Advanced Modular Sub-Atmospheric Hybrid Heat Engine

Award No. DE-FE0031614

> **University Turbine System Research Project Review**

Presented by:

Project Lead - Yaroslav Chudnovsky, Ph.D., MBA
Principle Investigator - Aleksandr Kozlov, Ph.D., Sc.D.

> **Hilton Daytona Beach Oceanfront Resort**

November 1, 2018

Project Objective and Goals

- **Objective:** Develop and characterize a conceptual design of the novel advanced Modular sub-atmospheric Hybrid Heat Engine (MHHE) for fossil energy applications to produce electric or mechanical power from various fuels such as coal derived syngas, hydrogen, or natural gas
- **Goals:**
  - Phase I work will develop a conceptual design of the MHHE, including thermodynamic cycle analysis, define the nominal engine component boundary conditions and identify technology gaps
  - Characterize MHHE at a most marketable size and operating conditions in the range of 500kW-60MW that could be used to create larger capacities, as needed
  - Develop a technology maturation plan for the follow-on pilot-scale design, engineering, fabrication and testing in framework of Phase II

Project Team

- **Gas Technology Institute** (headquartered in Des Plaines, IL)
  - Independent, not-for-profit established by the natural gas industry in 1941
  - Providing research, development and technology deployment services to industry and government
  - Contract research, program management, consulting, and professional training
  - Wellhead to the burner tip including energy conversion reuse technologies
  - Over 1200 patents and over 500 products commercialized
- **SoftInWay Inc., Turbomachinery Engineering** (headquartered in Burlington, MA)
  - Founded in 1999
  - Development of efficient turbomachinery and power plants
  - Extensive expertise through software, engineering services, and training to industry and government
  - Five offices worldwide in the United States, Switzerland, Ukraine, and India
- Engine/Turbine/HMX **OEMs, consultants and suppliers** (TBD during Phase I)

Gas Technology Institute (GTI)

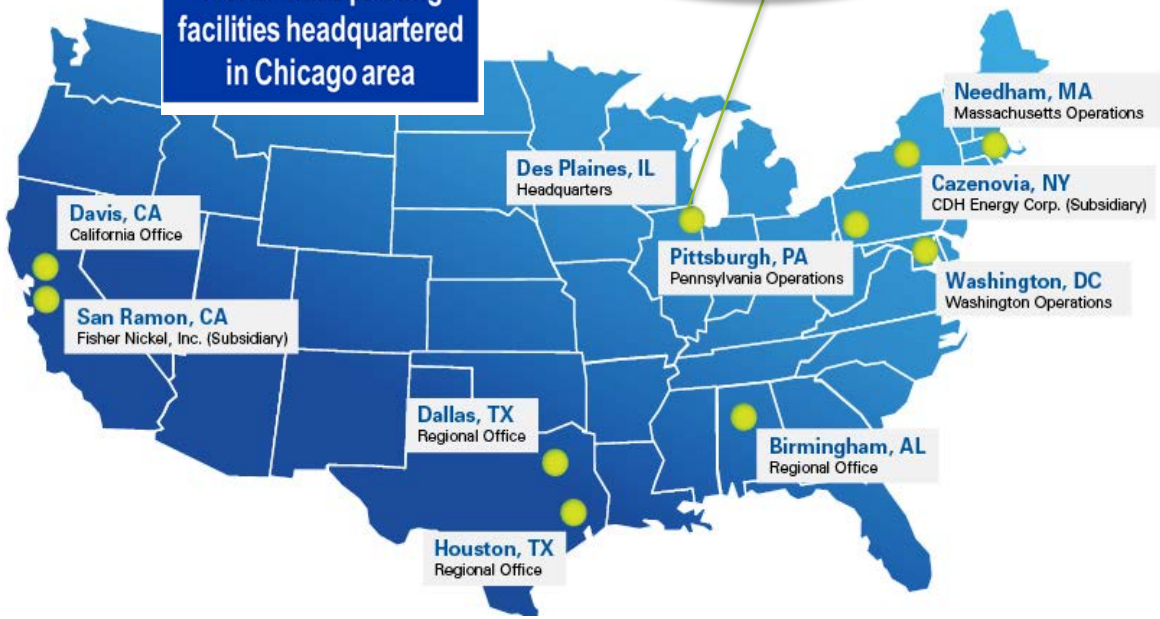
Panoramic View of GTI Applied Industrial R&D Laboratory

Panoramic View of GTI Boiler and Turbine Research Facility

Panoramic View of GTI Commercial and Residential Test Facility

World-class piloting facilities headquartered in Chicago area

- 18-acre campus
- 200,000 ft^2
- 28 specialized labs



Turning Raw Technology into Practical Energy Solutions

FOR A BETTER ECONOMY AND A BETTER ENVIRONMENT

SUPPLY ▶ CONVERSION ▶ DELIVERY ▶ UTILIZATION

RESEARCH & DEVELOPMENT

PROGRAM MANAGEMENT

TECHNICAL/ ANALYTICAL

CONSULTING

TRAINING

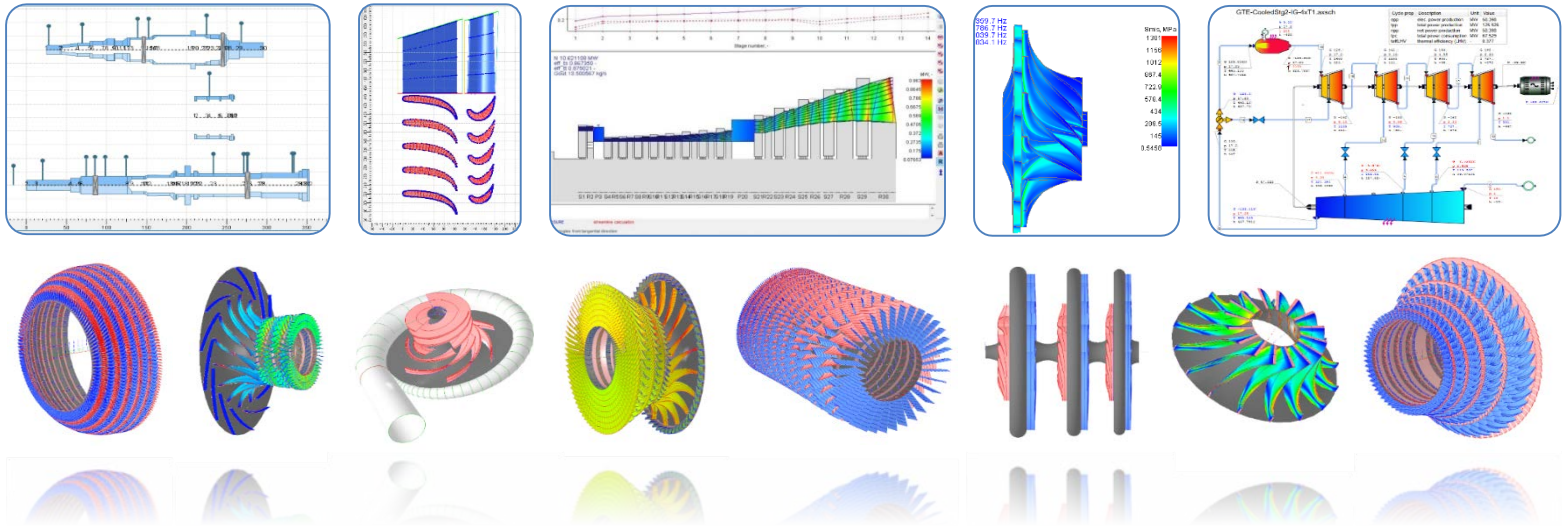
360+ EMPLOYEES

60% scientists/ engineers

44% advanced degrees

SoftInWay - Turbomachinery Mastered

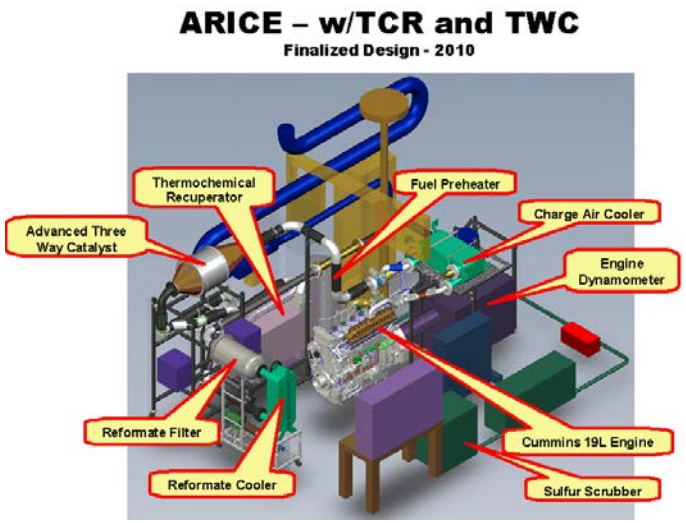
- Supports over 350 customers worldwide
- AxSTREAM® in-house software platform
- Over 190 consulting projects completed
- 70+ engineers, most with advanced degree
- Integrated design process for new-age



Project Team Background Work

- **Turbomachinery research, development, design and manufacturing (SoftInWay, GTI)**

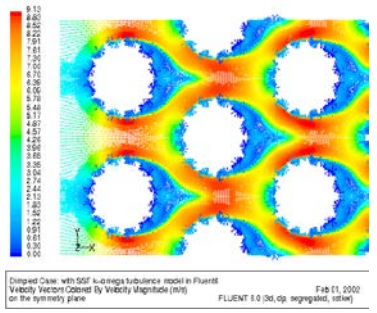
- **Cummins 331kW QSK19 engine with thermochemical heat recovery (GTI) for improved efficiency and lower NOx**

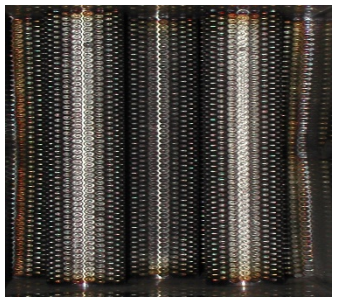


- **Stirling engine combustion system (GTI)**

- **Advanced heat and mass exchangers (GTI)**

Dimpled tubular heat exchanger

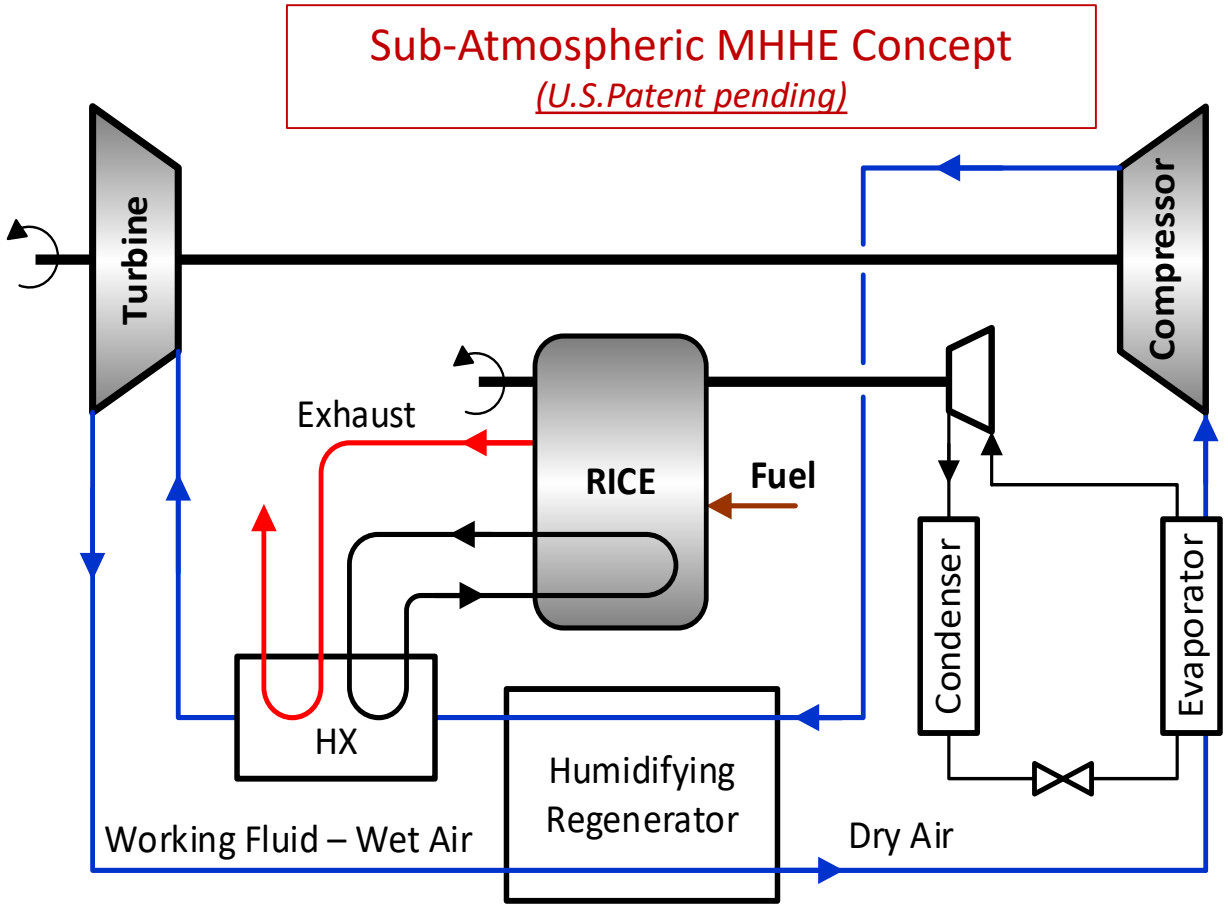




Evaporative distillation

Technical Concept

- **Unique combination** of a sub-atmospheric air turbine and RICE into hybrid heat engine enhanced by a humidifying regenerator and cooling system, that allows achieving >65% (LHV) net efficiency and meeting the most stringent emissions requirements
- **Prior to the turbine**, the working flow (air at atmospheric pressure) is humidified and heated to below 300°C which is much lower compared to the temperature level of conventional gas turbines
- **Prior to the compressor**, the air is dehumidified and cooled to near or below 0°C by the RICE-powered VC cooling system
- **Increased volume** of the air flow at the turbine inlet and **reduced volume** of this flow at the compressor inlet boosts the turbine cycle efficiency to an ultra-high level



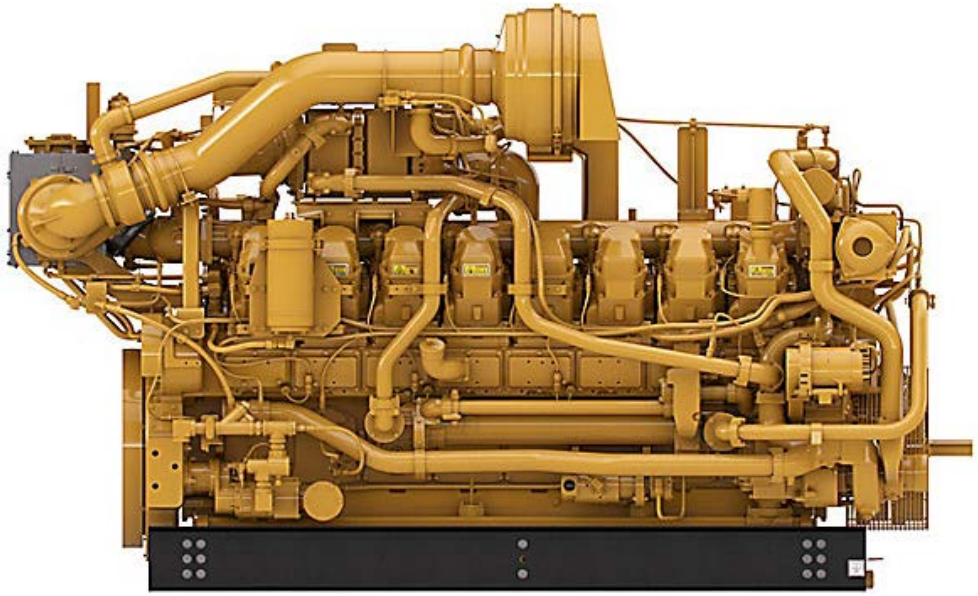
Technical Approach - based on existing designs

- **Sub-atmospheric air turbine and compressor** – straightforward modifications of existing designs. Low temperature, low pressure, low cost materials
- Existing natural gas-driven **Reciprocating Internal Combustion Engine (RICE)** designs. Should be able to operate or easy recalibrated for hydrogen or syngas
- **Low temperature cooler** – e.g. vapor compression refrigeration cycle with COP>1.0 is a straightforward modification or enhancement of existing designs
- **Air heat exchanger (HX)** – straightforward modifications of existing designs. Advanced, enhanced or compact designs can be considered due to large temperature difference between the flows
- **Humidifying regenerator** – unique component of the turbine cycle. To be preliminary designed in Phase I and then engineered, fabricated and pilot-tested in Phase II
- **Advanced control** – should be developed and verified in the scope of Phase II

Potential OEMs for Key Components

- **Sub-atmospheric air turbine** – similar design to a low temperature steam turbine by:
  - Dresser Rand, GE, DeLaval Turbine, Magnetek, Siemens, Elliot
- **RICE** – available (500kW-20MW). Rich burn engines are preferable for achieving low emissions. Potential OEMs:
  - Caterpillar (Various gaseous fuels, 600kW-4MW, efficiency 34-43%)
  - Cummins (NG/syngas, 500kW-2MW, efficiency >40%)
  - Waukesha (NG/biogas, 540kW-3.6MW, efficiency 30-38%)
  - Kawasaki (NG, 5-7.5 MW, efficiency 36%)
  - Siemens (NG/syngas/biogas/etc., 500kW-2MW, efficiency 43-55%)
- **HX and cooler** – variety suppliers on the marketplace
- **Humidifying regenerator** – humidifying/evaporative equipment producers, such as:
  - Coolerado/Seeley International, Evapco, BAC, SPX, Munters

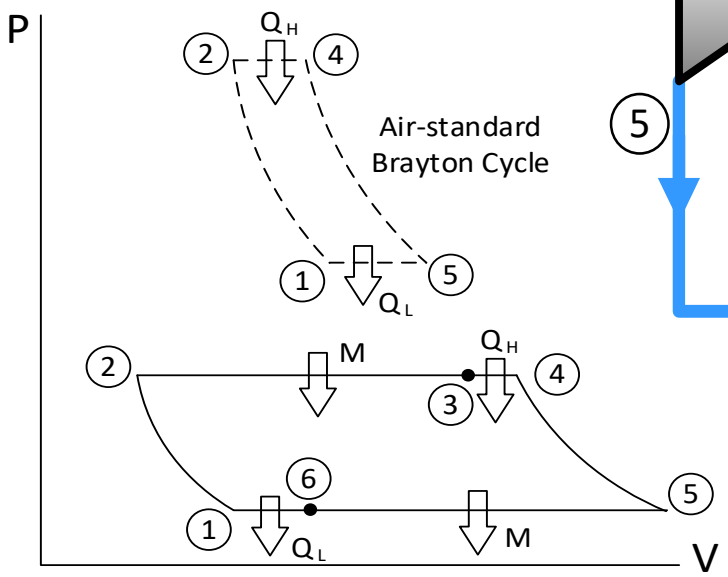
1300kW Caterpillar G3516 stoichiometric gas engine

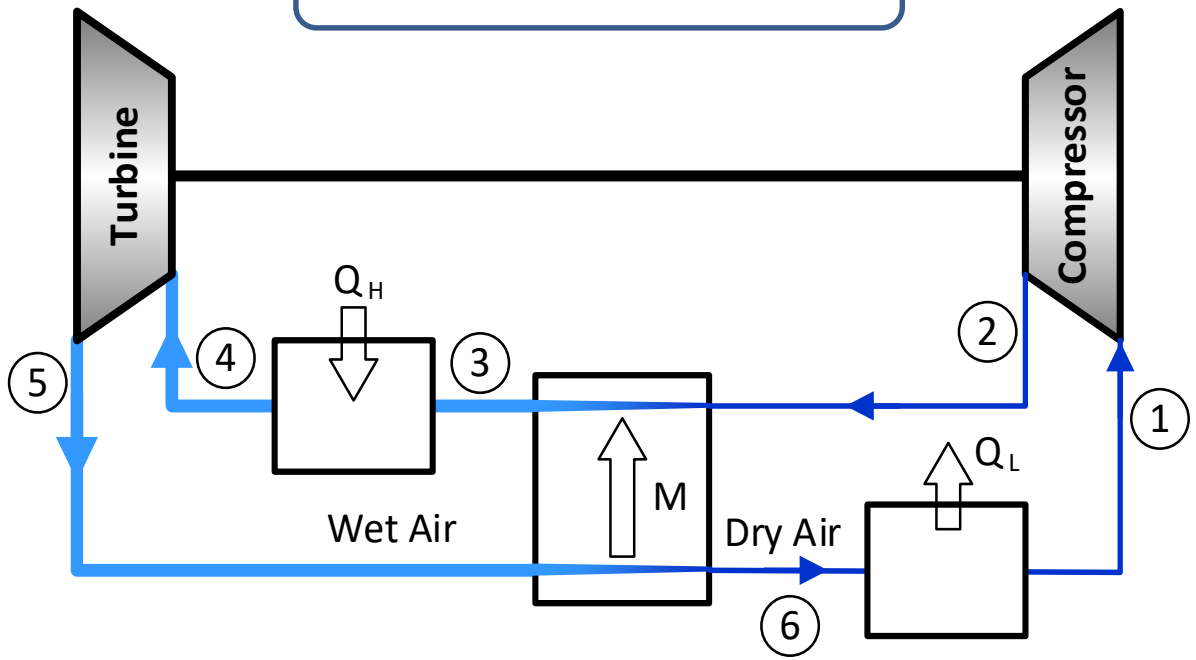


Sub-atmospheric Air Turbine Fundamentals

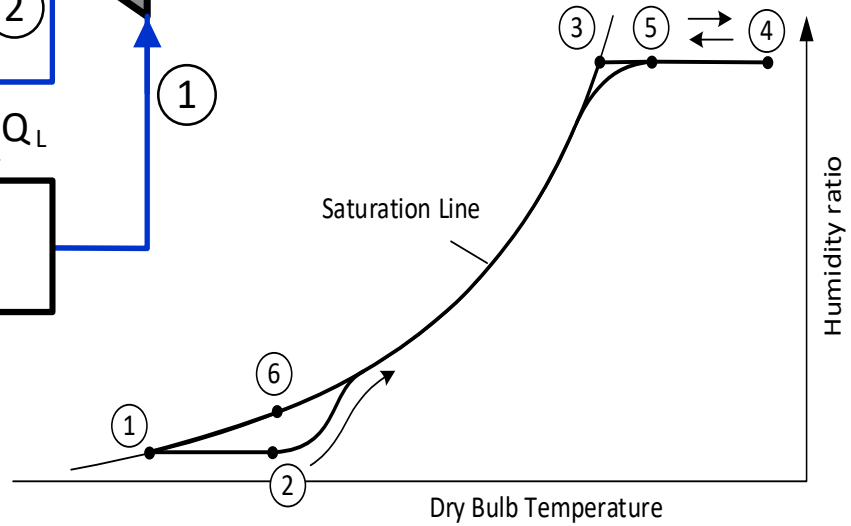
Modified Closed Brayton Cycle

P-V Chart





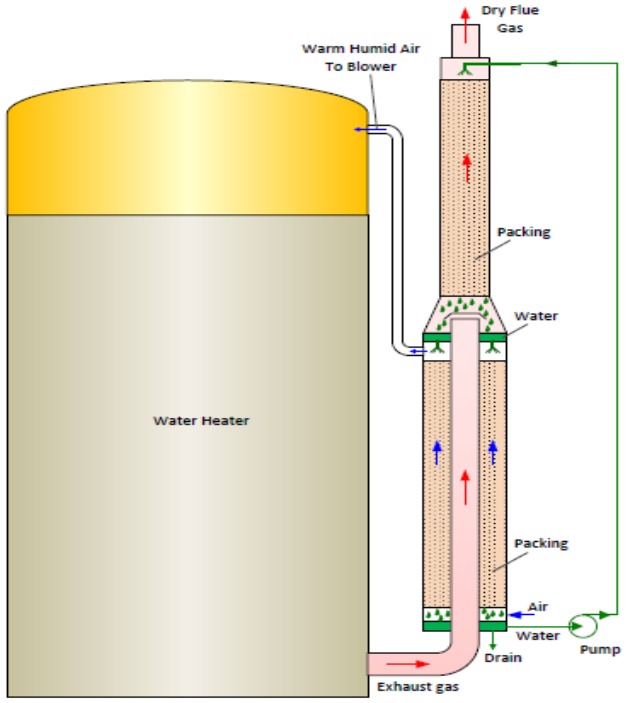
Psychometric Chart



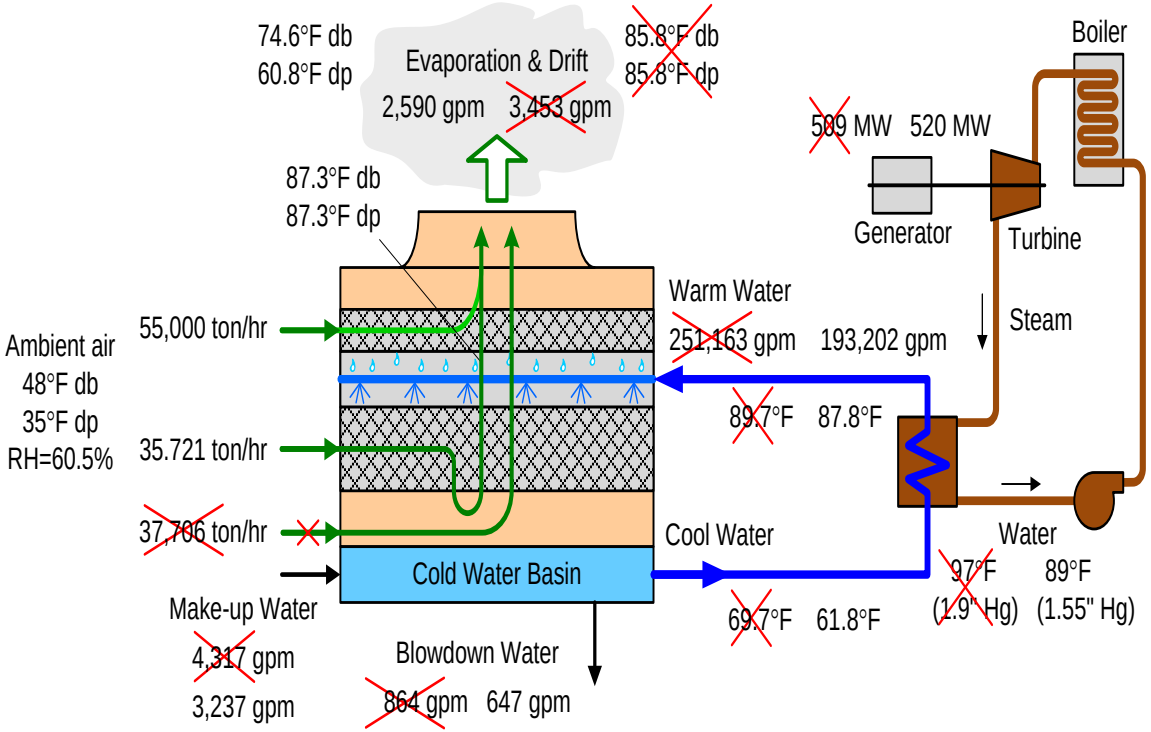
Humidification/Dehumidification

Recent Humidifying Regenerator Projects

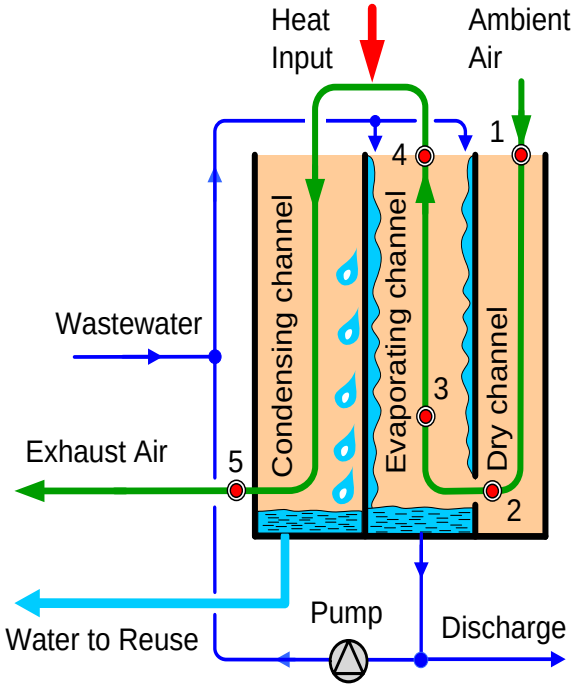
Condensing Humidified Air Recuperator



Dew Point Cooling Tower



Water Recovery and Re-Use



Scope of Work

	Task/Subtask Description	Q3-2018	Q4-2018	Q1-2019	Q2-2019	Q3-2019	Q4-2019
Task 1	**Project administration**						
S1.1	Project management and communication						
S1.2	Project review and reporting						
Task 2	**Market analysis and fuel spectrum for MHHE**						
S2.1	Application assessment and market penetration						
S2.2	Primary and alternative fuel use						
Task 3	**MHHE conceptual design and characterization**		2018 UTSR				
S3.1	Refine MHHE integrated layout						
S3.2	MHHE thermodynamic analysis and modular performance						
S3.3	MHHE operating regimes and components specification						
Task 4	**Path to Phase II**						
S4.1	Technology maturation plan for pre-commercial testing						
S4.2	Phase II budget estimate and planning						

> Red triangles – milestones/reviews

Present Status

- **Task 1 – Project management and planning** - *ongoing*
- **Task 2 (Subtask 2.1): Market assessment** - *completed*
  - Potential market: power plants, distributed power generation, coal gasification stations
  - MHHE unit size: 500kW – 60MW (unit size >30MW requires two RICEs and one air turbine)
  - Competitive to RICE and gas turbine power generation technologies
  - Ultra-low emissions to meet strictest requirements (CARB 2007) are achievable
- **Task 2 (Subtask 2.2) Fuel spectrum analysis** – *completed*
  - MHHE is capable to operate within a wide spectrum of gaseous fuels including natural gas, coal derived syngas gas, hydrogen, biogas, etc.
- **Task 3** – *in progress*
  - Optimal regimes and parameters of the hybrid engine cycle are preliminary evaluated
  - Discussions with major RICE OEMs is initiated (turbine OEM is underway)
  - Concept layout to be refined, if needed, upon selecting the best RICE candidate for MHHE

Preliminary Results (work in progress under Task 3): Thermodynamic and economic analysis

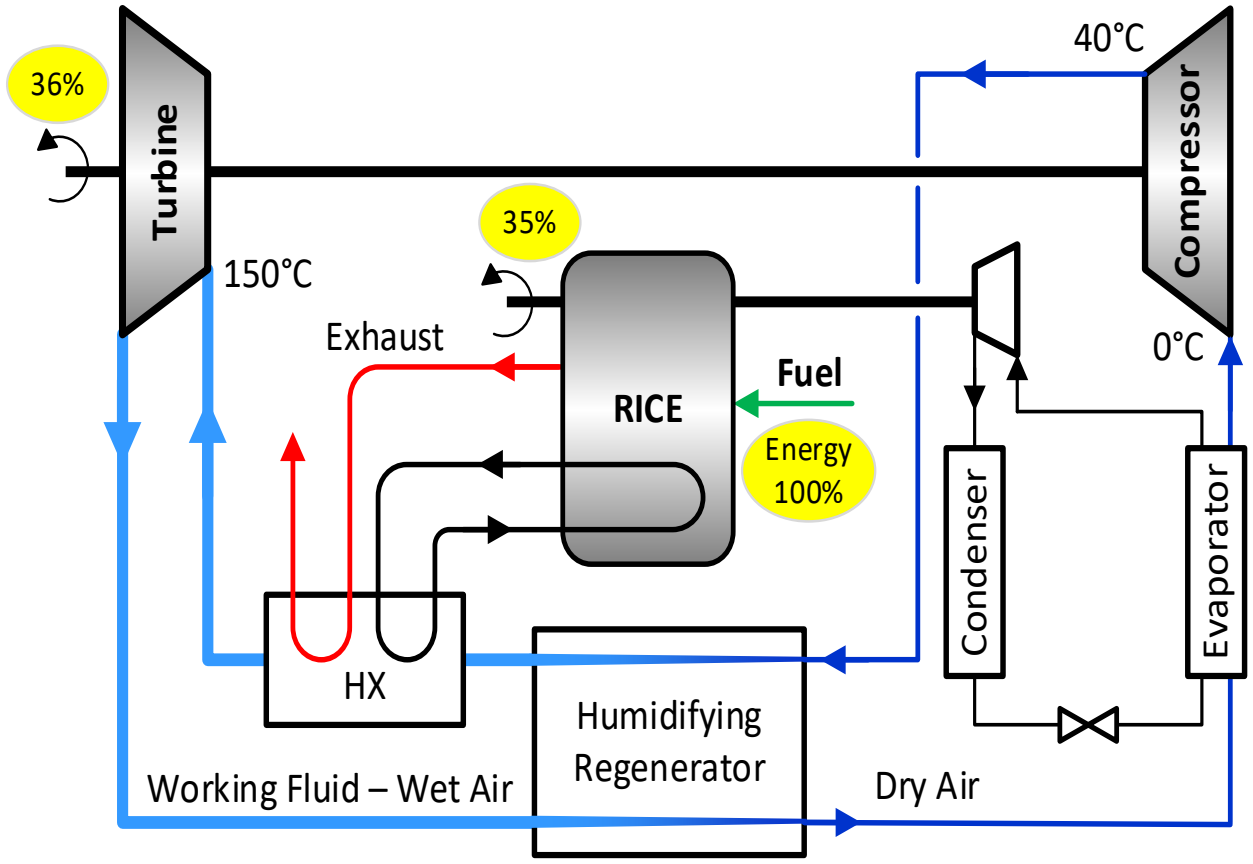
> Performance estimate:

- Output power: 500kW-60MW
- Turbine cycle efficiency: up to 90%
- RICE efficiency: 35-45%
- Total efficiency: >65%

> CapEx estimate:

- Turbine/compressor: 100-500 $/kW
- RICE generator: 900-1,650 $/kW
- Regenerator: 70-300 $/kW
- MHHE: 660-1,440 $/kW

  (lower cost potential for mass production)



Upcoming Plans

- **Task 3 scope to be continued:**
  - RICE candidate selection based on OEM evaluation (Q4-2018)
  - Concept layout adjustment as per selected RICE model (Q4-2018)
  - Characterize and specify the key MHHE components (Q1-2019)
  - Conceptual design for OEM and partners review (Q3-2019)
- **Task 4 scope to be initiated:**
  - Perform cost/benefits analysis and technology maturation plan (Q3/Q4-2019)
- Phase I completion:
  - Identify the technological gaps to be addressed in Phase II
  - Phase II budget estimate for MHHE engineering, fabrication and testing
  - Topical report and application for Phase II renewal

Questions