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Advanced Thermal Management for Future Electrified Transport

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DER
Midlands Industrialisation Centre

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- Current development on thermal management
- Oil spray/impingement cooling
- Conclusion

Myself

- Myself (Dr. Fengyu Zhang)
  - Senior Research Fellow and Anne McLaren Fellow in Electric Drive (E-drive) Systems at University of Nottingham, with multi-background in both electrical and thermal engineering
  - 18 journal papers (6 as first author), including 15 IEEE Transactions/Proceedings papers plus 9 conference papers, 1 Best Paper Award, 1 granted patent (first inventor)

- Educational background
  - PhD in Electrical Engineering, 2019, University of Nottingham, Nottingham, UK
  - Bachelor in Thermal Engineering, 2014, Huazhong University of Science and Technology, Wuhan, China

- Zero-carbon target by 2050
    - Aerospace is the most difficult transportation sector

- Electrification is the only realistic technology to decarbonise aircraft

Image source: Aerospace Technology Institute

Importance of thermal management

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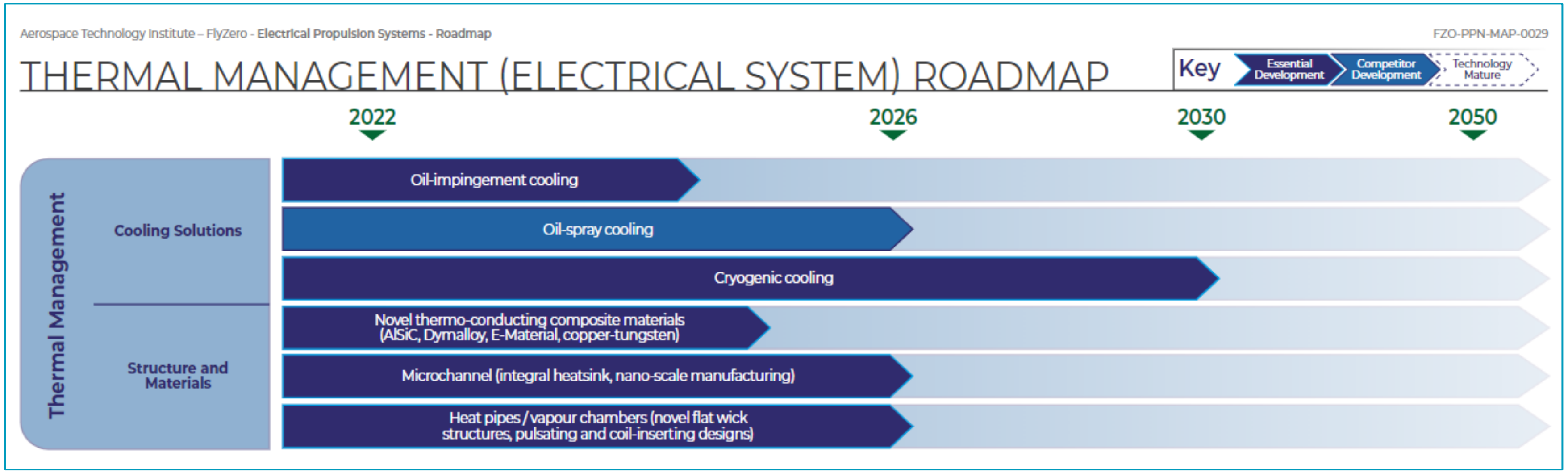
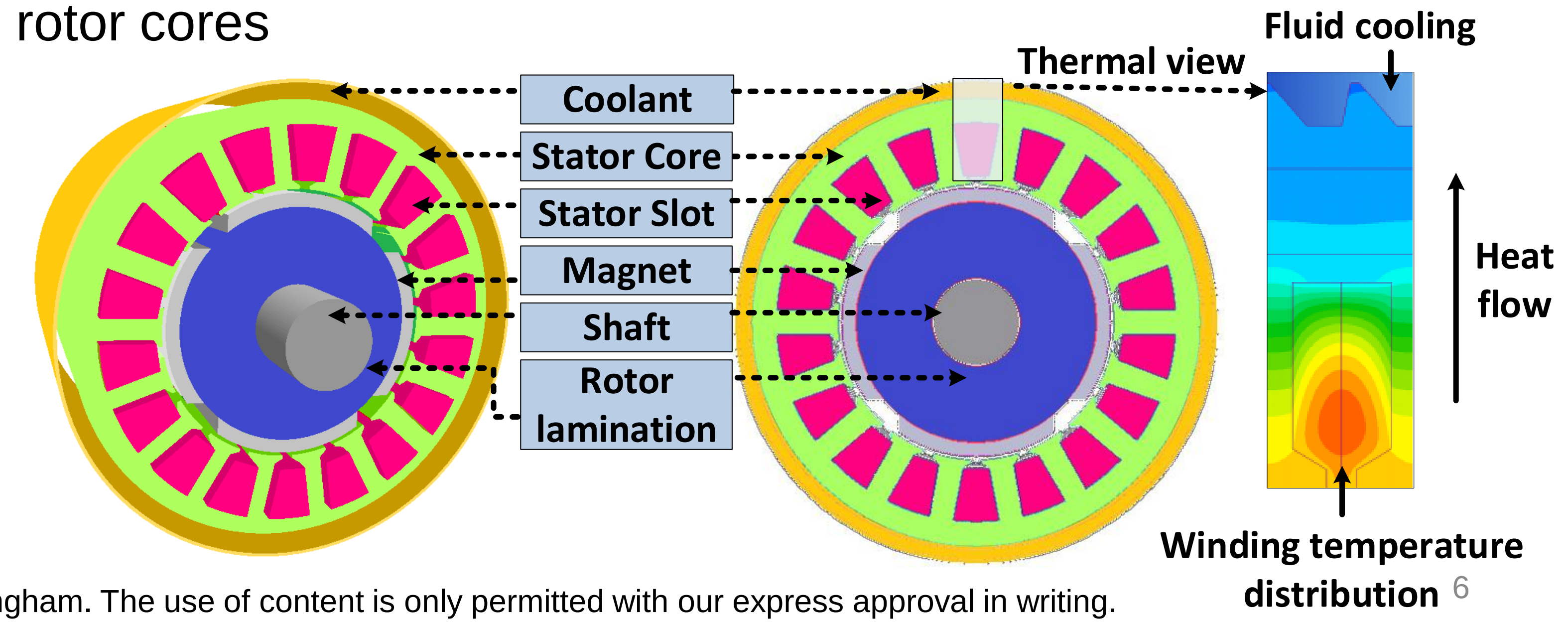
TECHNOLOGY INDICATORS

		2026	2030	Ultimate Target 2050
Electric motor	Power Density (kW/kg)	13	23	25
Power electronics (Inverter)	Power Density (kW/kg)	22	40	60
Power electronics (DC-DC)	Power Density (kW/kg)	15	40	60
Fuel cell stack	Power Density (kW/kg)	7	9	16
Thermal management system*	Power Density (kW/kg)	6	7	20
Air-supply system*	Power Density (kW/kg)	1	1	3
Electrical propulsion system	Power Density (kW/kg)	1.0-1.5	1.5-2.0	3.0-3.5



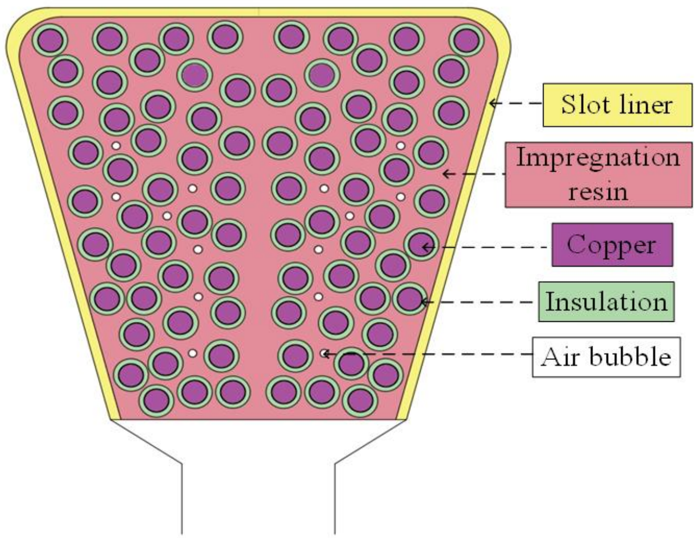
Importance of thermal management

- Crucial thermal management
  - Aim: To push more current for more power
  - Thermal limit & machine failure
- Losses
  - Significant losses are generated within the stator slot (winding): including DC and AC loss
  - Iron losses in both stator and rotor cores
  - Magnet losses
  - Mechanical losses

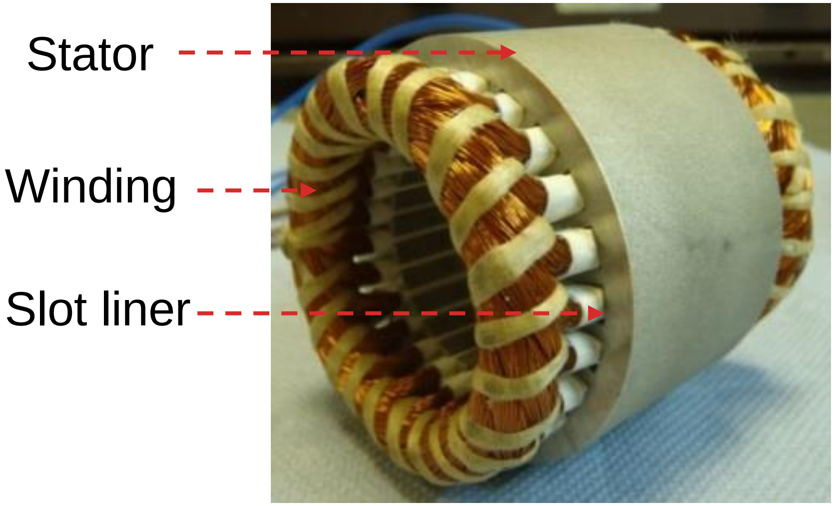


Importance of thermal management

- Crucial thermal management
  - Poor thermal performance in the stator slot
  - Heat transfer path between the heat sources and the coolant
  - Cooling methodologies and thermal modelling tool



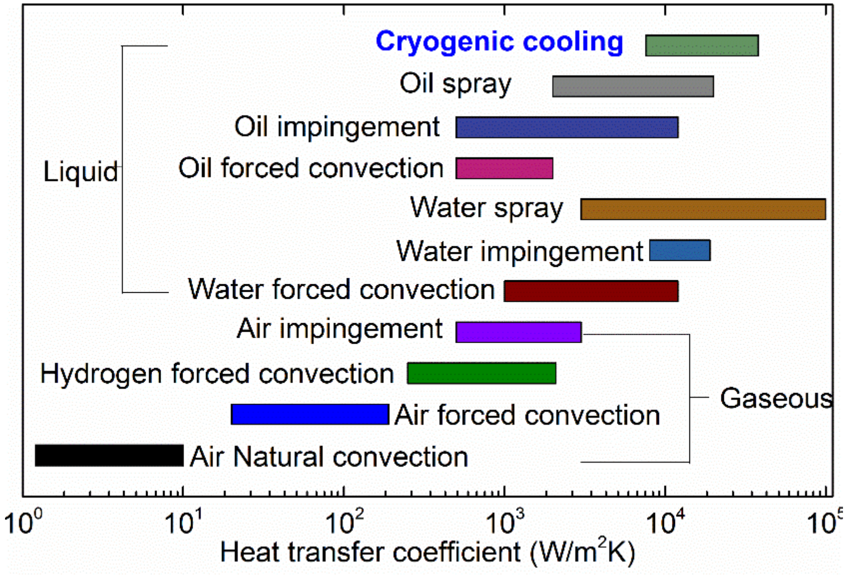
Stator slot



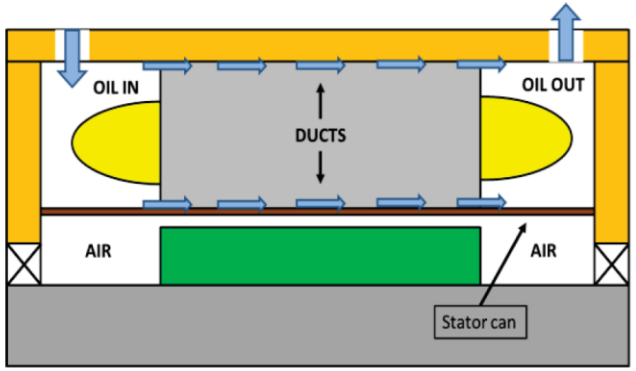
F. Zhang et al., "Electrical Machine Slot Thermal Condition Effects on Back-Iron Extension Thermal Benefits," in IEEE Transactions on Transportation Electrification, vol. 7, no. 4, pp. 2927-2938, Dec. 2021, doi: 10.1109/TTE.2021.3085822.

Current development on thermal management

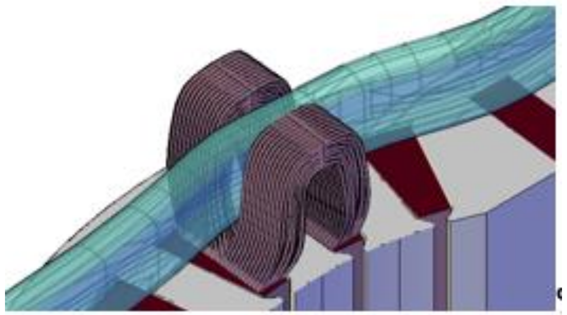
- Coolant
  - Air
  - Water
  - Oil
  - Cryogenic fluids



- Structure improvement
  - Slot improvement
  - End-winding
  - Slot cooling channel



Semi-flooded oil cooling

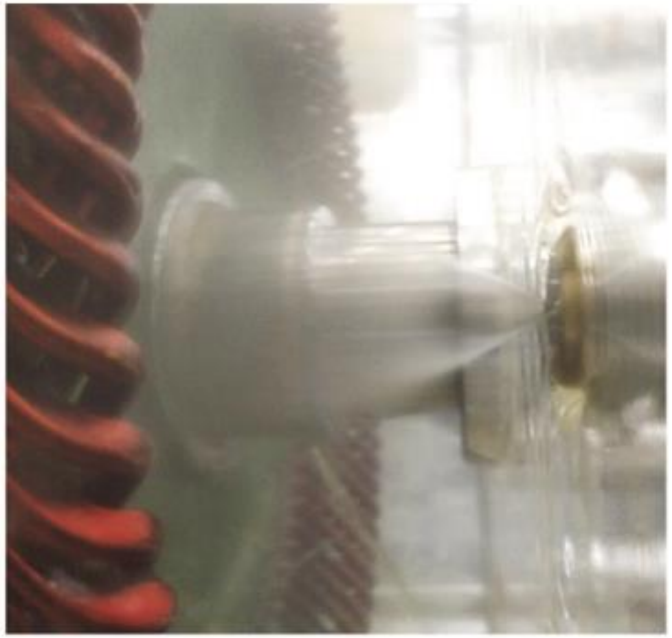


Water cooled end-winding

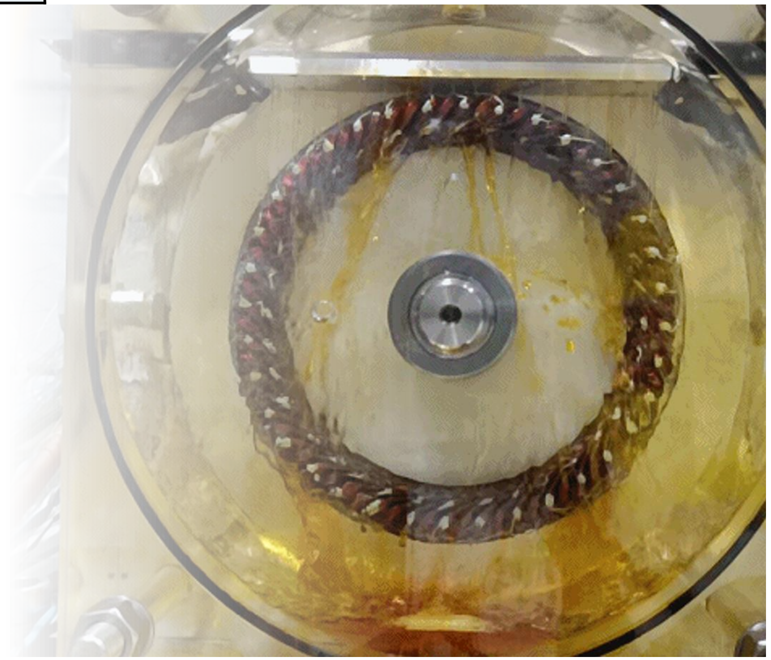
Oil Spray and Jet Cooling of Electrical Machines

Oil spray and impingement cooling comparison

	Droplet	Pressure	Performance	Manufacturability/ Cost
Oil spray	10-30µm, 50µm and 150µm	🟡	🟢	🟡
Oil impingement	0.1-0.5mm	🟢	🟡	🟢

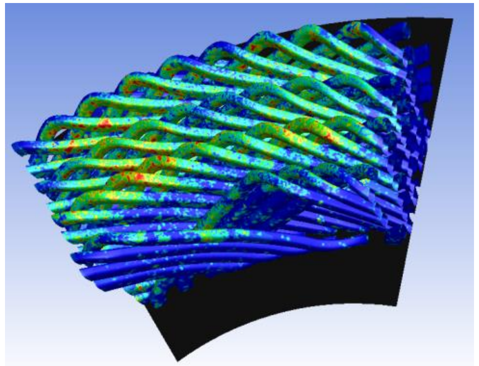


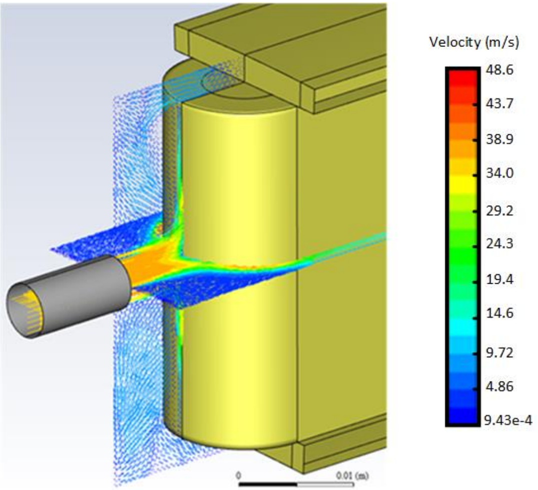
- Research areas
    - Stator winding layers number (up to 8)
    - Nozzles types, numbers and locations
    - Speed (up to 12000rpm)
    - Rotor splash/shaft cooling
    - Modelling and experimental testing



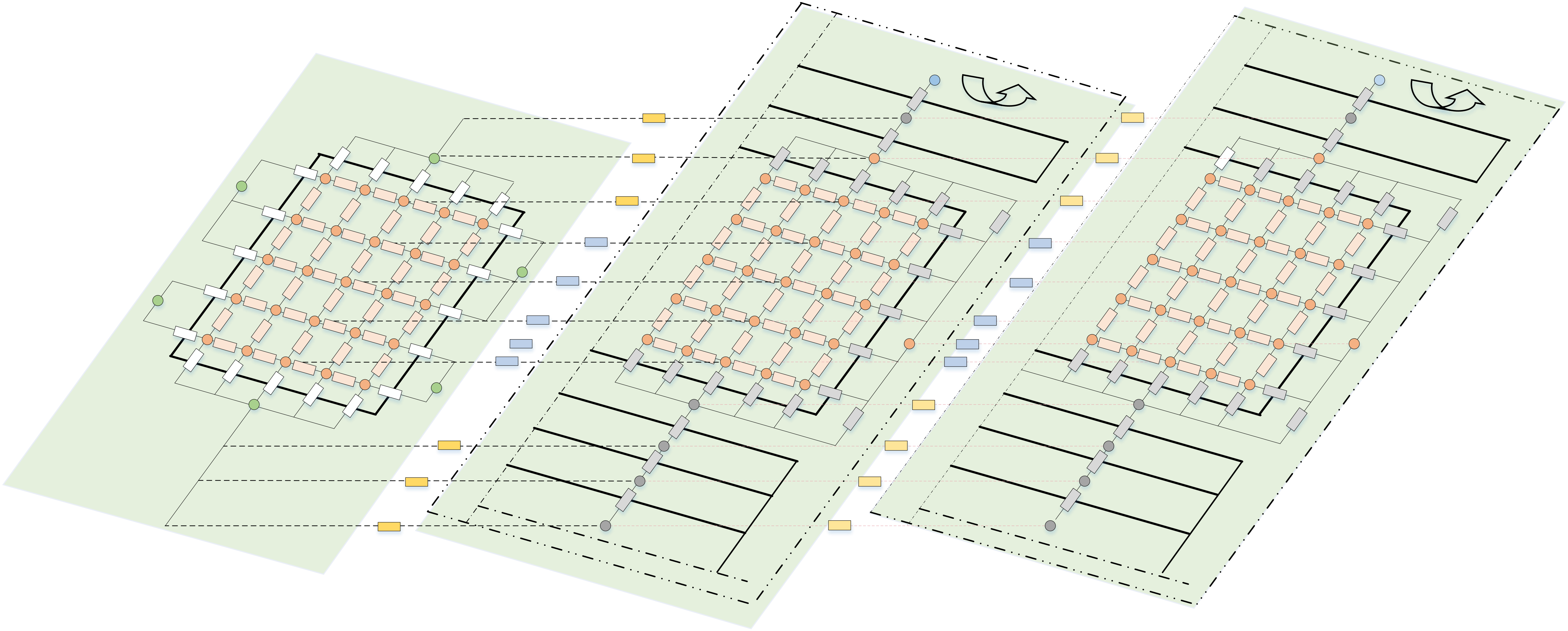
Modelling and experimental testing

- Modelling
    - Heat transfer coefficient determination
    - Full machine simulation
- Experimental testing
    - Test rig design and testing



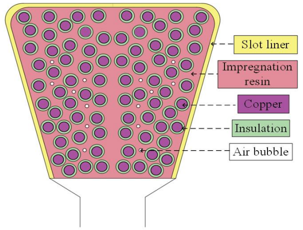
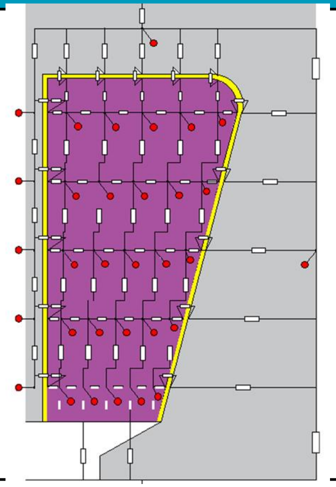
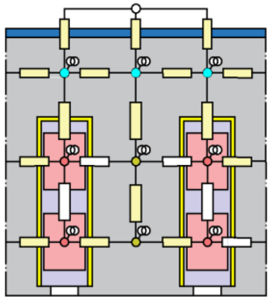
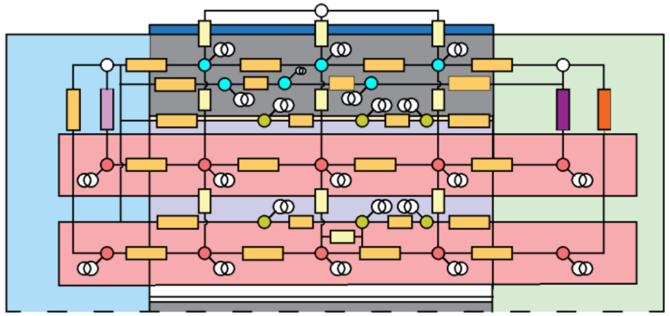


Thermal network on spray cooling



F. Zhang *et al.*, "Slot Number Thermal Effects on Electrical Machines," in *IEEE Transactions on Energy Conversion*, vol. 36, no. 1, pp. 23-35, March 2021, doi: 10.1109/TEC.2020.3008219.

Simulation methods

	Slot	End-winding	Slot simulation
Traditionally cooled round windings	 	Assumed uniform for all the slots	Half slot
Oil spraying cooled hairpin windings	 	Heat transfer coefficient and convection area (following slides)	Full machine

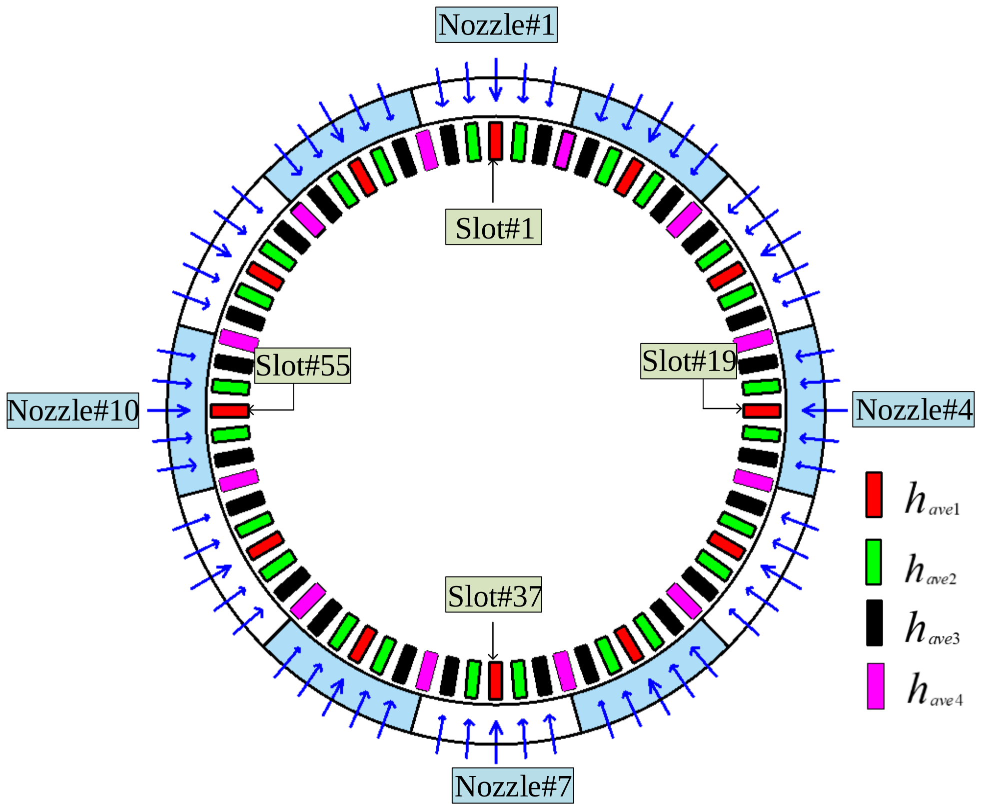
F. Zhang et al., "A Thermal Modeling Approach and Experimental Validation for an Oil Spray-Cooled Hairpin Winding Machine," in IEEE Transactions on Transportation Electrification, vol. 7, no. 4, pp. 2914-2926, Dec. 2021, doi: 10.1109/TTE.2021.3067601.

Simulation methods

End-winding heat transfer coefficient determination

- $q = \frac{Q}{2 \times N}$
- #1: $h_{ave} = q/[A_{end}(T_{ave} - T_{oil})]$
- #2: $h_{ave1} = q/[A_{end}(\frac{\sum T_i}{12} - T_{oil})]$
- #3: $h_{\#slot} = q/[A_{end}(T_{\#slot} - T_{oil})]$

average h		Slot#	Total slots
h_{ave1},	i	1, 7, 13, 19, 25, 31, 37, 43, 49, 55, 61, 67	12
h_{ave2},	j	2, 6, 8, 12, 14, 18, 20, 24, 26, 30, 32, 36, 38, 42, 44, 48, 50, 54, 56, 60, 62, 66, 68, 72	24
h_{ave3}	M	3, 5, 9, 11, 15, 17, 21, 23, 27, 29, 33, 35, 39, 41, 45, 47, 51, 53, 57, 59, 63, 65, 69, 71	24
h_{ave4}	N	4, 10, 16, 22, 28, 34, 40, 46, 52, 58, 64, 70	12



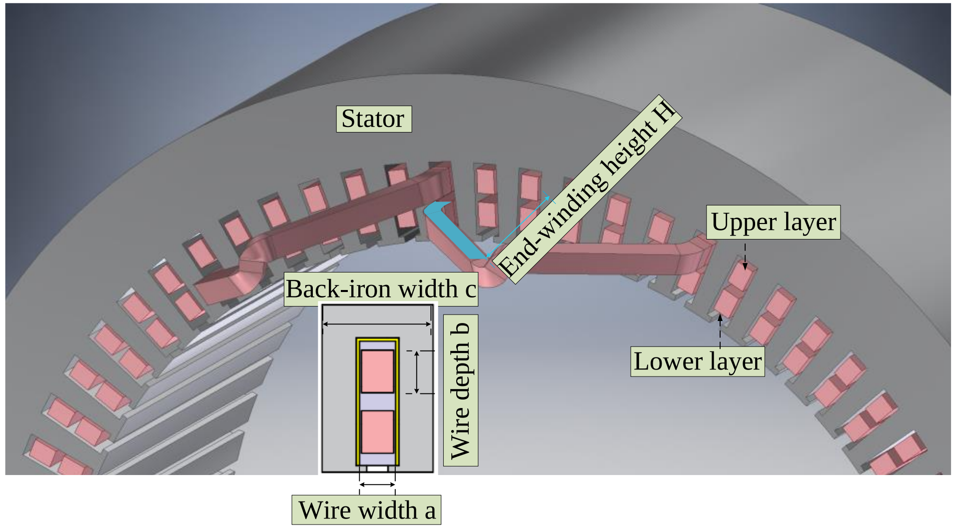
*Nozzle type A, 12 nozzles as example

'q' is the corresponding loss of a single conductor dissipated to the sprayed-oil, 'Q' is the total heat loss dissipated to the sprayed-oil, 'N' is the slot number; 'T_{ave}' and 'T_{oil}' are average conductor end-winding temperature and sprayed-oil temperature, respectively.

Simulation methods

End-winding effective convection area

- Full surface area $s_{end} = (2a + 2b) \times l,\ l = H + 3c$
- #1: $s_1 = s_{end}$
- #2: $s_2 = \beta_0 \times s_{end},\ \beta_0 = (a + 2b)/(2a + 2b)$ - constant
- #3: $s_3 = \beta \times s_{end},\ \beta = \frac{\beta_0 (T_{ave} - T_{oil})}{T_{\#slot} - T_{oil}}$ - dependent on single slot

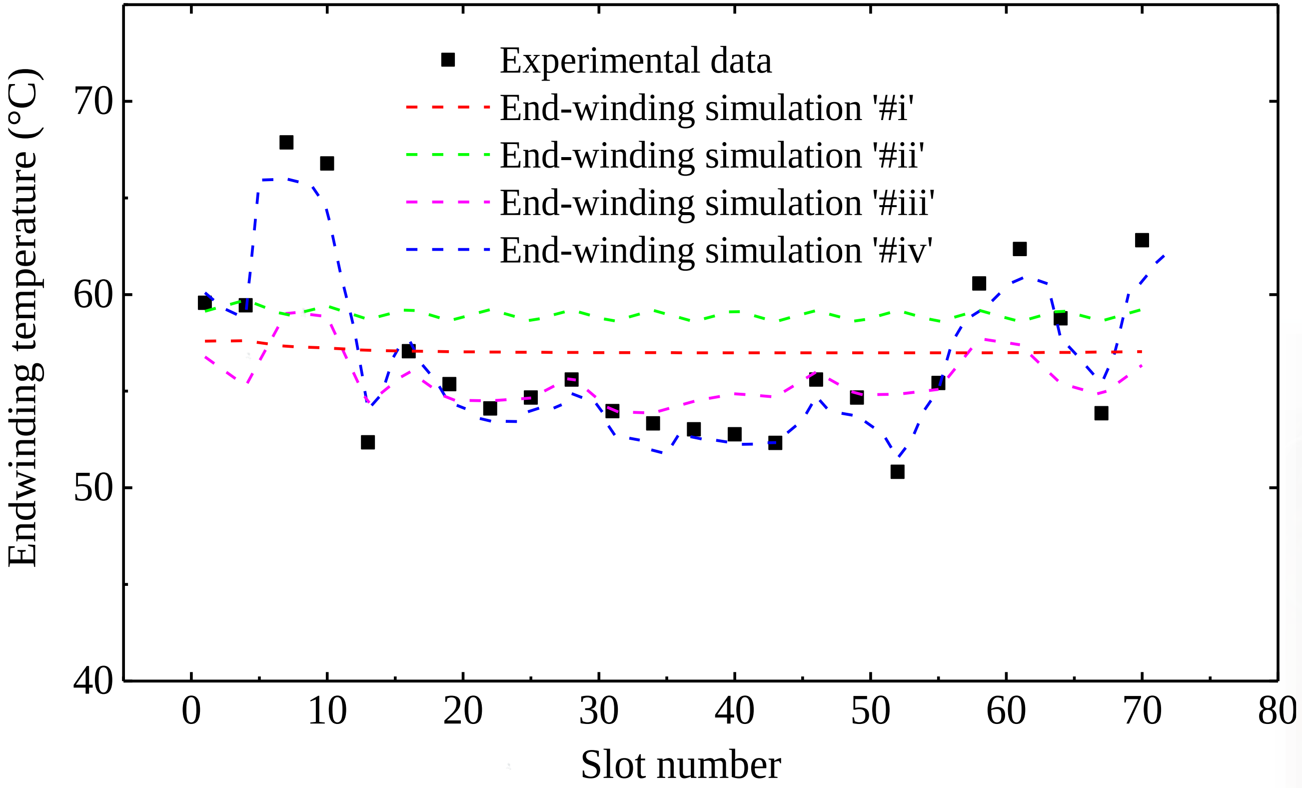


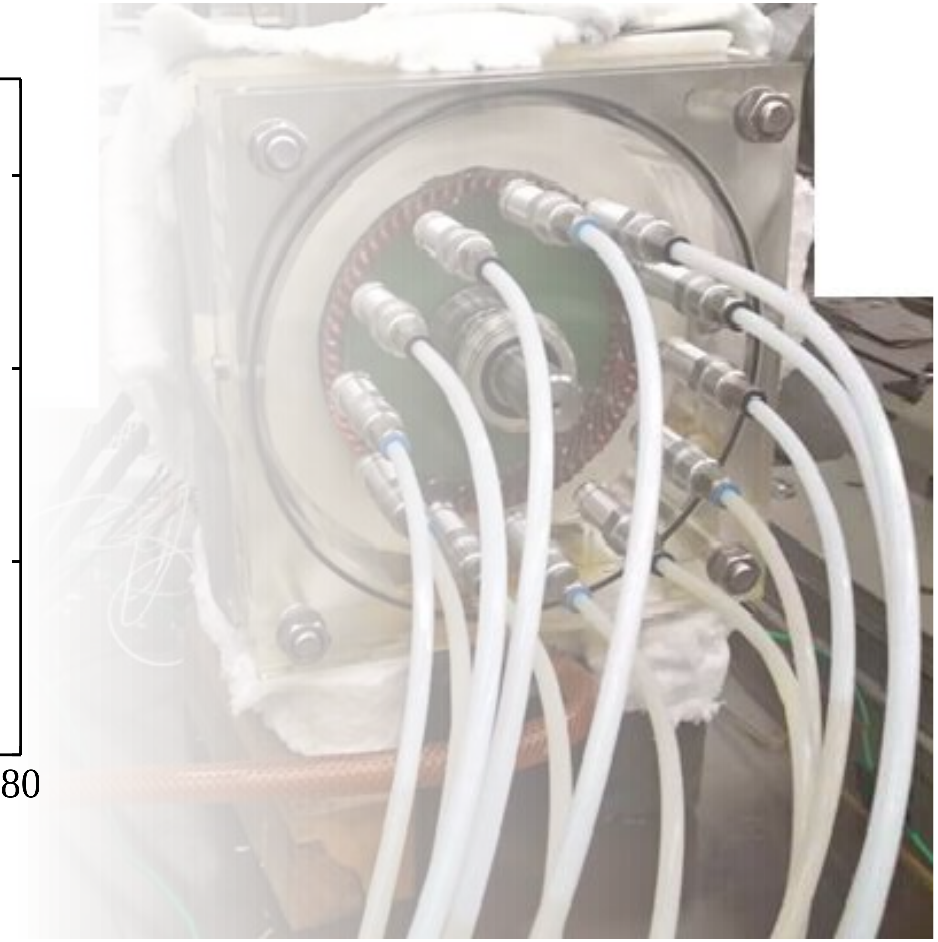
End-winding methodology (#i, #ii, #iii, #iv)

End-winding methodology	h	A_{conv}
#i	h_{ave} for all end-winding	$A_{conv} = A_1 = (2a + 2b) \times l$
#ii	$h_{ave1}, h_{ave2}, h_{ave3}, h_{ave4}$	$A_{conv} = A_2 = \beta_0 \times (2a + 2b) \times l$
#iii	$h_{ave1}, h_{ave2}, h_{ave3}, h_{ave4}$	$A_{conv} = A_3 = \beta \times (2a + 2b) \times l$
#iv	Single conductor local $h_{\#slot}$	$A_{conv} = A_3 = \beta \times (2a + 2b) \times l$

'a', 'b' are the conductor width and depth respectively, 'c' is the distance between the centers of two adjacent slots, while 'H' is the end-winding height.

Simulation methods





Temp	Thermal network with end-winding methodology#				Measured
	i	ii	iii	iv	
Ave (°C)	57.08 (1.73%)	58.97 (12.98%)	55.59 (-7.15%)	56.19 (-3.57%)	56.79
Peak (°C)	57.61 (-36.81%)	59.71 (-29.28%)	59.12 (-31.4%)	65.98 (-6.78%)	67.87

Conclusion

- Thermal improvement

- Oil spray and impingement cooled machines
  - Modelling and experimental testing

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Thank you!

Any questions?