Test Results of a 1.5MW High Speed Motor-Generator in a Pressurized CO_2 Environment

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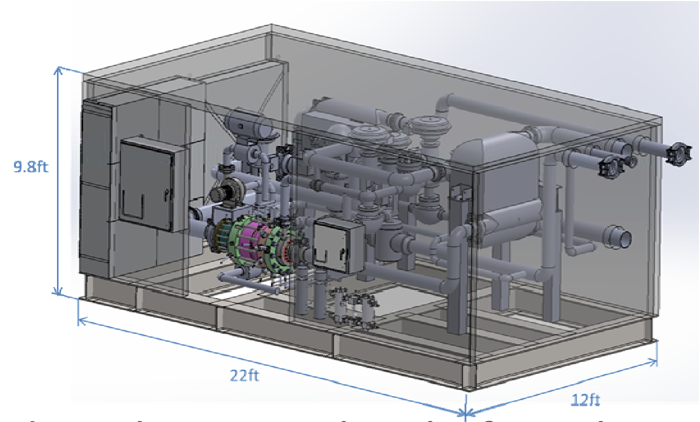
ECHOGEN power systems

Project Overview

- Echogen was commissioned to design and fabricate a 1.3 MW_e waste heat recovery heat engine by GE Marine for ship board applications
  - Highly space constrained environment – sCO2 cycles fit well because of high power density turbomachinery and cycle
  - A leak free system was a requirement due to limited ability to transport and store CO2
  - Standard turbine-gearbox-generator precluded due to turbine shaft seal
  - A high speed permanent magnet alternator encapsulated in the working fluid was proposed to eliminate the shaft seal.



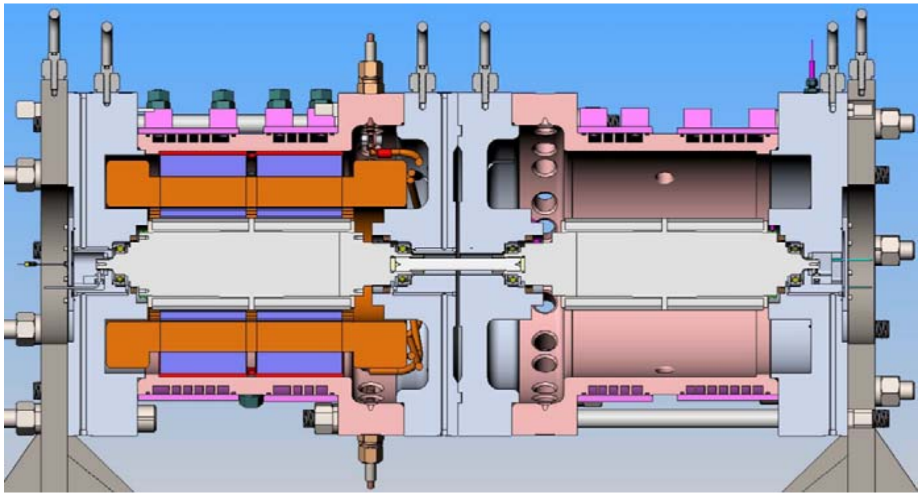
Key Suppliers

- Elektromaschinen und Antriebe (e-a)
  - Designed and fabricated a high speed permanent magnet alternator (HSA)
  - 1.5 MW_e at 25,000 RPM, carbon fiber wrapped rotor

- Abstract Power Electronics
  - Designed and fabricated power electronics
  - Utilizes SiC based FETs for high switching frequency
    - Rated to 1200 V and frequencies up to 20 kHz
    - Very power dense build – 1/3 of the volume of IGBT PE
  - Current controlled machine – reduces risk of circulating currents in HSA, helps with cooling

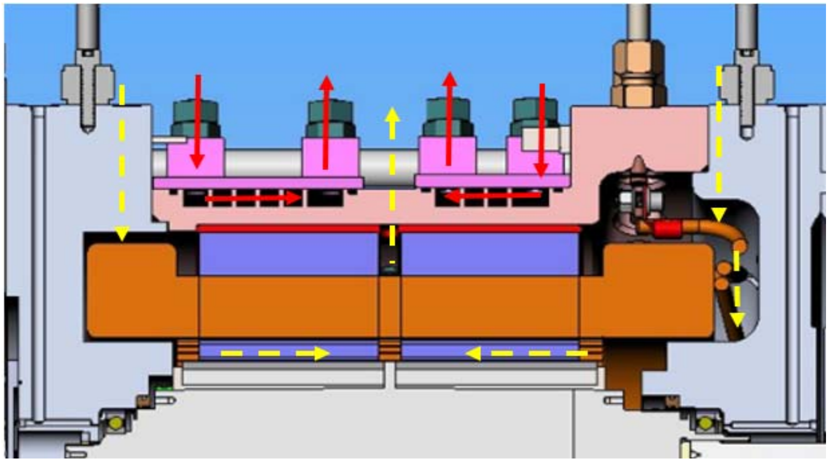
Objectives

- High speed, power output and operation in pressurized environment impose significant cooling challenges for the HSA
- Back-to-back motor/generator test completed to verify heating and loss models and the proposed cooling scheme



- Two machines coupled with custom flexible spline and utilize oil lubricated ball bearings
- Power electronics were reconfigured to convert electric power from the alternator side to a DC bus
- DC bus power converted back to high frequency to power the motor
- The make up power was supplied by the local grid

Flow Path and Heat Sources



- Water cooling path through stator jacket shown in red
- CO_2 cooling path through HSA stator and over rotor shown in yellow
- Alternator chamber being held to 0.7 MPa to reduce windage heating

- HSA loss estimates provided by e-a
  - All losses scale proportionally with speed
  - Copper (stator) losses also scale with power
- Bearing loss estimate provided by supplier
  - Assumed to scale proportionally with speed
- Lamination and copper losses account for 95% of component generated heat load

Heating Source	Load (kW)
Copper (25,000 RPM and 1.5 MWe)	10.00
Rotor (25,000 RPM)	0.65
Lamination (25,000 RPM)	15.00
Magnet (25,000 RPM)	0.55
Ball Bearing (25,000 RPM)	0.10

Windage Heating Estimate – 1D Models

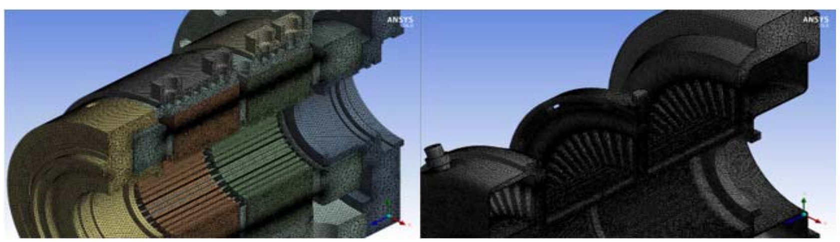
- Hamm Model
  - $Q_{gen} \propto \rho \cdot N^3 \cdot D^5$
- Saari Model
  - $Q_{gen} = Q_{gap} + Q_{disk} + Q_{gas}$
    - $Q_{gap} \propto \rho \cdot N^3 \cdot D^4$
    - $Q_{disk} \propto \rho \cdot N^3 \cdot D^5$
    - $Q_{gas} \propto \rho \cdot N^2$
  - $Q_{gap} = 0.90 \cdot Q_{gen}, Q_{disk} = 0.05 \cdot Q_{gen}, Q_{gas} = 0.05 \cdot Q_{gen}$
- Based on above analysis, and using the Saari windage estimate, a CO2 cooling flow rate of 0.65 kg/s was chosen to keep alternator and rotor temperatures within design limits

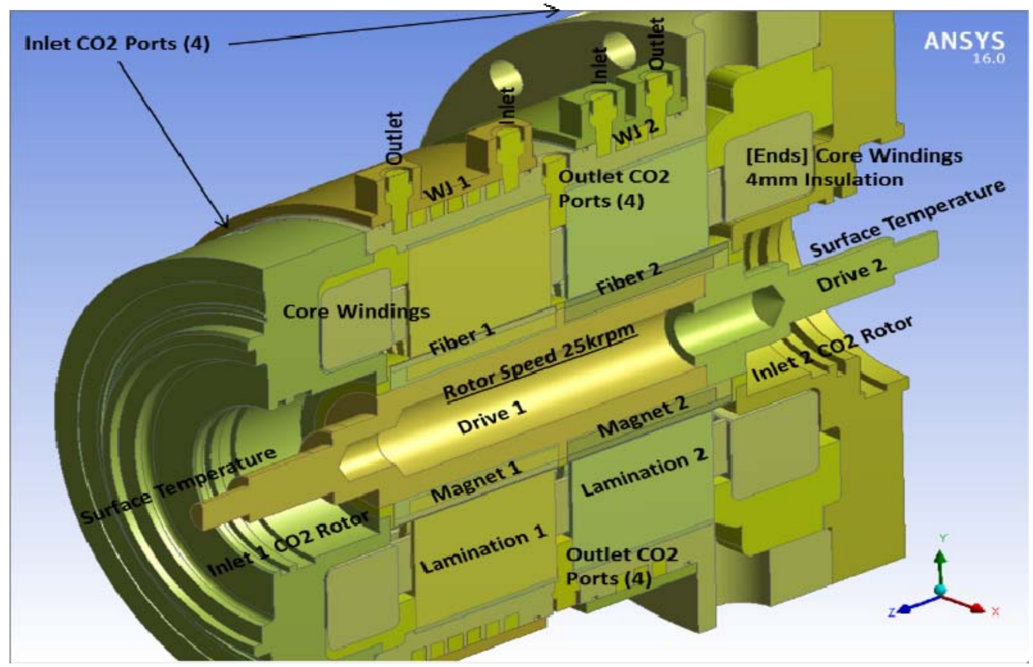
Rotor radius (mm)	88
Stator radius (mm)	90
Rotor length (mm)	381
CO2 density (kg/m^3)	14.78
CO2 viscosity (10^{-6} Pa-s)	18.37
Rotor speed (RPM)	25,000
Hamm windage estimate (kW)	28.3
Saari windage estimate (kW)	41.5

3D – CFD Model

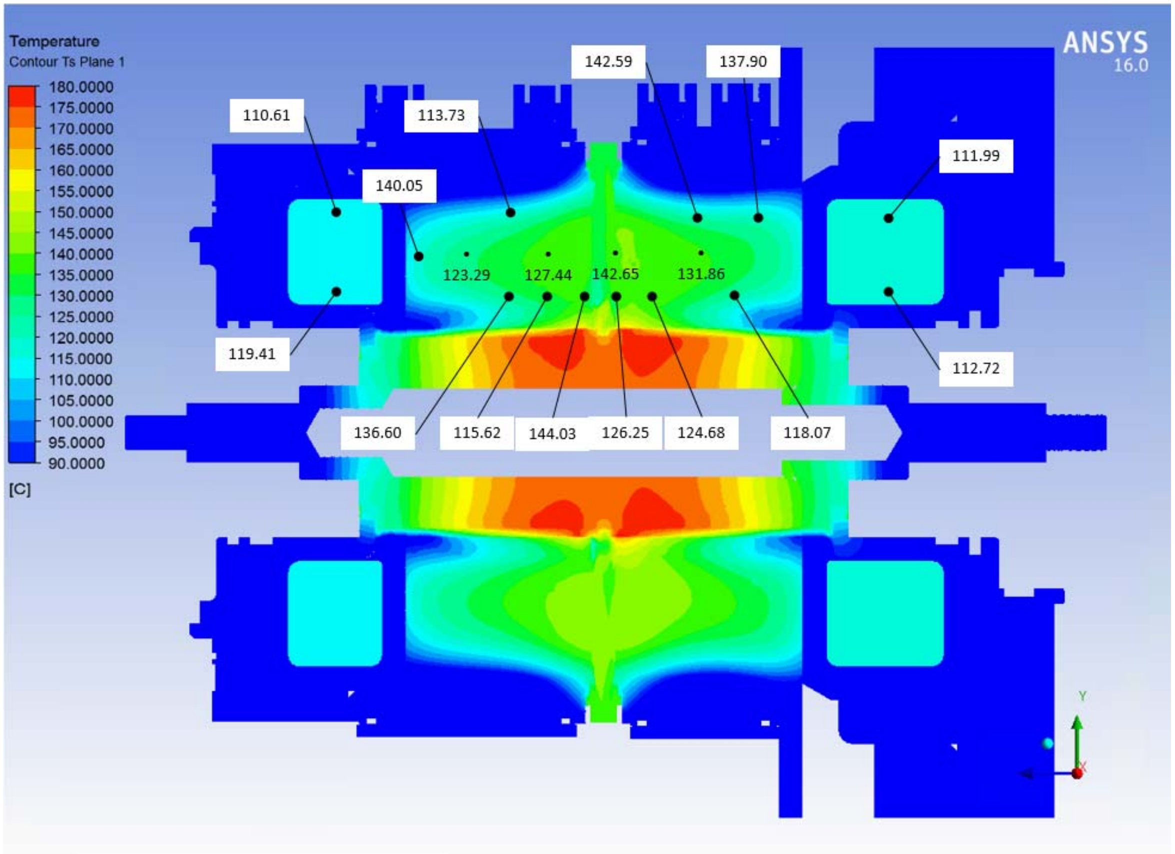
- 3D – CFD simulation completed using ANSYS-CFX 16.0 and REFPROP values for CO2 thermodynamic and transport properties
- Assumed heat loads for the HSA were provided by e-a, bearing heat load not included
- Conjugate heat transfer methods used to define the solid-fluid interactions
- Windage calculated directly by CFD simulation based on assumed rotor surface roughness
- Windage estimate agrees well with the Saari model, Hamm under predicts the CFD results

CO2 Inlet Temperature (°C) / Inlet Pressure (MPa)	50 / .9950
Total CO2 Mass Flow Rate (kg/s)	0.65
Cooling Water Temperature (°C) / Pressure (MPa)	38 / 0.2
Cooling Water Flow Rate (kg/s)	0.95
Windage Loss Calculated (kW)	44.912





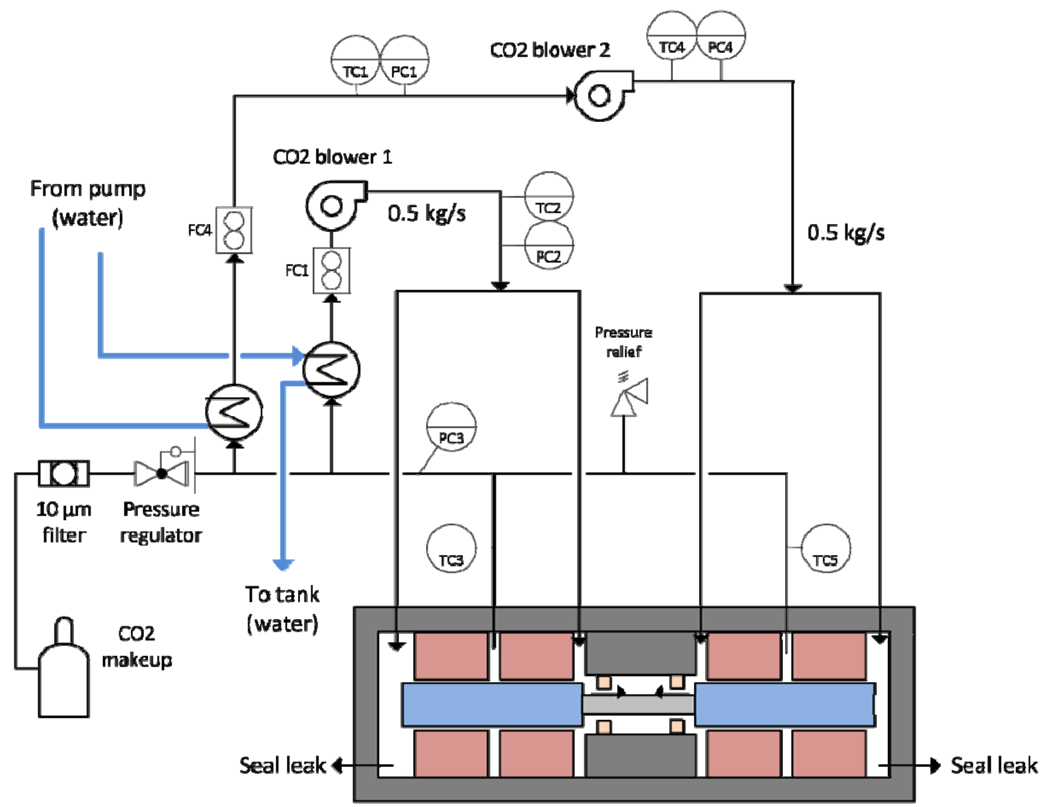
3D – CFD Temperature Profile



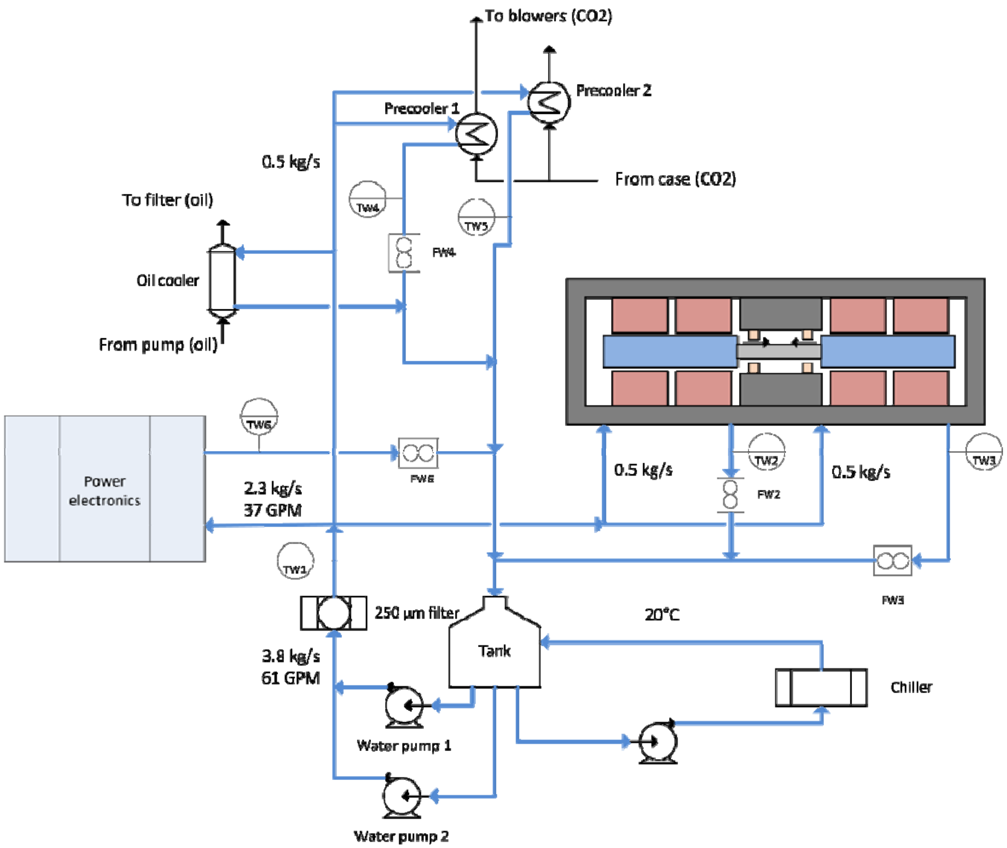
- Resulting CFD temperature field with measured temperature data overlaid
- Measured temperatures were adjusted to compensate for the lower coolant temperature used during testing
- All measured temperatures are projected circumferentially onto the plane shown.
- Relatively good agreement between test data and predicted temperatures (within 10degC in most places)

CO2 Cooling Loop

- Each machine is supplied by semi-independent cooling loop
- CO2 lost through labyrinth seals at each of the machine is replenished from CO2 make up tank, loops communicate here
- Alternator cavity pressure is regulated with a pressure regulating valve located on CO2 supply line
- Pressure transducers, RTDs and coriolous flow meters used for direct measurement of CO2 condition at inlet and outlet of the alternator cavity



Water Cooling Loop

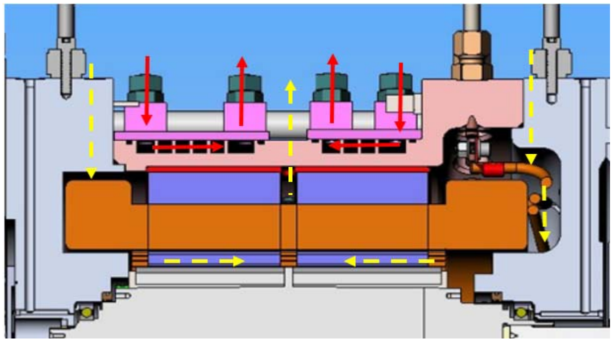


- Loop designed to remove heat directly from the HSA, Power Electronics, CO_2 blowers, lubrication oil, and heated CO_2
- Hot water rejects heat to cooling tower
- Flow, temperature and pressure are measured directly to define water condition

Experimental and Predicted Loss Calculations

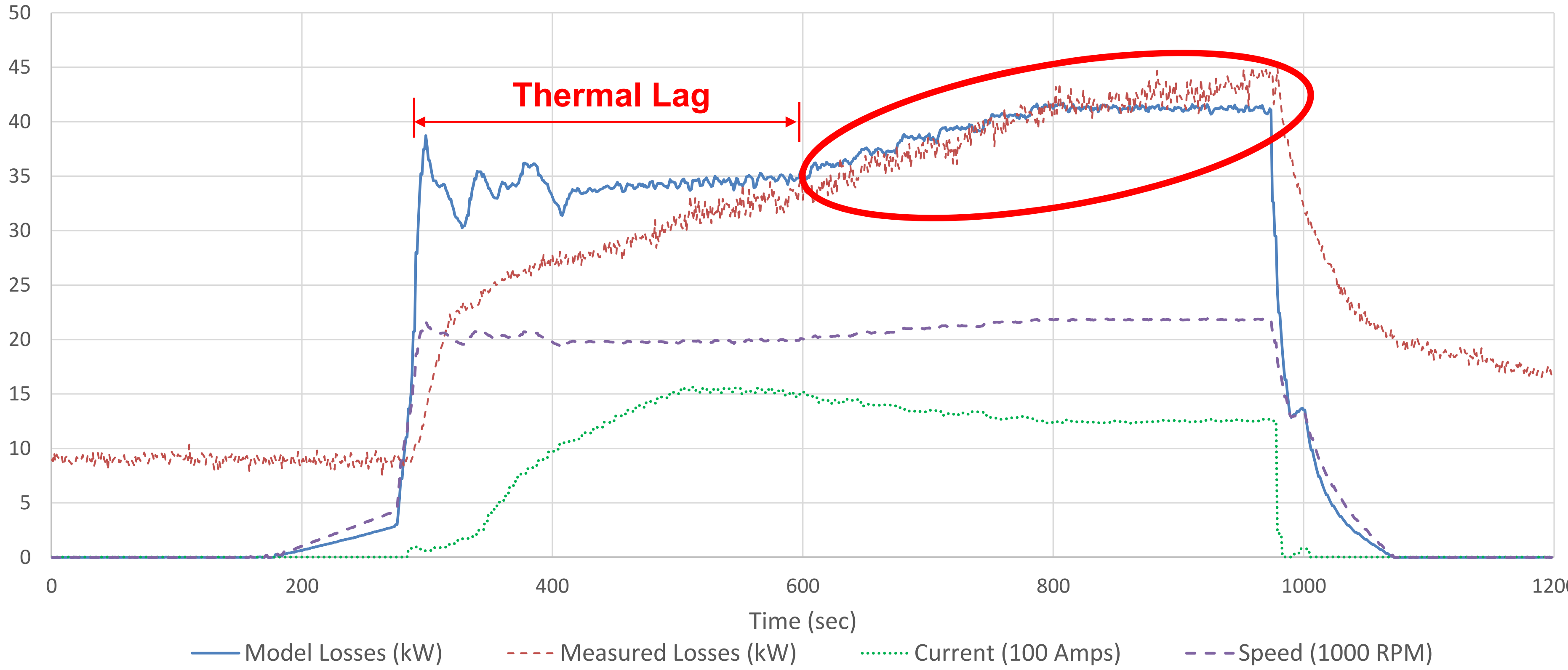
- *CO2 and Water Heat and Mass Balance*
  - $Q_{CO2} = w_{CO_2in} * (h_{CO_2out} - h_{CO_2in}) - w_{leak} * h_{CO_2out}$
  - $Q_{H2O} = w_{H_2O} * (h_{H_2O_{out}} - h_{H_2O_{in}})$
  - $Q_{Tot} = Q_{CO_2} + Q_{H_2O}$
- Scaling Relationships for loss estimates
  - $Q_{Windage} = 41.54 * \left(\frac{N_{act}}{25{,}000\ RPM}\right)^3 * \left(\frac{\rho}{14.78\ kg/m^3}\right) kW$
  - $Q_{Copper} = 10 * \left(\frac{N_{act}}{25{,}000\ RPM}\right) * \left(\frac{P_{HSA}}{1.5\ MW_e}\right) kW$
  - $Q_{Laminations} = 15 * \left(\frac{N_{act}}{25{,}000\ RPM}\right) kW$
  - $Q_{Magnets} = 0.55 * \left(\frac{N_{act}}{25{,}000\ RPM}\right) kW$
  - $Q_{Bearing} = 0.1 * \left(\frac{N_{act}}{25{,}000\ RPM}\right) kW$
  - $Q_{Tot_{pred}} = Q_{Windage} + Q_{Copper} + Q_{Laminations} + Q_{Magnet} + Q_{Bearing}$

- HSA control volume

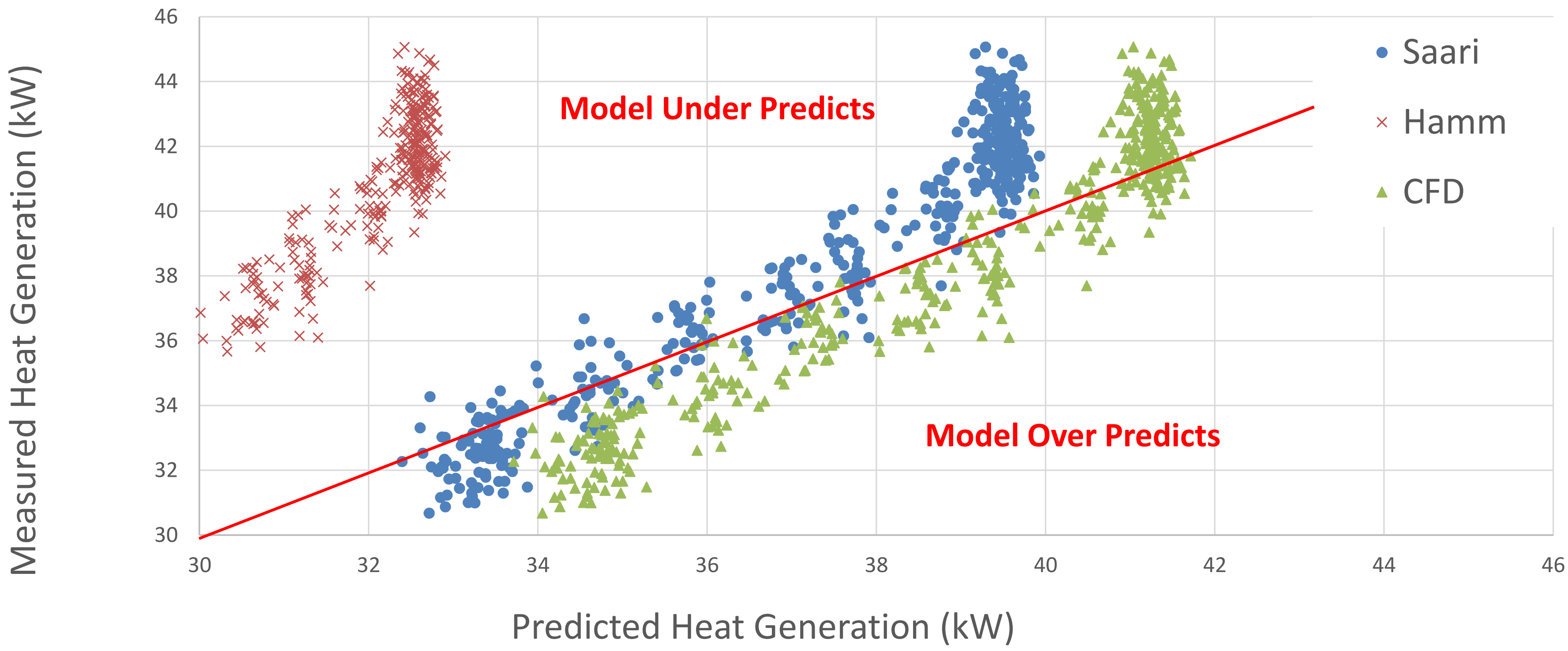


- Reference state: 25,000 RPM, 14.78 kg/m^3, 1.5 MW$_e$
- Multipliers are predicted design loads

Typical Alternator Run



Comparison of Windage Models



Conclusions

- A high speed permeant magnet alternator was tested in a pressurized CO2 environment
- Two identical machines were used to run a back-to-back motor generator test
  - Test completed to verify operation of the HSA and thermal management system and validate heat generation models
- Experimental data was taken and compared to three windage models: Hamm, Saari, and 3-D CFD
- Experimental data most closely matched the 3D CFD and Saari models of windage
  - Saari model slightly under predicts while the CFD model slightly over predicts
  - Hamm model significantly under predicts windage heating