{fan} - \text{Savings}_{fan} = 2.88\text{ watt}

Baseline Data Center Power Breakdown

\Delta P := 10\text{-in}_Hg \cdot \frac{Q_{CPU}^2}{\left(\frac{350\text{ cm}}{\text{min}}\right)^2} + 10\text{-in}_Hg \quad \Delta P = 11.19\text{ in}_Hg

\theta_{\text{C-HS}} := 0.08\frac{\text{C}}{\text{watt}} \quad \text{Includes thermal paste}

\theta_{\text{HS-A}} := 0.3\frac{\text{C}}{\text{watt}} \quad \text{at low fan speed}

System pressure drop

\theta_{\text{C-HS}} := 0.08\frac{\text{C}}{\text{watt}} \quad \text{Includes thermal paste}

\theta_{\text{HS-A}} := 0.3\frac{\text{C}}{\text{watt}} \quad \text{at low fan speed}

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P_{fan} - \text{Savings}_{fan} = 2.88\text{ watt}

Baseline Data Center Power Breakdown

FractionHVAC := 34\% \quad \text{chiller system with some containment}

FractionUPS := 0\% \quad \text{no ups}

FractionOther := 1.5\% \quad \text{Efficient lighting}

FractionServer := 1 - FractionOther - FractionHVAC - FractionUPS

FractionServer = 64.5\%

PUE := \frac{1}{\text{FractionServer}}

PUE = 1.55 \quad \text{Matches data from LBNL}
Analysis: Server level

Electrical Analog of thermal system:

Cool - Flo System
Hybrid Cold Plate Heat Sink

Standard Air Cooled
Heat Sink

Electric Analog of Thermal Circuit

\[ T_a - P_a \cdot \theta_{HS_A} = T_w + \left( P_a + P_{cpu} \right) \theta_{HS_L} \]

Solve for Power from air to heat sink.

\[ P_a := \frac{-\left(T_a + T_w + P_{cpu} \cdot \theta_{HS_L}\right)}{\left(\theta_{HS_A} + \theta_{HS_L}\right)} \]

Heat sink Temperature

\[ T_{hs} := T_a - P_a \cdot \theta_{HS_A} \]

Core Temperature

\[ T_c := T_{hs} + P_{cpu} \cdot \theta_{C_HS} \]

Air Cooled Core Temp

\[ T_{c\_air} := T_a + P_{cpu} \left( \theta_{HS_A} + \theta_{C_HS}\right) \]

Heat transfer to water

\[ P_w := P_a + P_{cpu} \]

\( P_a = 11.59 \text{ watt} \)

\( P_a \cdot N_{cpu} = 23.17 \text{ watt} \)

\( T_{hs} = 27.52 \text{ C} \)

\( T_c = 31.56 \text{ C} \)

\( T_{c\_air} = 50.15 \text{ C} \)

\( P_w = 61.99 \text{ watt} \)
Chilldyne

Percentage of heat to water (not more than 100%)

\[ \text{Fraction}_{\text{heat liquid}} = \min(\text{Fraction}_{\text{heat liquid}}, 1) \]

\[ \text{Fraction}_{\text{heat liquid}} = 77\% \]

CPU liquid cooled power savings due to lower core temp

\[ \text{Savings}_{\text{cpu}} := (T_{c \text{ air}} - T_{c}) \cdot P_{\text{vsTcpu}} \cdot P_{\text{cpu}} \cdot N_{\text{cpu}} \]

\[ \text{Savings}_{\text{cpu}} = 1.69 \text{ watt} \]

Liquid cooled Server Power

\[ P_{\text{server liq}} := P_{\text{server air}} - 2 \cdot \text{Savings}_{\text{cpu}} - \text{Savings}_{\text{fan}} \]

\[ P_{\text{server liq}} = 149 \text{ watt} \]

Percentage power savings, server level

\[ \frac{P_{\text{server air}} - P_{\text{server liq}}}{P_{\text{server air}}} = 7\% \]

**Analysis: Data Center level**

Total data center power per air cooled server,

\[ \text{Power}_{\text{Total air}} := \frac{P_{\text{server air}} \cdot N_{\text{cpu}}}{\text{Fraction}_{\text{Server}}} \]

\[ \text{Power}_{\text{Total air}} = 249.6 \text{ watt} \]

HVAC power,

\[ P_{\text{HVAC air}} := \text{Fraction}_{\text{HVAC}} \cdot \text{Power}_{\text{Total air}} \]

\[ P_{\text{HVAC air}} = 84.9 \text{ watt} \]

Total cooling load:

\[ \text{Heat}_{\text{Load}} := \text{Power}_{\text{Total air}} - P_{\text{HVAC air}} \]

\[ \text{Heat}_{\text{Load}} = 0.05 \text{ ton} \]

**Standard units**

\[ \text{EER} := \frac{\text{Heat}_{\text{Load}}}{P_{\text{HVAC air}}} \]

\[ \text{EER} = 1.94 \]

\[ \text{EER} = 6.62 \frac{\text{BTU}}{\text{hr}} \cdot \frac{1}{\text{watt}} \]

Percent of server heat captured by fins on cold plate

\[ \frac{P_{\text{server air}} \cdot N_{\text{cpu}}}{P_{\text{server liq}}} = 16\% \]
Fan and pump for cooling tower (based on typical cooling tower efficiency)

\[ P_{\text{cool}} := P_{W} \cdot N_{\text{cpu}} \cdot 1.5 \% \quad \Rightarrow \quad P_{\text{cool}} = 1.86 \text{ watt} \]

Power for cooling tower plus Pump for processor cooling assuming 25% efficient CDU pump

Flow per server

\[ Q_{\text{CPU} \cdot N_{\text{cpu}}} = \frac{0.24 \text{ liter}}{\text{min}} \]

Revised Water flow and power required for cooling

Flow Rate

\[ Q := \frac{P_{\text{server liq}} \cdot \text{Fraction}_{\text{heat liquid}}}{\rho \cdot C_{p} \cdot \Delta T} \quad \Rightarrow \quad Q = \frac{0.27 \text{ liter}}{\text{min}} \]

Pump power for CDU

\[ P_{\text{pump}} := \frac{Q \cdot \Delta P}{\eta} \quad \Rightarrow \quad P_{\text{pump}} = 0.69 \text{ watt} \]

Total liquid cooling power including cooling tower

\[ P_{\text{liq cooling}} := \frac{Q \cdot \Delta P}{\eta} + P_{\text{cool}} \quad \Rightarrow \quad P_{\text{liq cooling}} = 2.55 \text{ watt} \]

UPS power

\[ P_{\text{UPS air}} := P_{\text{server air}} \cdot \frac{\text{Fraction}_{\text{UPS}}}{\text{Fraction}_{\text{Server}}} \quad \Rightarrow \quad P_{\text{UPS air}} = 0 \text{ watt} \]

Power for lights, etc.

\[ P_{\text{Other}} := \text{Fraction}_{\text{Other}} \cdot \frac{P_{\text{server air}}}{\text{Fraction}_{\text{Server}}} \quad \Rightarrow \quad P_{\text{Other}} = 3.74 \text{ watt} \]

Check

\[ P_{\text{server air}} + P_{\text{HVAC air}} + P_{\text{UPS air}} + P_{\text{Other}} = 249.6 \text{ watt} \quad \text{Matches } P_{\text{total}} \text{ above} \]

With liquid cooling

UPS power, considering reduced server power

\[ P_{\text{UPS liq}} := P_{\text{server liq}} \cdot \frac{\text{Fraction}_{\text{UPS}}}{\text{Fraction}_{\text{Server}}} \quad \Rightarrow \quad P_{\text{UPS liq}} = 0 \text{ watt} \]

HVAC power, minus power bypassing HVAC

\[ P_{\text{HVAC liq}} := \left( \frac{P_{\text{server liq}} + P_{\text{UPS liq}} + P_{\text{Other}} - \text{Fraction}_{\text{heat liquid}} \cdot P_{\text{server liq}}}{\text{EER}} \right) \]
HVAC Power reduction

\[ 1 - \frac{P_{HVAC\_liq}}{P_{HVAC\_air}} = 76.93\% \]

\[ P_{HVAC\_air} - P_{HVAC\_liq} = 65.29\text{ watt} \]

Total power for liquid cooled system

\[ Power_{Total\_liquid} := P_{server\_liq} + P_{HVAC\_liq} + P_{UPS\_liq} + P_{Other} + P_{liq\_cooling} \]

\[ Power_{Total\_liquid} = 174.88\text{ watt} \]

Power savings with liquid

\[ Power_{Total\_air} - Power_{Total\_liquid} = 74.73\text{ watt} \]

\[ 1 - \frac{Power_{Total\_liquid}}{Power_{Total\_air}} = 30\% \]

Savings per year based on $0.11 per kWh

\[ Price := \frac{0.11}{\text{kwhr}} \]

Savings for given system:

\[ (Power_{Total\_air} - Power_{Total\_liquid}) \cdot Price \cdot \text{yr} = 72.06 \]

Savings per server

\[ (Power_{Total\_air} - Power_{Total\_liquid}) \cdot Price \cdot \frac{278\text{ watt}}{P_{server\_air}} = 124 \]

New PUE

\[ \frac{Power_{Total\_liquid}}{P_{server\_liq}} = 1.17 \]

Server power other than CPUs and fans for air and liquid cooled cases

\[ P_{server\_air} - 2 \cdot P_{\text{cpu}} - P_{\text{fan}} = 48.7\text{ watt} \]

\[ P_{server\_liq} - 2 \cdot (P_{\text{cpu}} - Savings_{\text{cpu}}) - (P_{\text{fan}} - Savings_{\text{fan}}) = 48.7\text{ watt} \]

CPU power air and liquid cooled

\[ 2P_{\text{cpu}} = 100.8\text{ watt} \quad 2 \cdot (P_{\text{cpu}} - Savings_{\text{cpu}}) = 97.43\text{ watt} \]
**Liquid and air power breakdown per server:**

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Air</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{cpu} - \text{Savings}_{cpu} = 48.71$ watt</td>
<td>$P_{cpu} = 50.4$ watt</td>
<td>$\frac{\text{Savings}<em>{cpu}}{P</em>{cpu}} = 3%$</td>
</tr>
<tr>
<td>$P_{server_liq} = 149$ watt</td>
<td>$P_{server_air} = 161$ watt</td>
<td>$\frac{P_{server_air} - P_{server_liq}}{P_{server_air}} = 7%$</td>
</tr>
<tr>
<td>$P_{HVAC_liq} = 19.6$ watt</td>
<td>$P_{HVAC_air} = 84.9$ watt</td>
<td>$\frac{P_{HVAC_air} - P_{HVAC_liq}}{P_{HVAC_air}} = 77%$</td>
</tr>
<tr>
<td>$P_{UPS_liq} = 0$ watt</td>
<td>$P_{UPS_air} = 0$ watt</td>
<td>$P_{Other} = 3.7$ watt</td>
</tr>
<tr>
<td>$P_{Other} = 3.7$ watt</td>
<td>$P_{Other} = 3.7$ watt</td>
<td>$P_{\text{liq_cooling}} = 2.55$ watt</td>
</tr>
<tr>
<td>$P_{\text{Total_liquid}} = 174.9$ watt</td>
<td>$P_{\text{Total_air}} = 249.6$ watt</td>
<td>$\frac{P_{\text{Total_air}} - P_{\text{Total_liquid}}}{P_{\text{Total_air}}} = 30%$</td>
</tr>
</tbody>
</table>

**Total system power savings**

Number of servers

Servers := 292

Air cooled server power total

$P_{\text{server\_air}} \cdot \text{Servers} = 47.01$ kw

Total power savings per year

$\left(P_{\text{Total\_air}} - P_{\text{Total\_liquid}}\right) \cdot \text{yr} = 655.1$ kwhr

$\left(P_{\text{Total\_air}} - P_{\text{Total\_liquid}}\right) \cdot \text{yr} \cdot \text{Servers} = 1.91 \times 10^5$ kwhr

Money saved per year, assuming average California industrial electricity rate.

$\left(P_{\text{Total\_air}} - P_{\text{Total\_liquid}}\right) \cdot \text{Servers} \cdot \text{yr} \cdot \frac{11}{\text{kwhr}} = 21041.68$

"Analysis of the efficiency characteristics of the first High-Temperature Direct Liquid Cooled Petascale supercomputer and its cooling infrastructure" http://dx.doi.org/10.1016/j.jpdc.2017.04.005
Constants

\[ \text{kw} = 1000\text{-watt} \]
\[ \text{ton} = 12000\frac{\text{BTU}}{\text{hr}} \]
\[ \text{kwhr} = 1000\text{-watt-hr} \]

Pump efficiency, water density, heat capacity of water

\[ \eta = 25\% \]
\[ \rho = 999\frac{\text{kg}}{\text{m}^3} \]
\[ C_p = 4.18\frac{\text{joule}}{\text{gm-K}} \]

\[ F(C) = \left(32 + 1.8\frac{C}{K}\right) \]

\[ C = K \]
\[ \text{KW} = 1000\text{-watt} \]