Heat Flux Requirements for Electrified Aircraft Wing Anti-Ice Systems

Nic Heersema
NASA Armstrong Flight Research Center

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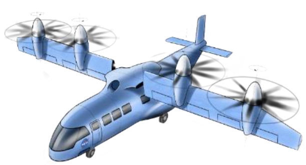
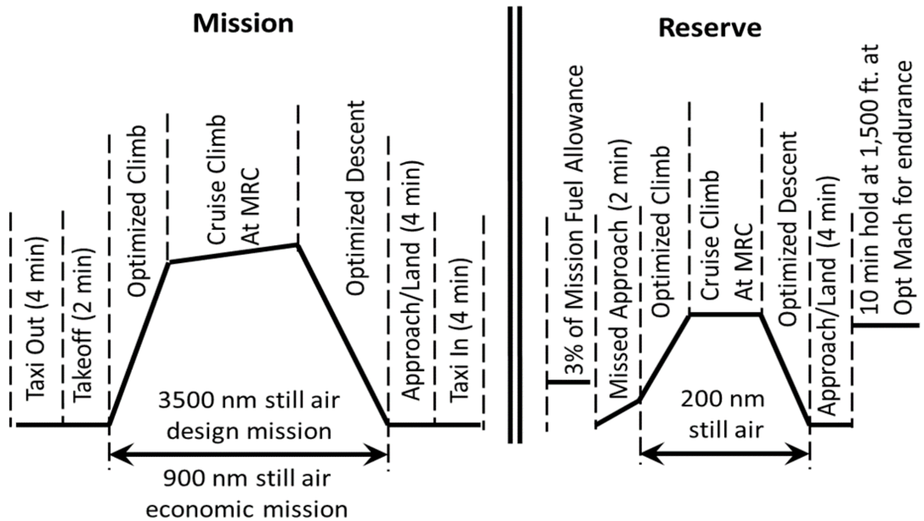
- The project goals:
  - Increase efficiencies of electric components to reduce waste heat generated
  - Manage waste heat using passive Thermal Management System (TMS)
- 3 representative aircraft considered:
  - Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsion (STARC-ABL)
    - 2 underwing turbofans drive an electric Boundary Layer Ingestion (BLI) motor

  - Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS)
    - Parallel hybrid-electric turboprop outboard engines, inboard all-electric engines, aft all-electric BLI motor

  - Revolutionary Vertical Lift Technology (RVLT) Tiltwing
    - VTOL with a central turboshaft engine driving 4 electric wing motors



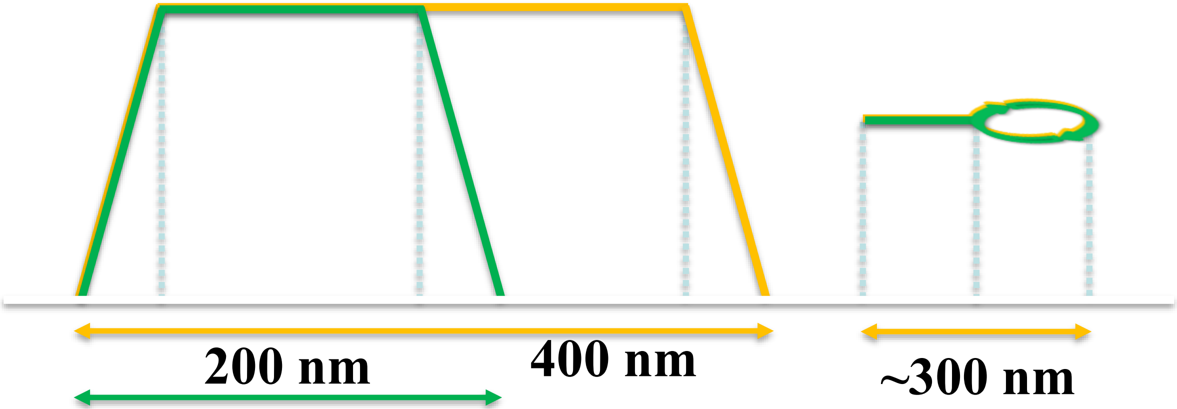
Flight Profile: STARC-ABL



- Icing conditions could be encountered during Takeoff, Climb, Descent, and Holding

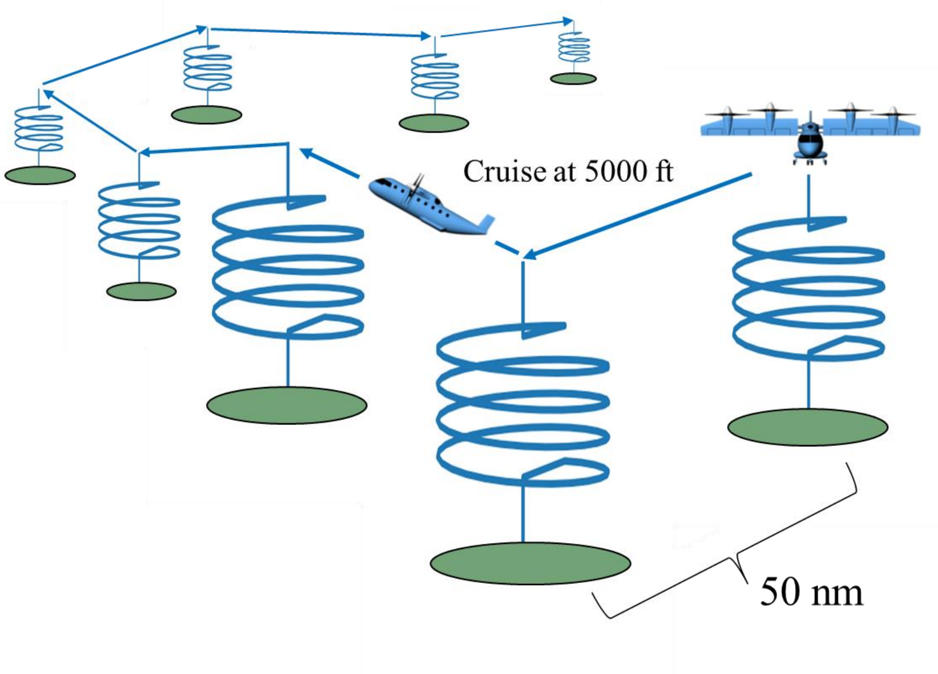
Run Number	Altitude (ft)	Mach No.	AoA (deg)	Temp (degF)	Temp (degK)	Droplet (microns)	LWC (g/m^3)	Duration (mins)	Envelope
WB41 T = -13	5000	0.36	0	8.6	260.15	20	0.361	45	Cont. max
IRT Run 1.07	5000	0.33	0	21.5	267.3167	20	0.504	45	Cont. max
IRT Run 2.03	10000	0.35	0	14	263.15	20	0.415	45	Cont. max
WB33 T = -4	10000	0.36	0	24.8	269.15	20	0.551	45	Cont. max
IRT Run 1.26	15000	0.39	0	0	255.372	35	0.095	45	Cont. max
IRT Run 1.05	15000	0.33	0	0	255.372	20	0.248	45	Cont. max
WB39 T = -25	22000	0.36	0	-13	248.15	20	0.175	45	Cont. max
WB37 T = -7	15000	0.46	0	20	266.483	35	0.19	45	Cont. max
IRT Run 1.19	10000	0.39	0	10	260.928	20	1.807	8	Int. max
IRT Run 1.29	15000	0.40	0	0	255.372	20	1.56	8	Int. max

Flight Profile: PEGASUS



- Profiles:
  - **All-Electric**: 200 nm range
  - **Hybrid-Electric**: 400 nm range
  - Reserves: 87 nm + 45 minutes
- Icing conditions could be encountered during Takeoff, Climb, Descent, and Holding

Run Number	Altitude (ft)	Mach No.	AoA (deg)	Temp (degF)	Temp (degK)	Droplet (microns)	LWC (g/m^3)	Duration (mins)	Envelope
WB41 T = -13	5000	0.36	0, 4.5	8.6	260.15	20	0.362	45	Cont. max
IRT Run 1.12	5000	0.36	0, 4.5	20	266.483	35	0.19	45	Cont. max
IRT Run 2.03	10000	0.35	0, 4.5	14	263.15	20	0.425	45	Cont. max
WB33 T = -4	10000	0.36	0, 4.5	24.8	269.15	20	0.553	45	Cont. max
IRT Run 1.26	15000	0.39	0, 4.5	0	255.372	35	0.096	45	Cont. max
IRT Run 1.05	15000	0.33	0, 4.5	0	255.372	20	0.26	45	Cont. max
Cruise T = -25	20000	0.45	0, 4.5	-13	248.15	20	0.177	45	Cont. max
Cruise T = -16.7	20000	0.44	0, 4.5	2	256.483	35	0.105	45	Cont. max



- Icing conditions could be encountered during all phases of flight

Run Number	Altitude (ft)	Mach No.	AoA (deg)	Temp (degF)	Temp (degK)	Droplet (microns)	LWC (g/m^3)	Duration (mins)	Envelope
WB41 T = -13	5000	0.271	0, 8	8.6	260.15	20	0.362	45	Cont. max
IRT Run 2.02	500	0.267	0, 8	20.2	266.59	35	0.192	45	Cont. max
IRT Run 2.03	5000	0.269	0, 8	14	263.15	20	0.425	45	Cont. max
IRT Run 2.05	500	0.273	0, 8	0	255.372	20	0.26	45	Cont. max
FT#1	5000	0.270	0, 8	11	261.483	40	0.421	8	Int. max

Types of AI/DI Systems

ThermoPneumatic

- In use on most large turbojets
- Bleed air extracted from engine fed through ducting, manifolds, valves, and pipes to leading edge
  - ~1.13-1.36 kg/s @ 0.26 MPa per wing
  - Performance impact from bleed air extraction
- Heat transfer per unit span: ~ 1-5 kW/m
- Requirements:
  - Weight: ~140-270 kg (737-size aircraft)
  - Power: information not available
  - TSFC Penalty: ~2.5-4.5% while system is active
- Risks/concerns:
  - Air leakage from system
  - Overheat

ElectroThermal

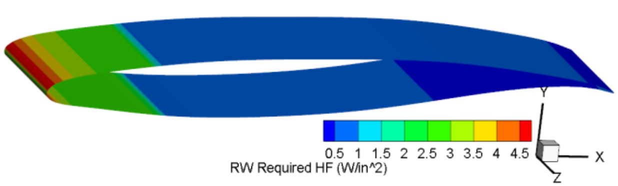
- Used primarily for:
  - Propeller blades
  - Wing anti-ice/de-ice on smaller planes
  - Wing de-ice on 787 Dreamliner
  - Windshields
- Reduced energy requirements, drag, and noise compared to ThermoPneumatic
- Heat transfer: information not available
- Requirements:
  - Weight: Lighter than bleed-air system, ~0.25 – 9.4 kg/m
  - Power: 45-75 kW
  - TSFC Penalty: ~1-2% while system active
- Risks/concerns:
  - Overheat (when used with Al alloys)
  - Power must be extracted from engine (performance impact) or a separate generator (weight penalty)

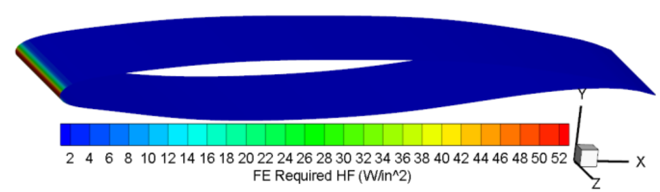
Running Wet (RW)

- Heats the incoming water to maintain temperature above freezing over heated section of wing chord
  - Water freezing on wing aft of heated section is called runback ice
- Often requires a de-icer to handle runback ice
- Lower heat transfer/power requirements
- Commonly employed as a parting strip on the leading edge of wing

Fully evaporative (FE)

- Evaporates incoming water on contact
  - No runback icing
- No de-icer required
- Localized to small area around leading edge of wing
- Higher heat transfer/power requirements
- Commonly used for windshields





Analysis of Anti-Ice Heat Requirements

- Heat flux requirements calculated using LEWICE2D for various icing conditions
  - 1D steady state analysis performed
    - 2D analysis performed with ANSYS FENSAP-ICE
      - Heat flux calculation not validated yet
      - FENSAP max heat flow rate requirements are ~4x lower for Running Wet and ~40% lower for Fully Evaporative
  - ‘Typical’ airplane CFRP material assumed
    - Heat flow rate requirements with 6061 Al are ~3% lower for STARC-ABL
  - Heat flow rate calculation assumes entire wing covered
- Icing conditions selected are a mix from NASA CRM 65% scale model and platform-specific icing flight conditions
  - Last 2 scenarios for STARC-ABL and RVLT cover more severe intermittent icing conditions and may not require the wing to be entirely free of ice for the short duration
    - More refined icing analysis would be required to determine impact to handling characteristics and performance from ice buildup in different regions of the wing

STARC-ABL Anti-Ice Heat Requirements

- Heat flow rate required for 10% chord anti-ice per wing at different icing conditions:

Scenario	Alt (ft)	Mach	Temp (degF)	Droplet size (microns)	LWC (g/m^3)	Heat flow rate (kW), RW	Heat flow rate (kW), FE	Max heat flux @ LE (kW/m^2), FE
1	5000	0.36	8.60	20	0.361	53.05	40.97	102.9
2	5000	0.33	21.5	20	0.504	32.36	43.77	108.5
3	10000	0.35	14.0	20	0.415	40.14	44.06	108.8
4	10000	0.36	24.8	20	0.551	13.11	55.46	127.2
5	15000	0.39	0	35	0.095	47.64	41.86	46.44
6	15000	0.33	0	20	0.248	47.43	34.37	77.67
7	22000	0.36	-13.0	20	0.175	55.85	31.97	63.49
8	15000	0.46	20.0	35	0.190	4.380	77.72	76.38
9	10000	0.39	10.0	20	1.807	50.61	166.9	411.2
10	15000	0.40	0	20	1.560	62.25	222.2	470.3

Heat flow requirements are within capability of thermopneumatic AI/DI system

PEGASUS Anti-Ice Heat Requirements

- Heat flow rate required for 10% chord anti-ice per wing at different icing conditions:

Scenario	Alt (ft)	Mach	Temp (degF)	Droplet size (microns)	LWC (g/m^3)	Heat flow rate (kW), RW	Heat flow rate (kW), FE	Max heat flux@ LE (kW/m^2), FE
1	5000	0.36	8.60	20	0.362	77.03	86.38	96.42
2	5000	0.36	20.0	35	0.190	49.91	104.7	69.14
3	10000	0.35	14.0	20	0.425	53.65	90.26	87.84
4	10000	0.36	24.8	20	0.553	19.23	123.4	126.3
5	15000	0.39	0	35	0.096	68.90	72.45	47.03
6	15000	0.33	0	20	0.260	69.67	61.19	59.09
7	20000	0.45	-13.0	20	0.177	88.73	86.69	78.11
8	20000	0.44	20.0	35	0.105	59.81	87.13	53.20

Heat flow requirements exceed current capabilities of thermopnuematic AI/DI system. Analysis in de-ice mode should be performed and/or area coverage should be reduced.

RVLT Anti-Ice Heat Requirements

- Heat flow rate required for 10% chord anti-ice per wing at different icing conditions:

Scenario	Alt (ft)	Mach	AoA	Temp (degF)	Droplet size (microns)	LWC (g/m^3)	Heat flow rate (kW), RW	Heat flow rate (kW), FE	Max heat flux @ LE (kW/m^2), FE
1	5000	0.271	0	8.6	20	0.361	50.2	57.3	68.3
2	500	0.267	0	20	35	0.192	48.8	57.4	47.8
3	5000	0.269	0	14	20	0.425	41.7	63.7	77.2
4	500	0.273	0	0	20	0.260	44.4	65.8	53.7
5	5000	0.271	8	8.6	20	0.361	48.9	50.9	72.4
6	500	0.267	8	20	35	0.192	47.7	50.6	52.8
7	5000	0.269	8	14	20	0.425	41.2	60.5	80.3
8	500	0.273	8	0	20	0.260	61.4	43.0	59.6
9	5000	0.270	0	11	40	0.421	49.2	157	102
10	500	0.270	8	11	40	0.421	54.0	163	113

LEWICE not designed to handle locations immediately downstream of a rotor so the validity of these values is uncertain

More refined analysis required

Integration Considerations

- Heat flux at leading edge (LE) required for fully evaporative system might not be achievable given material and heat transfer constraints

- Running wet system will likely require de-icer to handle runback ice
  - Detailed analysis required to evaluate effect of runback ice on handling characteristics and performance and determine need for de-icer
  - De-icer adds weight and power requirements compared to fully evaporative system
  - Electro-mechanical expulsion deicing system (EMEDS) in use on P-8A and other aircraft is a lightweight, low power option
    - Weight: ~23 kg
    - Power requirement: ~23-33 W/m (total for STARCABL: ~1 kW)
      - Power requirement can be reduced through use of Super AI anti-ice coating currently in development under SBIR

Conclusions

- Heat requirements calculated for maintaining ice free leading edge for 3 HEATheR variant aircraft
- Heat requirements in excess of capabilities of typical thermopneumatic AI/DI systems
  - Further analysis to determine heat requirements in cyclic de-ice mode recommended for at least PEGASUS and RVLT
- More refined analysis required
  - LEWICE not designed for wing surfaces directly aft of rotors - RVLT results may not be valid
  - Analysis required to determine effect of ice accretion on aerodynamics and handling characteristics
- Testing to validate results desired
  - Takeoff angle of attack for STARC-ABL and PEGASUS is above range previously validated for LEWICE

Acknowledgements

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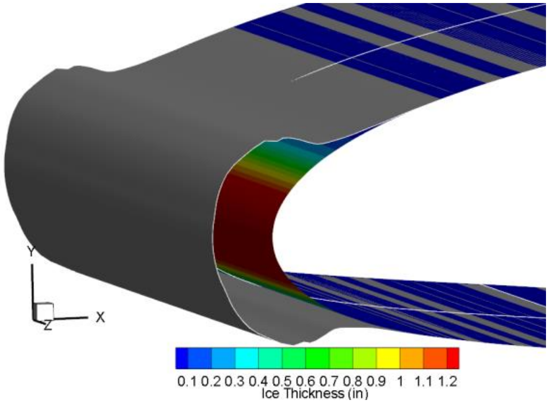
- GRC Icing Branch for their support
  - Eric Stewart for determining the icing conditions to analyze and generating FENSAP results
  - Bill Wright for assistance with LEWICE
- ARC for CFD analysis

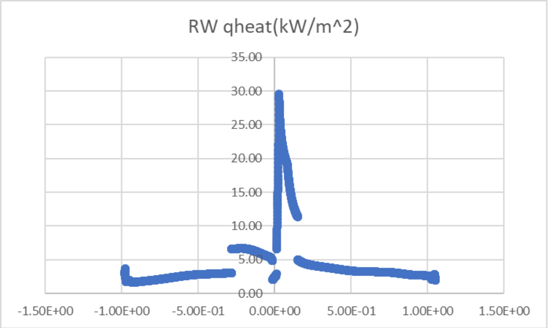
BACKUP

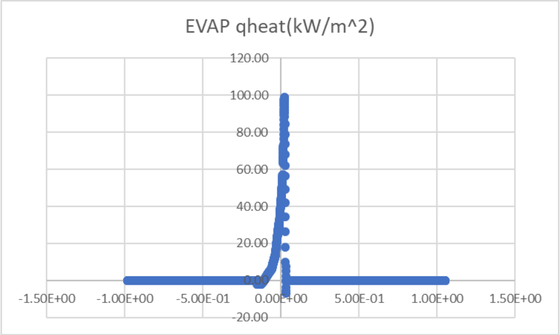
Scenario	Alt (ft)	Mach	Temp (degF)	Droplet size (microns)	LWC (g/m^3)	Heat flow rate (kW), RW	Heat flow rate (kW), EVAP	Max heat flux @ LE (kW/m^2), EVAP
3	10000	0.35	14	20	0.415	40.14	44.06	108.8

Ice accretion without anti-ice



LEWICE Results





FENSAP Results