# High-Effectiveness Heat Exchangers for PEM Fuel Cell Thermal Management

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**AMR Project ID #FC366**

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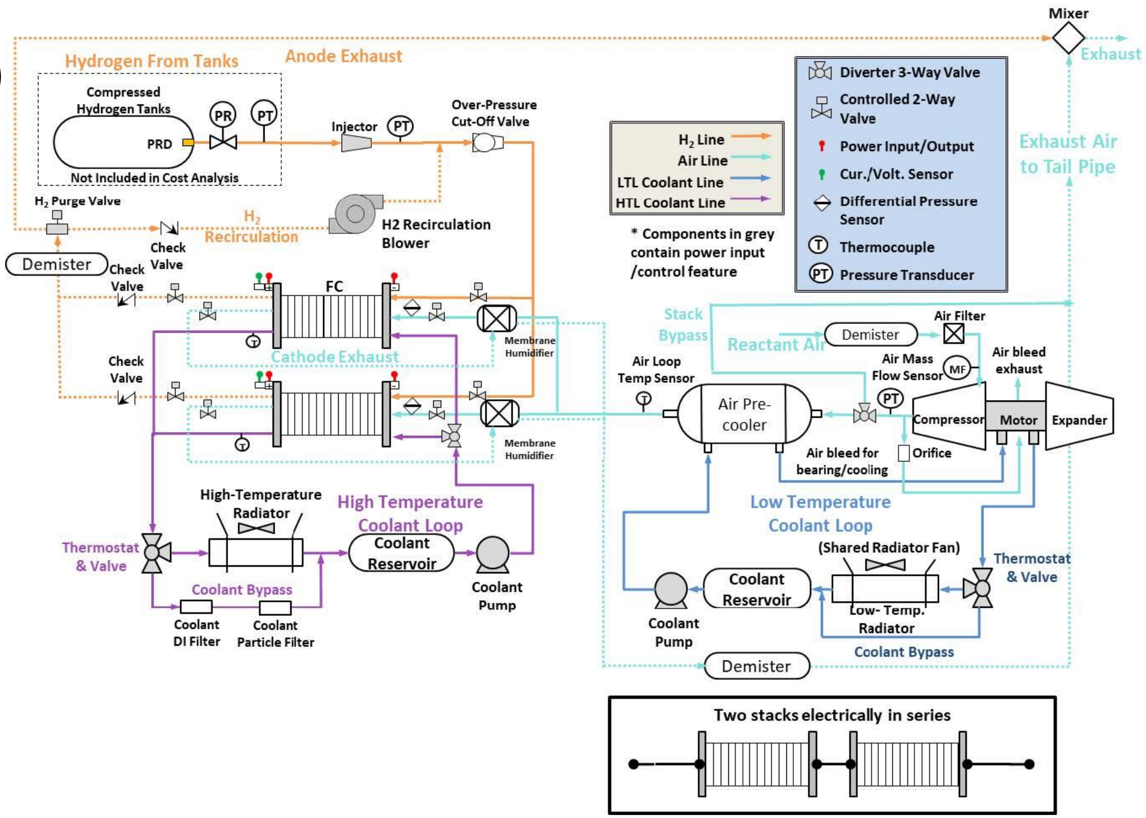
# Project Goal

- **Proton exchange membrane fuel cell (PEM FC) heavy-duty (HD) electric vehicles (EV) represent an opportunity to improve efficiency and emissions in a wide range of applications**
  - Project focus: Class 8 long-haul trucks, 275 $kW_{net}$
- **Relatively low operating temperature (80°C) compared to Diesel engines requires up to 5X larger radiator size**
- **Overall Objective (Phase I-Phase III): develop efficient, ruggedized thermal management system (TMS) for heavy-duty PEM FC electric vehicles**
- **Phase I Objective: develop compact high-temperature radiator for low ΔT operation**
  - Design full-scale non-round microtube radiator for PEM FC EV with <10% greater volume than commercially available radiator for comparable Diesel engine
  - Demonstrate scalable assembly method for the microtube radiator that takes less than 8 man hours
  - Demonstrate subscale non-round microtube radiator with capacity at least 2.5 kW at 80°C coolant temperature and 50°C air temperature




**Schematic of a Class 8 Long-Haul FC Truck with Liquid-Cooled TMS[1]**

[1]Kleen, G., et al. (2023). Heavy-Duty Fuel Cell System Cost – 2022. Record #23002. DOE Hydrogen Program Record.

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# Overview

## Timeline and Budget

- Project Start Date: 07/10/2023
- Project End Date: 07/09/2024
- Total Project Budget: $199,977
  - Total DOE Share: $199,977
  - Total Cost Share: $0
  - Total DOE Funds Spent*: $86,680
  - Total Cost Share Funds Spent*: $0

  * As of 03/01/2024

## Barriers

- **Barriers and Targets**
  - FC heavy-duty vehicles operate at lower temperatures than Diesel engines requiring significantly larger radiators
  - Cost-effective manufacturing processes need to be developed for advanced non-round microtube heat exchangers

## Partners

- Project lead: Daniel Murphy, Mainstream Engineering

# Potential Impact

- **This research will aid the adoption of FC heavy-duty trucks by making the radiator size requirements more comparable to conventional radiators for Diesel trucks**
  - 2025 DOE target radiator Q/ΔT is 4.2 kW/°C[1]
- **High-temperature coolant loop represents 21% of the balance of plant costs in HD FC trucks[1]**
  - Improvements to TMS can reduce overall costs
- **Adoption of hydrogen FC HD trucks will reduce emissions and pollutants**
- **DOE Goal: Strengthen US manufacturing and create jobs**
  - Mainstream manufactures all our custom heat exchangers in the US at our Rockledge, FL site

[1]Kleen, G., et al. (2023). Heavy-Duty Fuel Cell System Cost – 2022. Record #23002. DOE Hydrogen Program Record.

# Approach

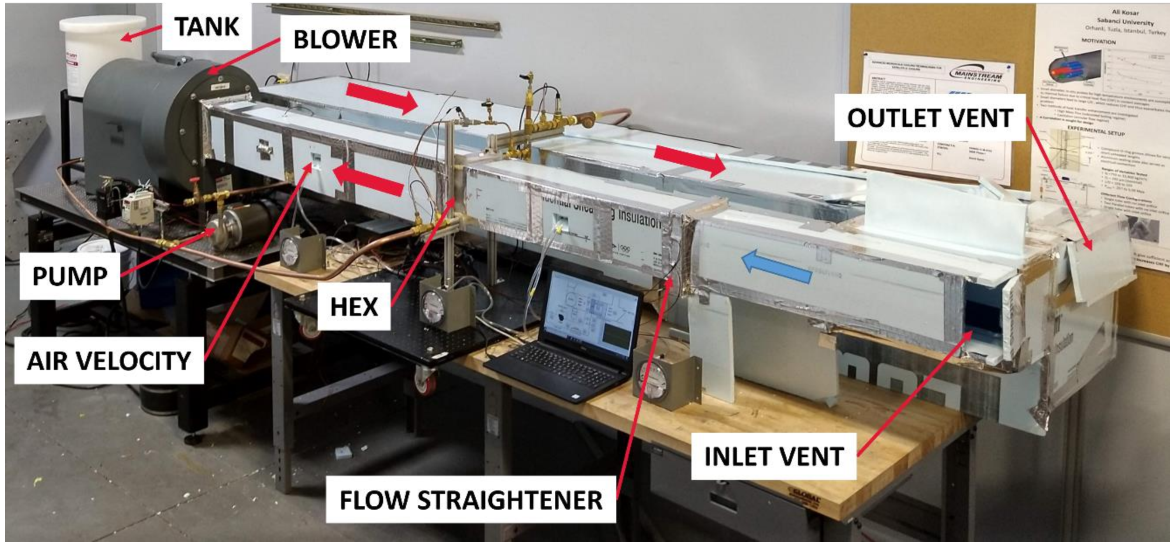
- **Traditional automotive radiators: all-aluminum brazed flat tubes and folded louvered fins**
  - Well-established supply chains and high-volume production
  - Capacity typically limited by air-side heat transfer
- **Novel non-round microtube radiator can improve volumetric cooling capacity by increasing heat transfer and reducing pressure drop**
  - State-of-the-art microtube heat exchangers (HEX) are made from stainless steel round tubes (heavy, low thermal conductivity)
  - Mainstream’s microtube HEX is all-aluminum (lightweight, high thermal conductivity)
  - Non-round tubes provide increased surface area and HEX effectiveness
- **Design metrics:**
  - Overall conductance ($UA$) – improve heat transfer coefficient, and HEX area density
    - Similar to Q/ΔT parameter for radiator sizing
  - Fluid- and air-side pressure drop – design tube shape to reduce frictional pressure losses
  - Pumping power – modeled based on commercial-off-the-shelf (COTS) fans and pumps marketed for FC HD trucks

**Subscale all-aluminum microtube HEX**

# Approach

- **HEX Optimization**
  - Used CFD & internal design models to simulate performance of different shape tubes and tube array geometries
  - Trade study and optimization based on *UA* and pumping power (pressure loss)
- **Manufacturing and Assembly**
  - Manufacturing study on production of non-round microtube profiles at scale
  - Develop assembly techniques for tube placement, orientation, insertion
  - Controlled atmosphere brazing (CAB)
    - Well established manufacturing technique for aluminum automotive radiators
- **Subscale Demonstration/Evaluation**
  - Test HEX performance at representative conditions

Mainstream's CAB furnace facility




Subscale HEX Performance Test Facility

# Approach: Safety Planning and Culture

- **This project was not required to submit a safety plan**
- **Prioritizing Safety and Analyzing Hazards**
  - Managers, PI, and project team are trained in safety procedures
  - Safety team evaluates test plans and equipment before testing
  - Hazardous equipment (e.g., CAB furnace) is only operated by authorized personnel
- **Addressing Incidents and Near-Misses**
  - No incidents or near misses associated with this project
  - Monthly safety meetings address all incidents and near misses and implement plans to mitigate future incidents
- **Incorporating Best Safety Practices and Lessons Learned**
  - We have added multiple layers of safety procedures associated with the CAB furnace and nitrogen systems

# Accomplishments and Progress

- **Performed optimization trade studies on non-round tube shapes and packing configurations**
  - Comparison of optimized microtube HEX with COTS radiator for Diesel Class 8 truck:
    - 2.4X conductance (*UA)*
    - 83% greater *UA*-to-pumping-power ratio
- **Developed a low-volume fabrication method to produce non-round microtubes**
  - Fabricated and evaluated multiple geometries
- **Developed a sorting and insertion mechanism for non-round microtube HEX**
- **Demonstrated performance of a subscale microtube HEX at representative temperatures and flow rates**

# Accomplishments and Progress:
# Responses to Previous Year Reviewers' Comments

- **This project has not previously been reviewed**

# Collaboration and Coordination

- **This project is part of the small business innovation and research (SBIR) program**
- **Prime contractor: Mainstream Engineering Corporation**
- **Phase I subcontractors: none**
- **Phase II partners**
  - Mainstream is pursuing partnerships for Phase II with FC and vehicle manufacturers to evaluate our radiator technology with actual PEM FC systems

# Remaining Challenges and Barriers

- **Improving manufacturing readiness level (MRL) for larger-volume production**
  - Continuous tube fabrication (e.g., extrusion, drawing, forming)
  - Full-scale HEX assembly
- **Ruggedization and qualification for vehicle environmental performance**
- **Cost reduction and marketing to overcome inertia to change in automotive sector**

# Proposed Future Work

- **Phase I End Date: 7/9/2024**
  - Complete characterization of subscale HEX
  - Refine design models based on experimental results
- **Phase II Plans**
  - Full-scale non-round microtube development and demonstration
    - Improve manufacturing
    - Full qualification testing (thermal, environmental, shock, vibration, etc.)
  - Integration with the rest of the FC TMS
  - Any proposed future work is subject to change based on funding levels

# Summary

- **All-aluminum, non-round microtube radiators can decrease the overall size of FC heavy duty truck radiators**
  - 2.4X *UA* relative to traditional radiator for diesel engine
  - >2X DOE target Q/ΔT
- **Developed fabrication and assembly techniques for microtube HEX production**
- **Demonstrated performance of a subscale radiator**
- **Results of this project will lead to size and power-per-cooling reduction of FC thermal management systems**