An Innovative, Self-Contained, High Efficiency Cooler for Large Electrical Machines

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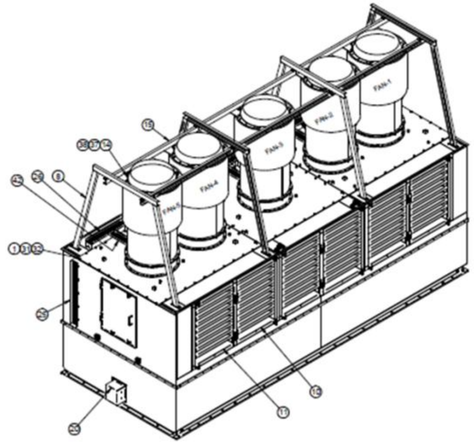
Avantair Innovation

- Avantair is Brand Name of Sterling Thermal Technology's CACA Cooler Using Heatpipe Technology (2-Phase Heat Transfer)
- Plug & Play Designed to Rapidly Remove Heat Away From Source.
- Ideal for Compact Environments.
- Able to Remove Heat With Differences as Little as 8 °C.

Avantair Statistics

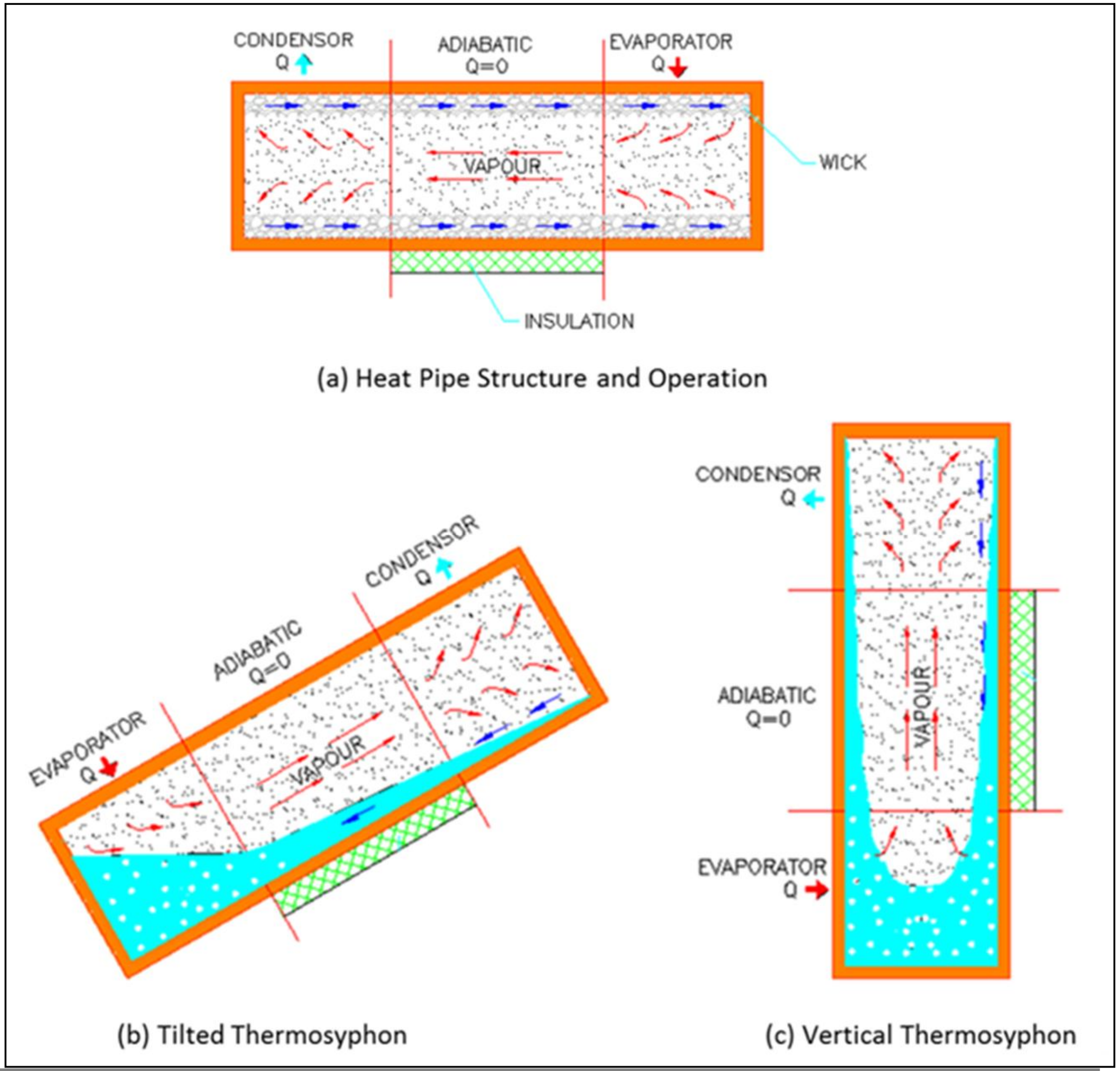


Coolers in Service	164
Smallest Power	25 KW
Largest Power	2300 KW
Total Dissipation Power	110 MW
Coils per Cooler	2 - 6

Principle of Heat Pipe Operation

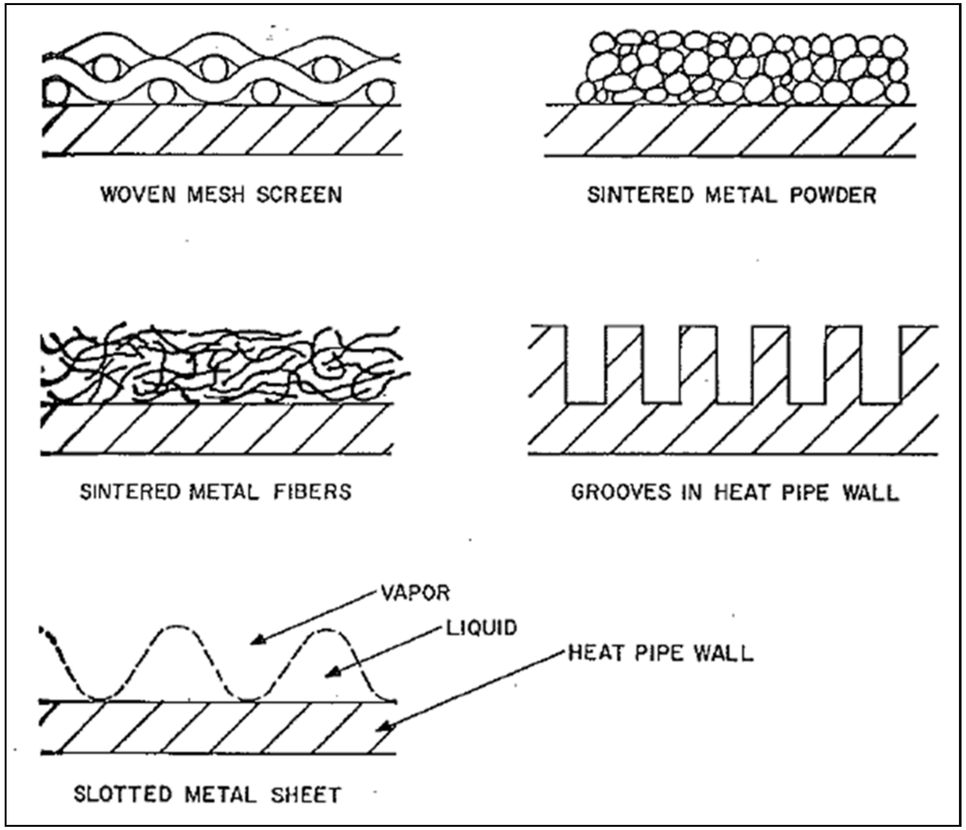
Components:

- Sealed Pipe
- Wick (~~Thermosyphon~~)
- Refrigerant



Heat Pipe Capillary Wick Structures

Not Required for Thermosyphon



Source: Design and Technology of Heat Pipes for Cooling and Heat Exchange; by Calvin C. Silverstein; Hemisphere Pub. Co. 1992. ISBN 0-89116-859-1

Working Fluids Operating Temperature Range

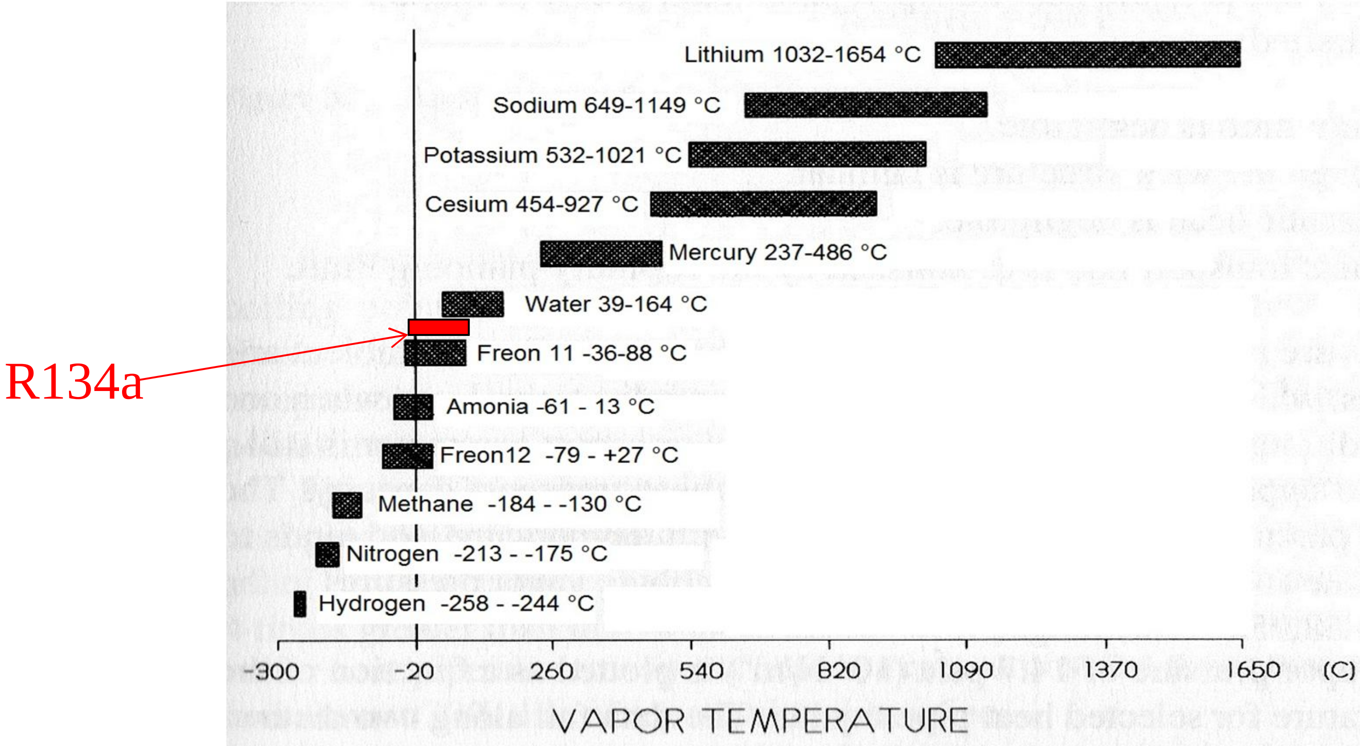


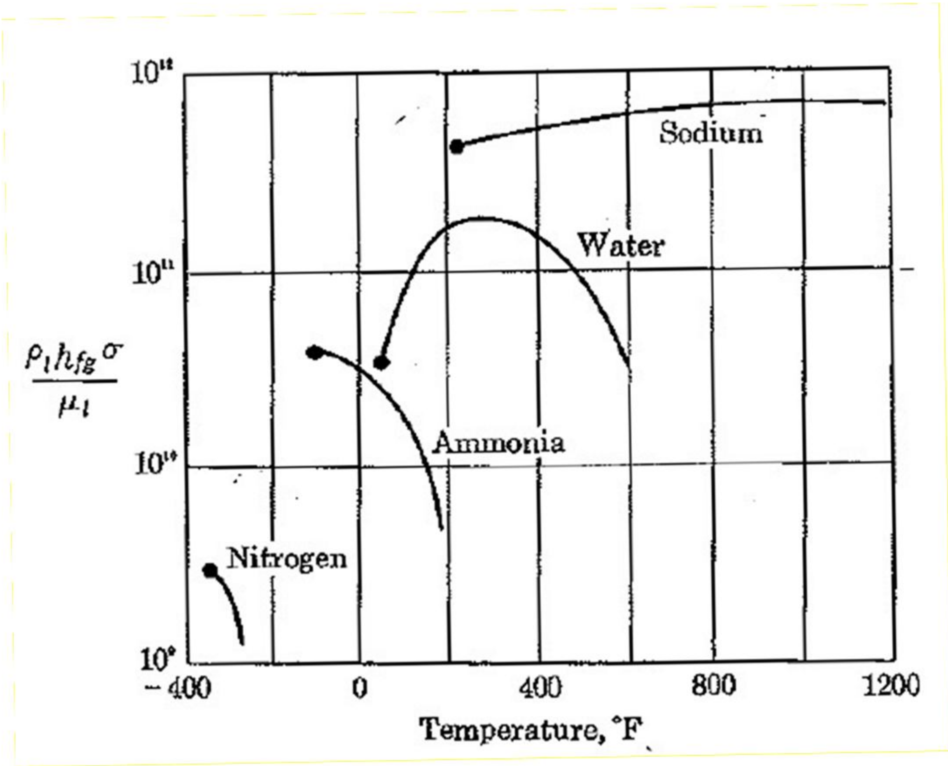
Figure 3.2. Operating temperature ranges of various heat pipe fluids.

Source: Design and Technology of Heat Pipes for Cooling and Heat Exchange; by Calvin C. Silverstein Hemisphere Pub. Co. 1992. ISBN 0-89116-859-1

Heat Pipe Liquid Transport Factor (Merit Number)

Direct Function of Thermophysical Properties of Liquid

$$M = \frac{\rho_l . h_{fg} . \sigma_l}{\mu_l}$$



M : Liquid Transport Factor. (W/m^2)

ρ_l : Liquid Density. (Kg/m^3)

h_{fg} : Latent Heat of Vaporisation. (kJ/kg)

σ_l : Surface Tension at I/F. (N/m)

μ_l : Liquid Viscosity. (N-S/m^2)

Source: Heat Transfer; 4th Ed. by Alan J Chapman; Macmillan Pub. Co. 1984. ISBN 0-02-946080-8

Thermosyphon Liquid Transport Factor (Merit Number)

Direct Function of Thermophysical Properties of Liquid

$$M' = \left(\frac{h_{fg} \cdot k_l^3 \cdot \rho_l^2}{\mu_l}\right)^{1/4}$$

Table 2.12 Maximum Thermosyphon Merit Number for Selected Fluids		
Fluid	**Temperature (°C)**	**M′ max($kg/K^{3/4}\ s^{5/2}$)**
Water	180	7542
Ammonia	−40	4790
Methanol	145	1948
Acetone	0	1460
Toluene	50	1055

M' : Liquid Transport Factor. ($kg/K^{3/4}.S^{5/2}$)
h_{fg} : Latent Heat of Vaporisation. (kJ/Kg)
k_l : Thermal Conductivity of Liquid. (W/m-K)
ρ_l : Liquid Density. (Kg/m^3)
μ_l : Liquid Viscosity. ($N\text{-}S/m^2$)

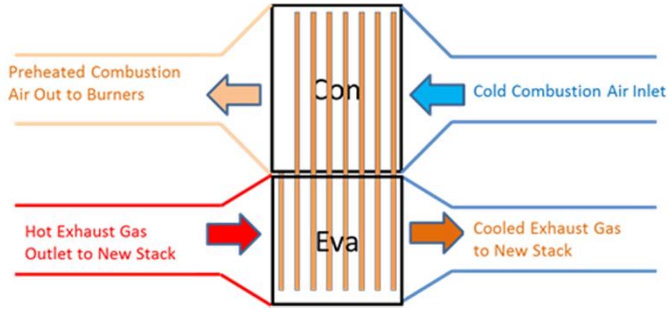
Source: Heat Pipes: Theory, Design and Applications; By David Reay, Ryan McGlen, Peter Kew; 6th Ed. 2014 Butterworth Heinemann pub; ISBN 978-0-08-098266-3

Heat Pipe & Thermosyphon Unique Characteristics

- High Heat Transport Capability Due to Use of Latent Heat.
- Ability to Transport Large Amounts of Heat with Small ΔT Over Relatively Long Distances.
- No Moving Part Leading to Longer Life & Lower Maintenance.
- Independent Cooling Circuits Prevents Cooler Total Failure.
- No Energy Required for its Operation (No Pump, No Compressor).
- No Wick in Thermosyphon, Leading to Simpler Structure & Cheaper Tube.
- Heat Transfer In One Direction (Thermal Diodes & Switches).
- **Thermosyphon is an attractive solution where Possible to Position Condenser Higher or Above Evaporator.**

Examples of Terrestrial Applications

1. Process Heat Recovery.



2. Power Generation.
   - Indirect Cooling: Cooling of Enclosures for Mobile Generators.
   - Direct Cooling: Cooling of Large Rotating Machines.

Sterling thermal technology

Cooling of Electrical Machines

Water-Air (CACW)

Low h on Air side.
High h on Water side.
Large Foot Print.
High maintenance.
Possible $\Delta T_{approach}$ = 5 °C.

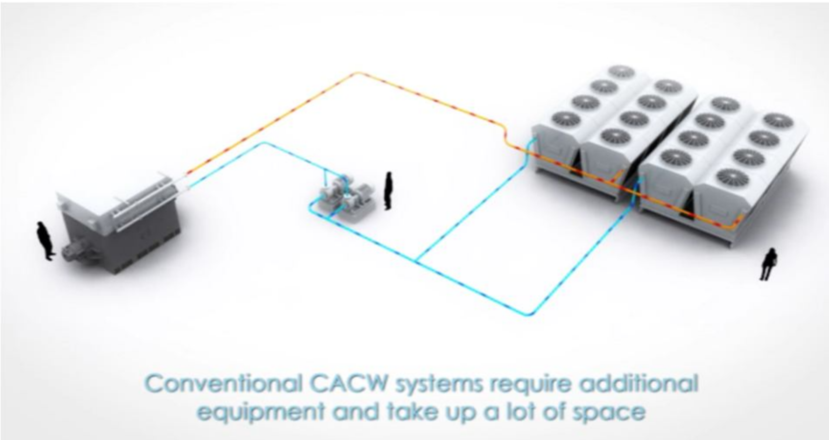
Air-Air (CACA)

Low h on Inside Air & Outside.
Low performance.
Large Size.
High Maintenance.
Economical $\Delta T_{approach}$ = 15-20 °C.
Cheap to Build.

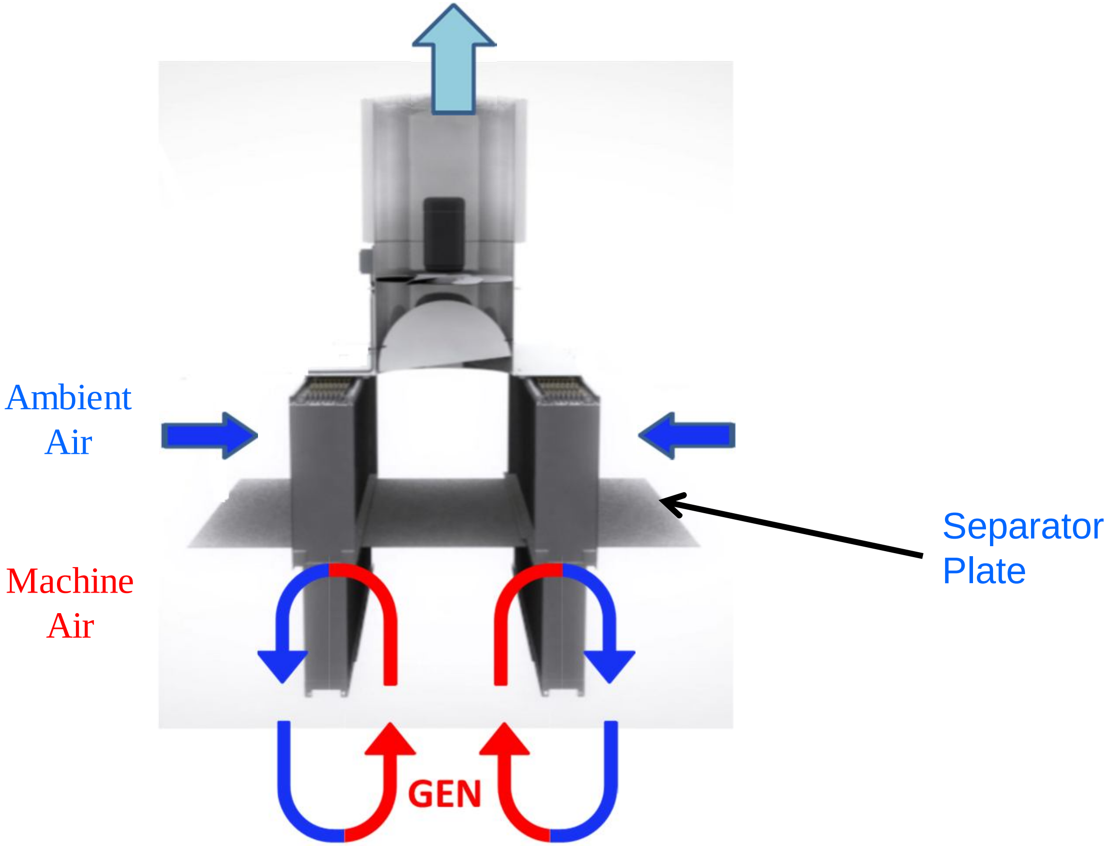
Avantair

Compact & Low Foot Print.
Plug & Play.
Low Maintenance.
Possible Economical $\Delta T_{approach}$ = 8 °C.
Smaller Machine Frame Size.
Cheaper over Life Cycle.

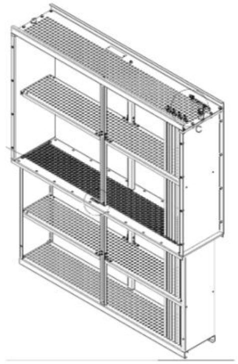
Evolution of Machine Cooling Systems

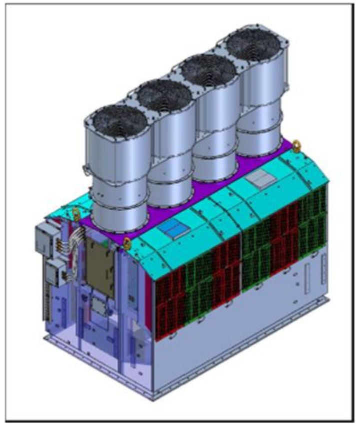


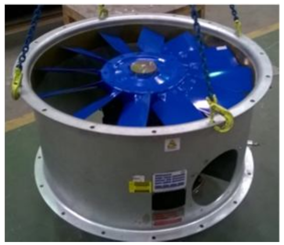
Avantair Heat Exchange Air Flow Circuits

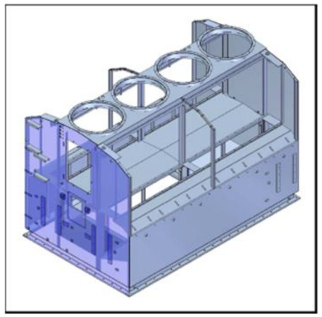


Main Components of Avantair Heat Exchanger









Case Study: Direct Cooling of a Generator

Cooling Requirements for Generator		
Fluid	Ambient Air (Condenser)	Machine Air (Evaporator)
Thermal Duty (kW)	750	750
Max Air Flow Rate (m^3/s)	19.5	19.5
Max Pressure Drop (Pa)	300	750
Inlet Temperature (°C)	41	49 (Re-Cooled)

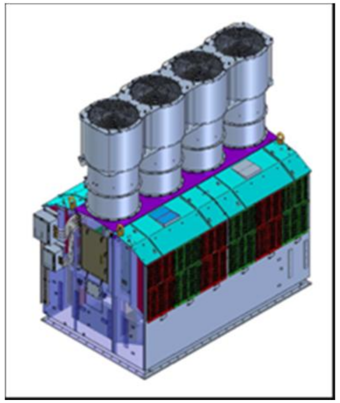
Ambient Conditions	
Environment	Hazardous Marine
Ambient Temperature Range	-10 to +41 °C
Relative Humidity	100%
Installation Site	Oil Platform

Case Study- Cooler Coil Specifications

Coolers & Coils / Cooler	3 & 4
Coil Approx. Dims	2m x 2m x 0.30m
Tube – Fin material	Cu - Cu
Finish	Corrosion Protective Coating
Casing	Galvanized Steel
Construction Method	Expansion of Tubes by Bulleting
Working Fluid	R134a

Avantair Coil After Assembly

Avantair Coil During Test

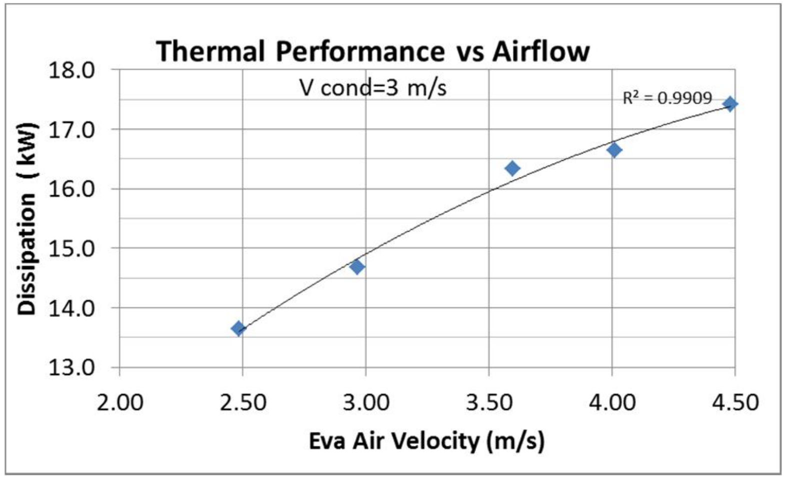


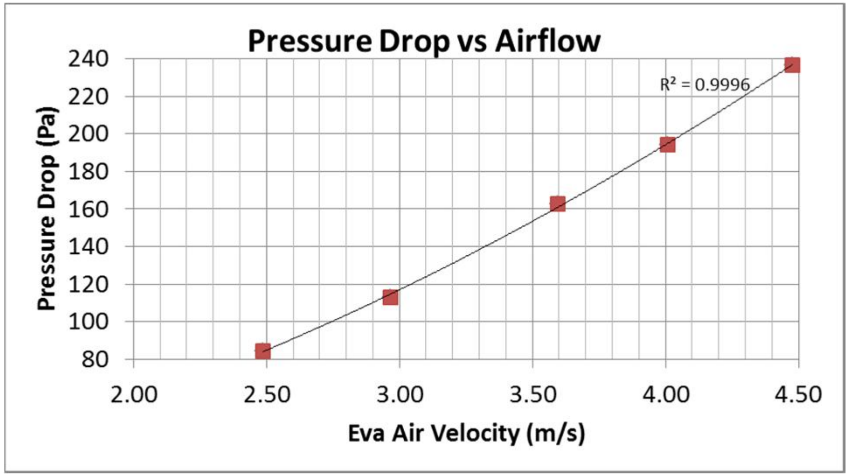
Completed Avantair

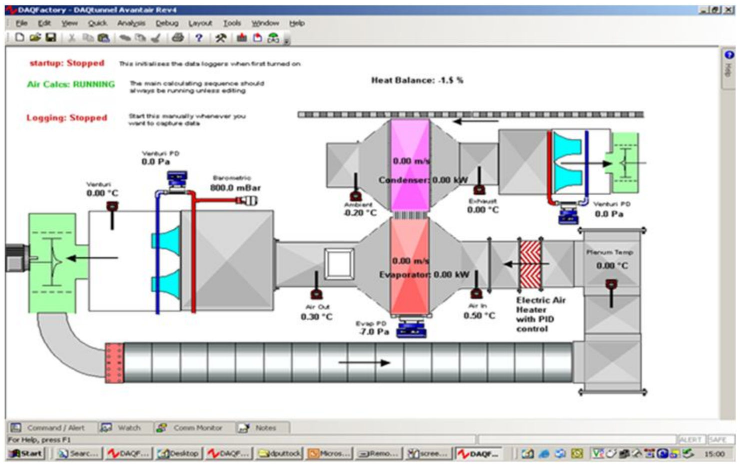
Overall Comparison of Cooling Systems

Cooling System	Cooling Sub-System	Coolant / Air Circulation System		Piping N/W	Power Supply	Relative System Foot Print	Relative Frame Size	Maintenance	Min Approach ΔT °C
		Pumps	Fans						
Water Cooled (CACW)	Fresh Water Closed Circuit	Yes	Yes	Yes	Extensive	Largest	Large	Highest	5
	Sea Water Open Circuit	Yes	No	Yes	Extensive	Large	Large	Highest	5
Air Cooled (CACA)	Air-Air	No	Yes	No	Fans	Large	Large	High?	15 - 20
Avantair Cooler	Passive Refrigeration (Heatpipe)	NO	Yes	No	Fans	Most Compact	Most Compact	Low	8

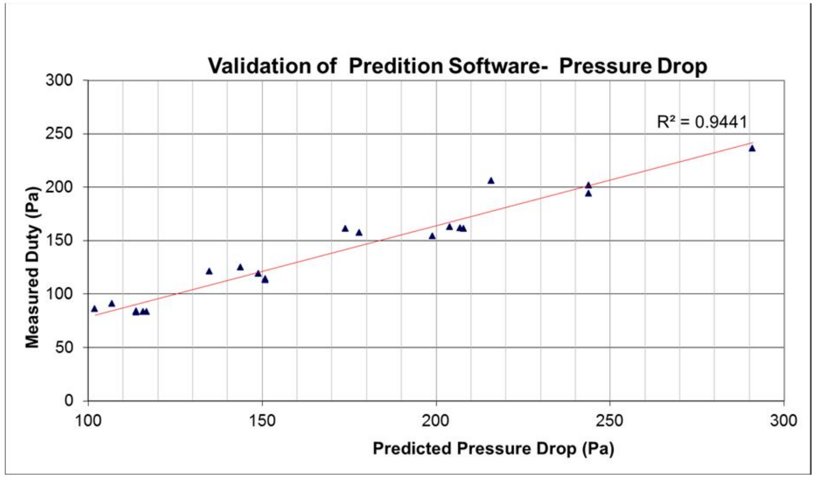
Experimental Results for Thermal Test Block

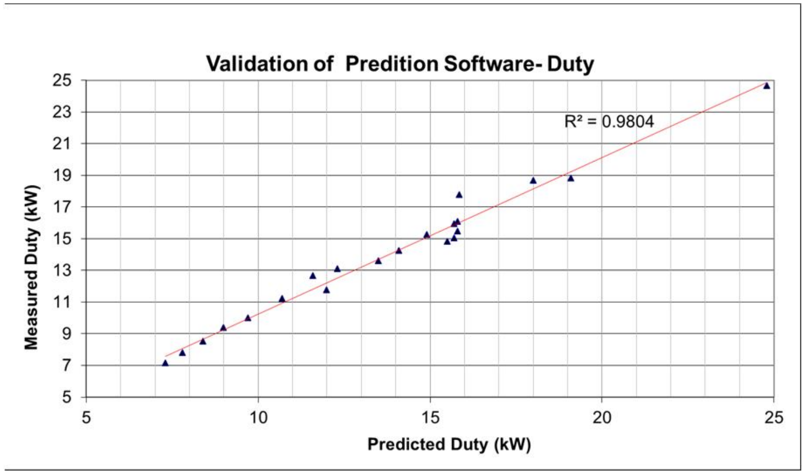


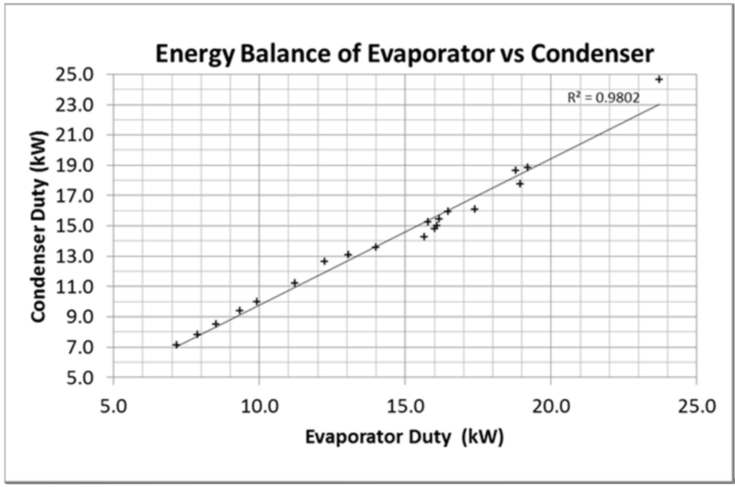


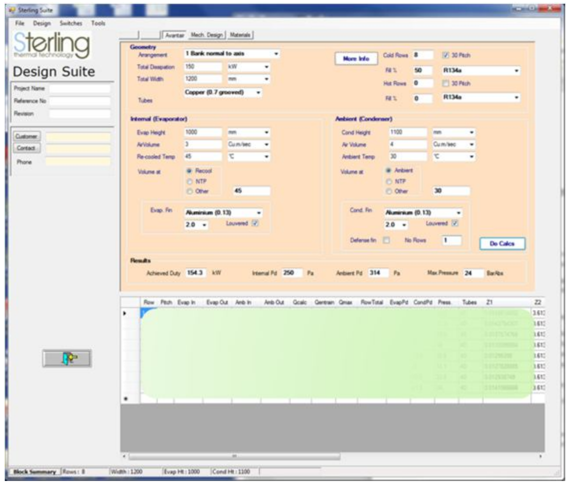


Validation of Performance Prediction Software









Summary & Conclusion

- Technology for Cooling & Heat Recovery Using Latent Heat.
- Suitable for All Ranges of Electrical Machines.
- Low Approach Temperature Leading to Potential Reduction of Generator Frame Size Compared to Conventional CACA Coolers.
- Major Improvement over CACA Coolers.
- Compact & Light. *No Piping N/W, Pumping, Aux Heat Exchangers.*
- Low Cost Over Life Cycle.
- Little or no Maintenance Required.