

Turboexpander: Alternative Fueling Concept for Fuel Cell Electric Vehicle Fast Fill

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Project ID # H2039

Overview

Timeline and Budget

- Project start date: 10/01/18
- Project end date: 06/01/19
- Total project budget: \$225K
 - Total recipient share: \$125K
 - Total federal share: \$100K
 - Total DOE funds spent*:
\$75K

* As of 3/01/19

Delivery Technical Barriers

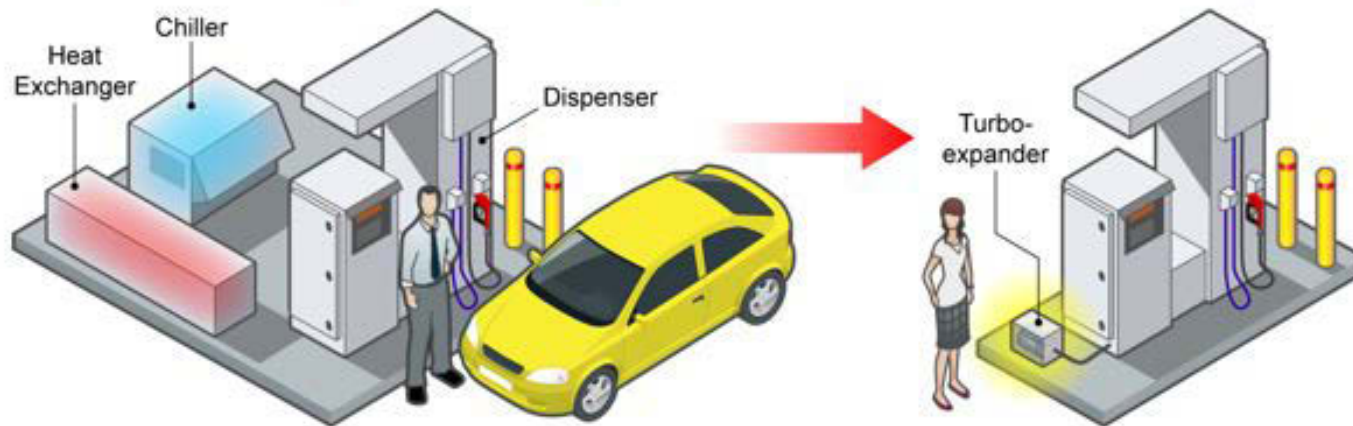
- Other Fueling Site/Terminal Operations
- Reliability and Costs of Gaseous Hydrogen Compression

Partners

- Toyota Motor Sales
- Honda R&D Americas, Inc.

Relevance: Problem Statement

Problem Statement: Station precooling is energy intensive and prone to high cost of installation and operation



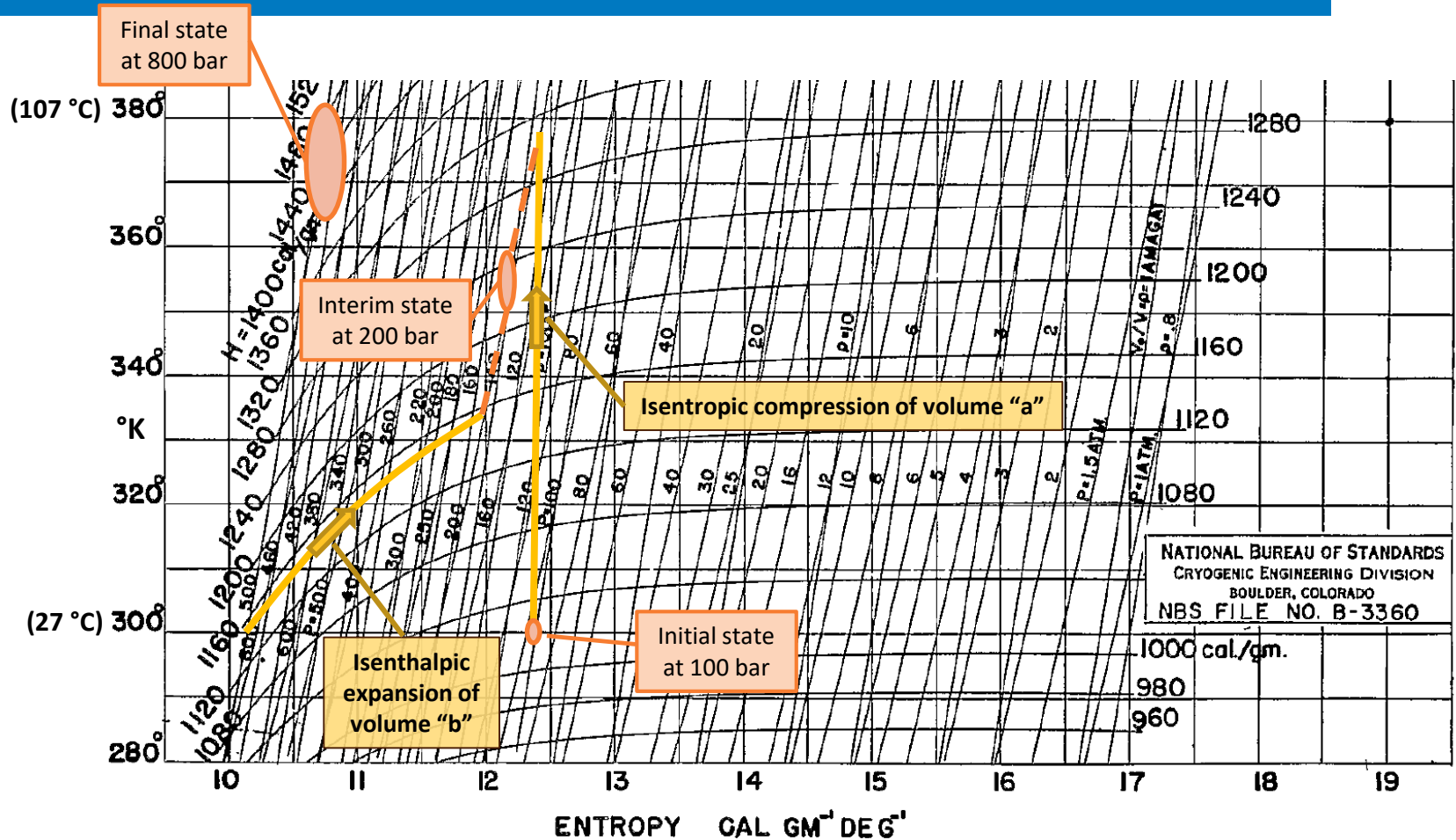
Current Technology

- NREL station: -40°C precooling system
- Control valve regulates pressure drop but induces Joule Thomson heating
- Chiller 12KW, \$130K, 26ft² footprint
- Heat Exchanger \$55K, 21ft² footprint
- Heat Transfer Fluid \$7K

Turboexpander Benefits

- Save capital & operating cost
- Minimize footprint/weight
- Improve station reliability
- Recycle percentage of pressure energy
- On demand chill down capability

Relevance: Hydrogen T-S Diagram

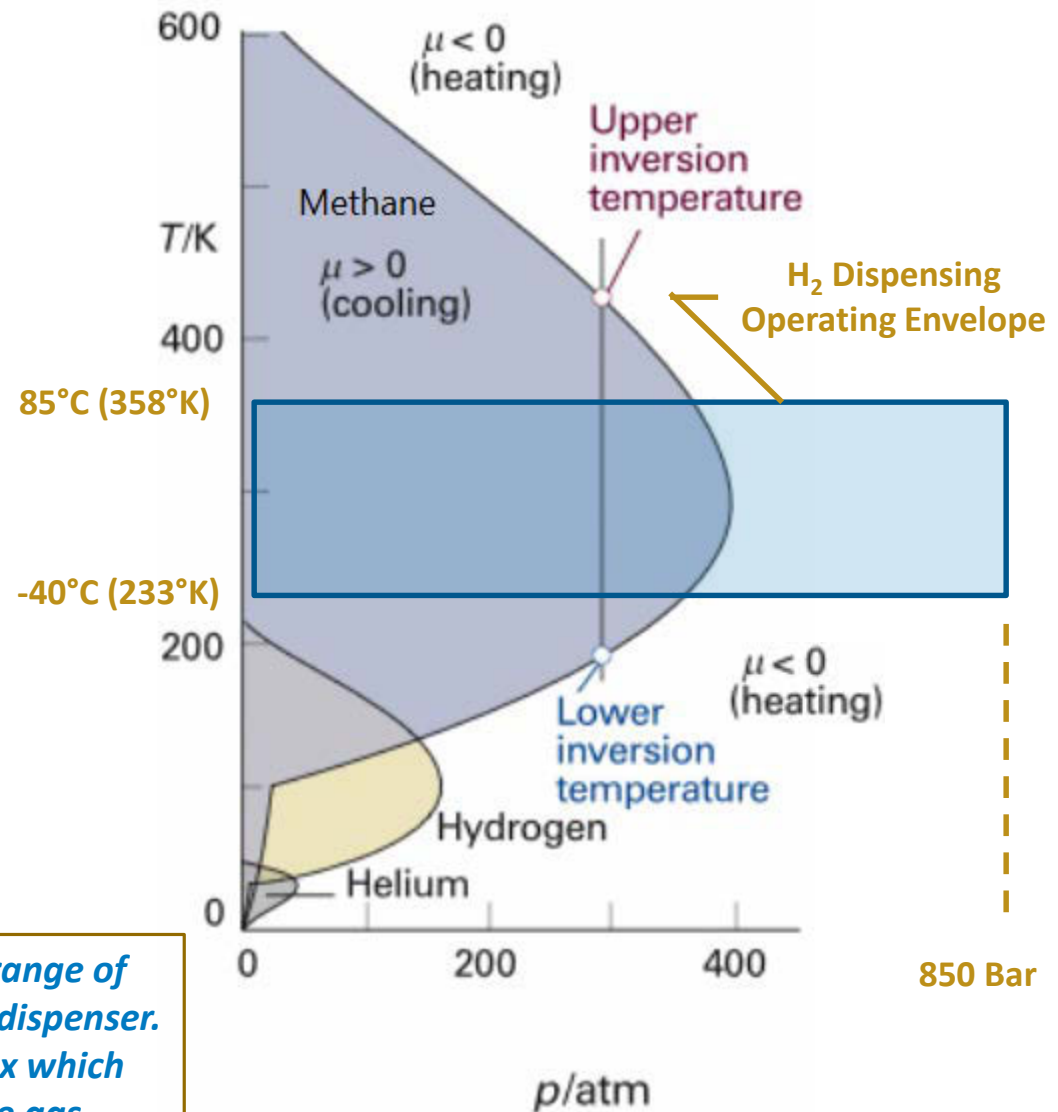


Heating of volume "a" and "b" are depicted on a T-S diagram, volumes will mix in the cylinder resulting in temperature which is "average" of the two volumes (mixing rate will depend on turbulent velocity)

Source: "Selected Cryogenic Data Notebook, Section III Properties of Hydrogen", Jensen et. al., BNL 10200-R, Revised August 1980

Relevance: Joule Thomson Expansion

- Joule Thomson coefficient is negative when operating within the pressures and temperatures experienced at a hydrogen dispenser ($\mu < 0$)
- Negative Joule Thomson coefficient will result in heating of the hydrogen across an isenthalpic expansion (control valve)
- Joule Thomson Effect Definition (Encyclopedia Britannica): “The change in temperature that accompanies expansion of a gas *without production of work or transfer of heat.*”



The blue box in the chart represents the range of temperatures and pressures in a hydrogen dispenser. Hydrogen is completely outside of the box which means a control valve will only heat the gas.

Relevance: Temperature Rise Effects – Comparison to CNG Compression Heating

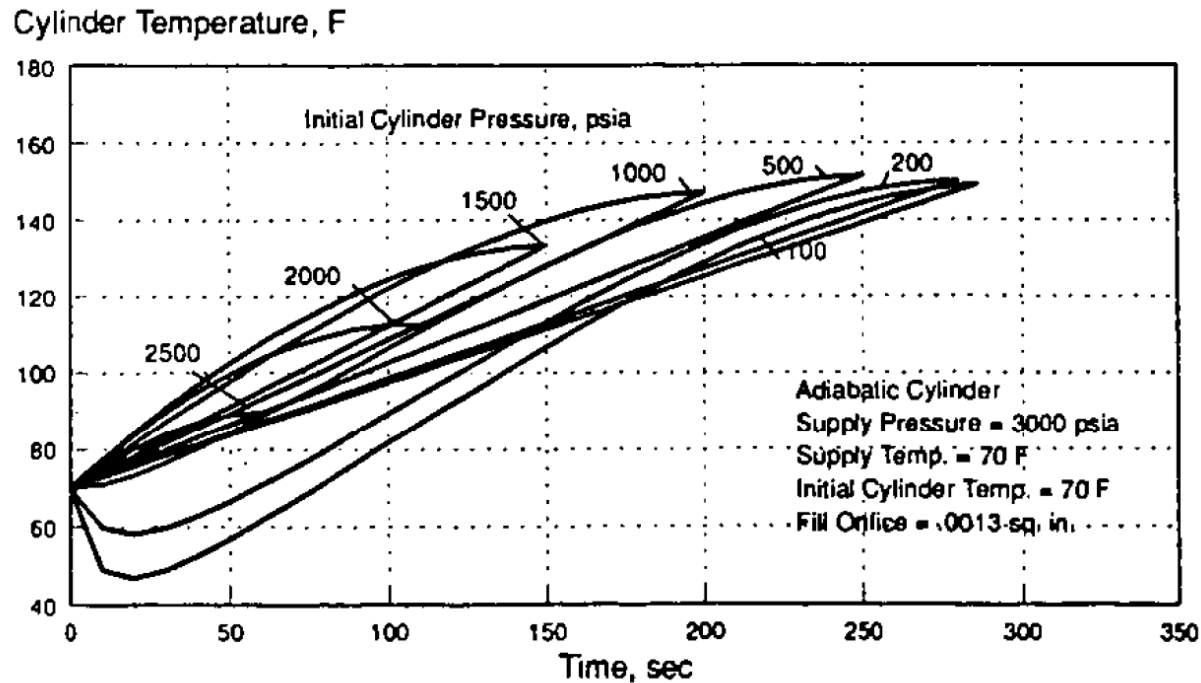


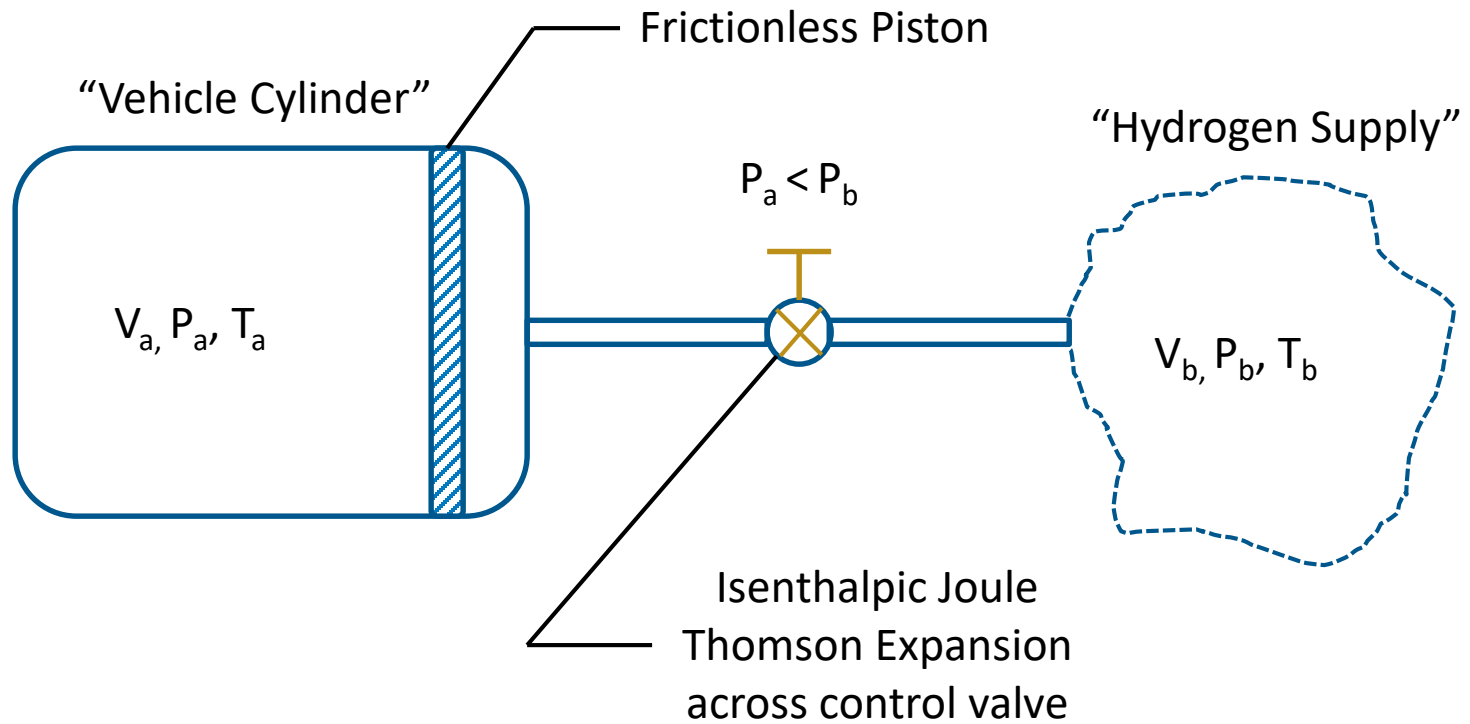
Fig. 4 Temperature in a 10"x50" Aluminum cylinder during a 3000 psia charge

CNG fast fill fueling shows a temperature rise under most conditions even though methane has a positive Joule Thomson Coefficient (i.e. cools as it expands through the control valve)

Hydrogen will heat similarly as it compresses in a cylinder and will also heat as it expands through a control valve unless work is extracted.

Source: "Modeling the Fast Fill Process in Natural Gas Vehicle Storage Cylinders", K. Kountz, Institute of Gas Technology, 1994

Relevance: Isentropic Compression & Isenthalpic Expansion

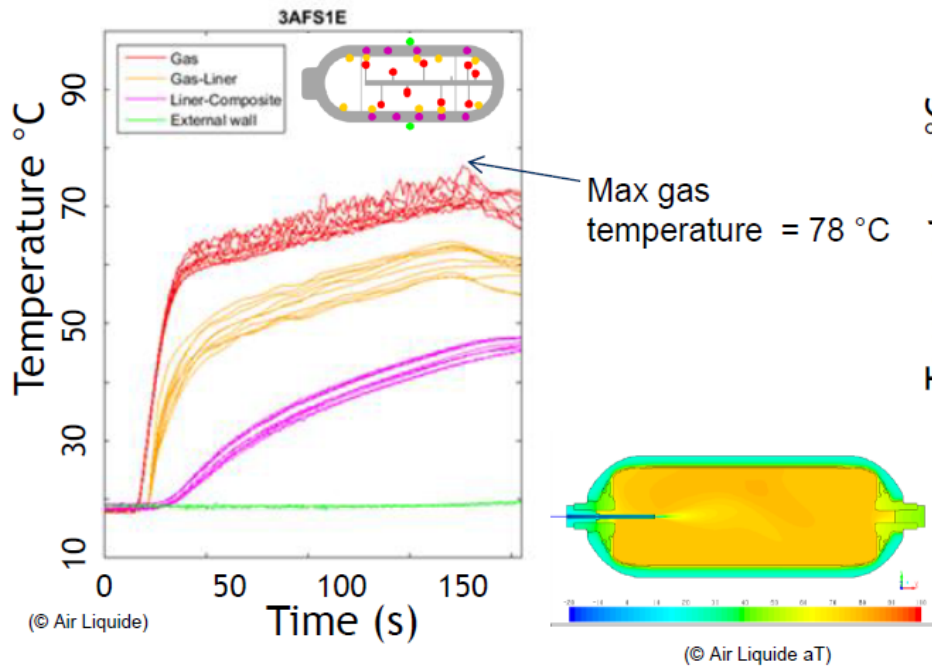


Gas in the cylinder is assumed to be undergoing isentropic compression, while the gas entering the cylinder is undergoing an isenthalpic expansion

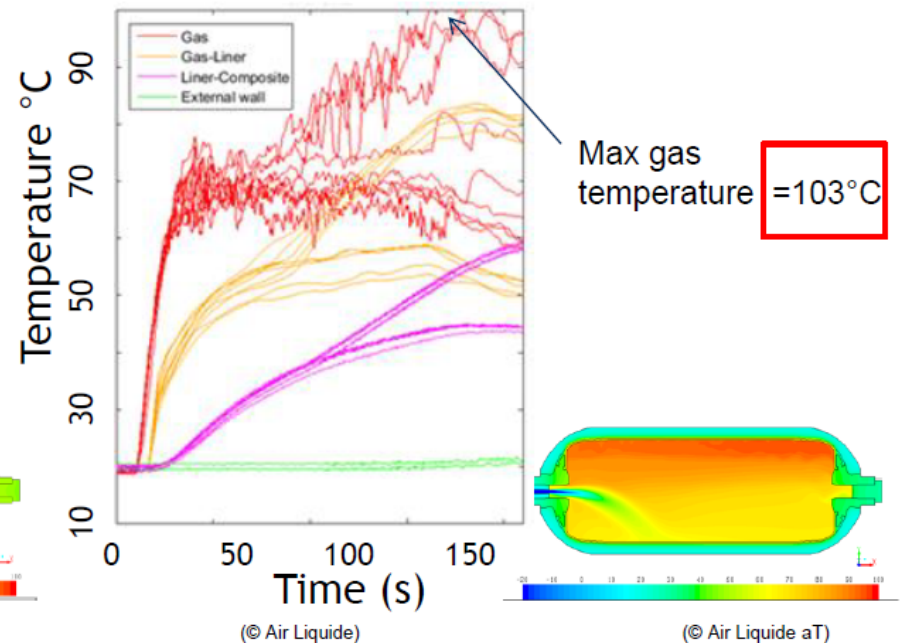
Relevance: HyTransfer Fill Temperature

- ▶ Horizontally filled tanks with H2 with a one-hole axial injector
- ▶ Type IV 36 l : 3 minute filling with Tinlet = -20°C

Injector with 3 mm
internal diameter



Injector with 10 mm
internal diameter



Ref : (Bourgeois, Brachmann et al., 2016)

Initially, gas in the cylinder heats rapidly due to 1) high ΔP across throttling valve and 2) high ΔT of isentropic compression in cylinder



Approach: Project Objectives

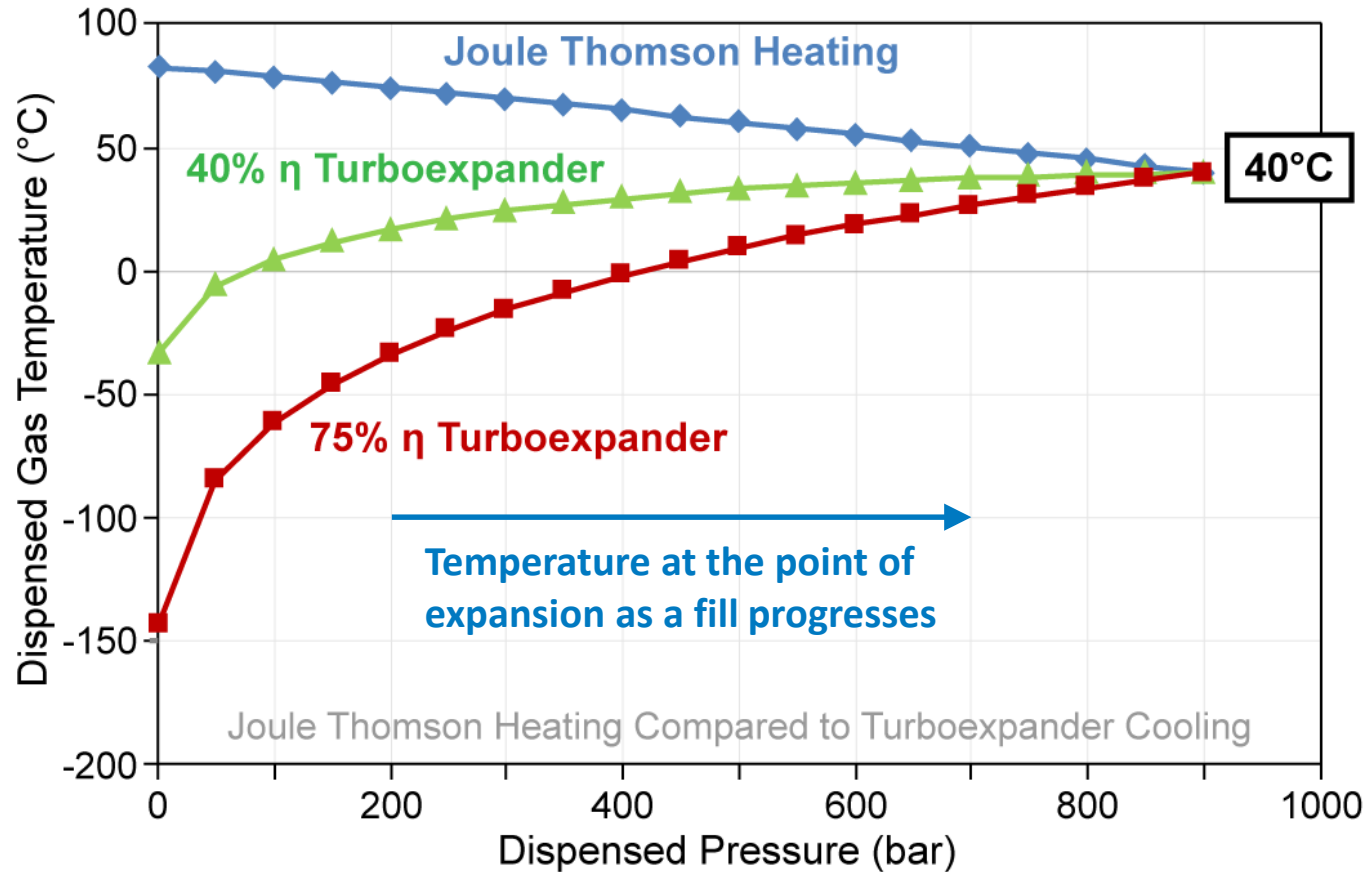
Drag Turbine Design/Build

- Proof of concept
- TRL 2 or 3
- Drag turbine type
- Efficiency is about 40% maximum
- Gas temperature can approach -40°C at the beginning of a fill
- Device is easier to manufacture
- Device is designed for testing proof of concept
- Built and tested at NREL
- Results and findings will be summarized in a report

Turboexpander Modeling

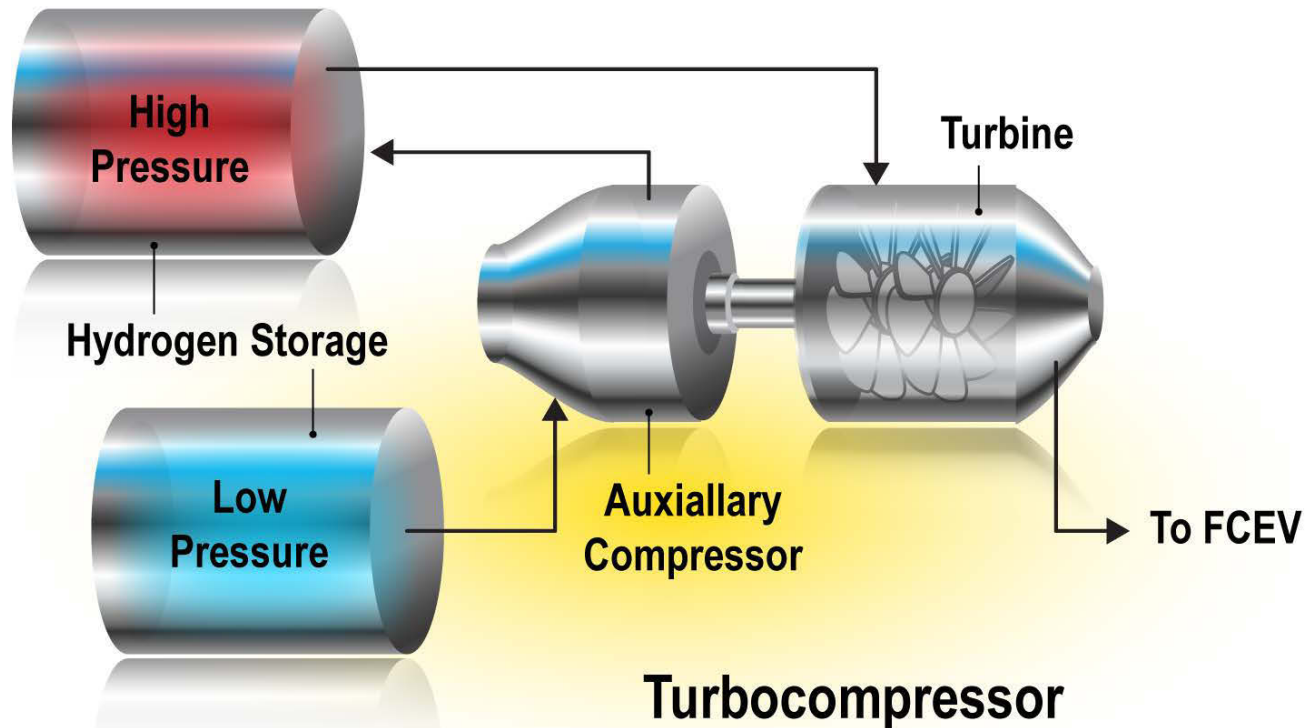
- Modeling will be integrated into NREL's Frontier Fueling Model
- A turboexpander plugin module is being created
- Module will include both drag and radial inflow turbine types
- Sizing data are being used to create the turboexpander module
- Module will be revisited after proof of concept testing
- Model will be used in further projects for sizing and design

Approach: Turboexpander Concept



At worst case 40°C ambient temperature conditions, a 40% efficient turbine (in green) is capable of achieving -40°C precooled temperatures while the currently used control valve (in blue) heats the gas to more than 80°C at the point of expansion.

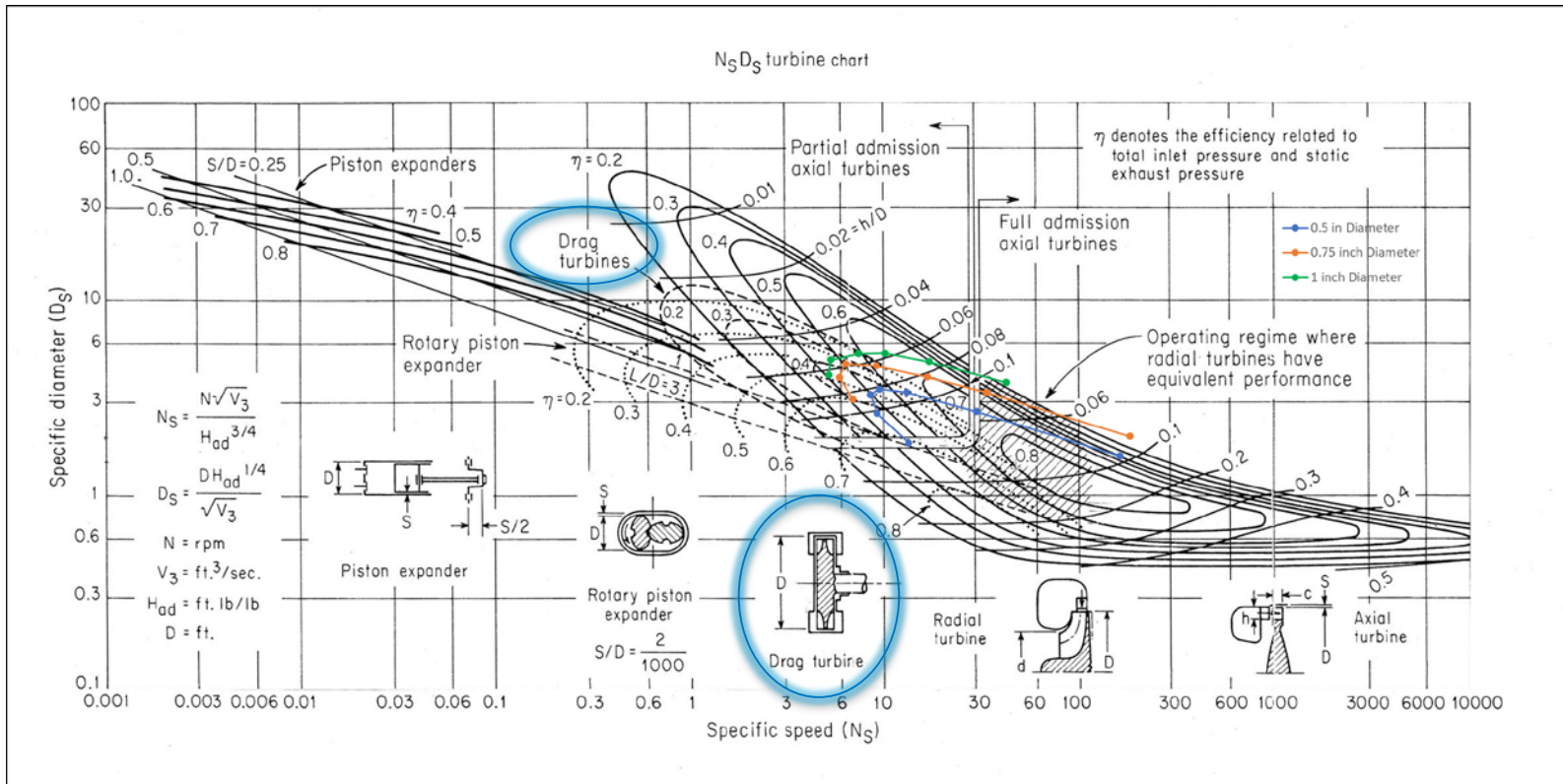
Approach: Turboexpander Concept



Turbine energy can be recovered by coupling to an auxiliary compressor which may show system level improvements over an electric generator power recovery concept

Accomplishments: Drag Turbine Selection

Using the $N_s D_s$ turbine chart, a drag turbine design (circled) was selected for the proof of concept project



Blade Diameter = 0.75 inches

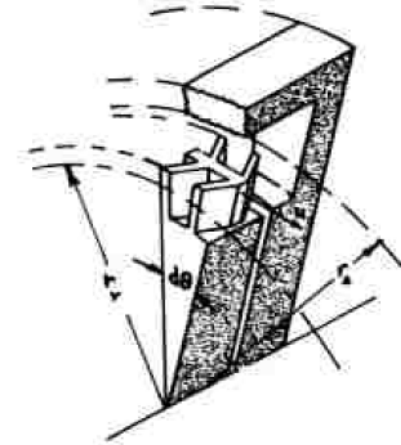
Spin Speed = 200K RPM

Source: "How to Select Turbomachinery For Your Application",
K. Nichols, Barber Nichols

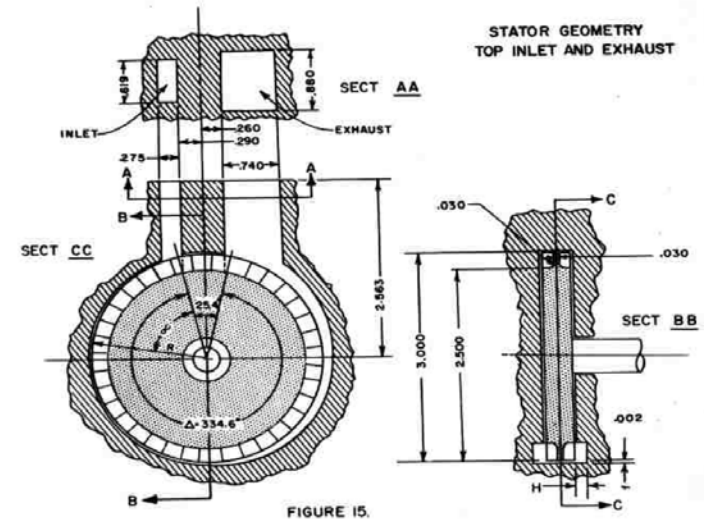
Three diameter sizes were overlaid on the selection diagram under the conditions that would be found in a dispenser

Accomplishments: Drag Turbine Sizing

- Inlet Nozzle
 - Gas inlet speed needs to be 5x the tip velocity of the blade
 - Nozzle sizes were identified and can be changed as needed
- Ball Bearings
 - NREL is working with a ball bearing manufacturer
 - Off-the-shelf bearings will be used and sent back for analysis
- Shaft Sizing
 - Shaft diameter was calculated based on expected torque
- Housing Material Selection
 - 1/8 Hardened Cold Worked 316L Stainless steel was selected
 - Material is often used in high pressure hydrogen applications
- Machining Tolerance
 - Critical tolerances will be machined to 0.002 inch tolerance



Flat blade design

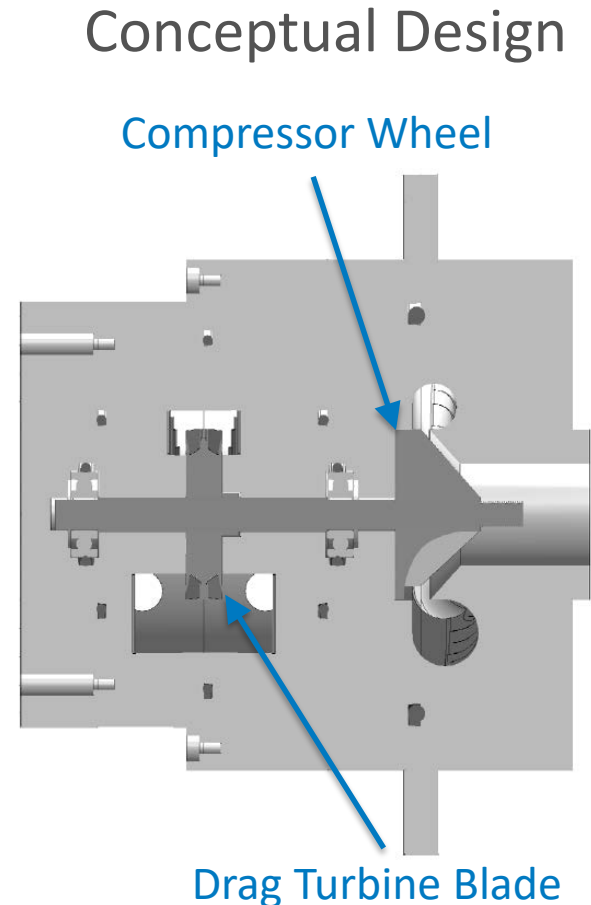


Flow path volume increases allowing expansion of the fluid

Image Source: "Study of Turbine and Turbopump Design Parameters. Volume II. A Study of High Pressure Drag Turbines Using Compressible Fluids. Final Report for Period February 1, 1958 through January 30, 1960", R. Spies, Sunstrand Turbo, 1960

Accomplishments: Drag Turbine Loading

- A turbine needs a load to function properly and can be removed as:
 - Electricity
 - Pressure
 - Heat
 - Motion
- The project utilizes a compressor wheel on the same shaft to add a load by building pressure.
- An electric generator load was considered, but a high pressure and high speed feedthrough is required and may be a future consideration.



Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

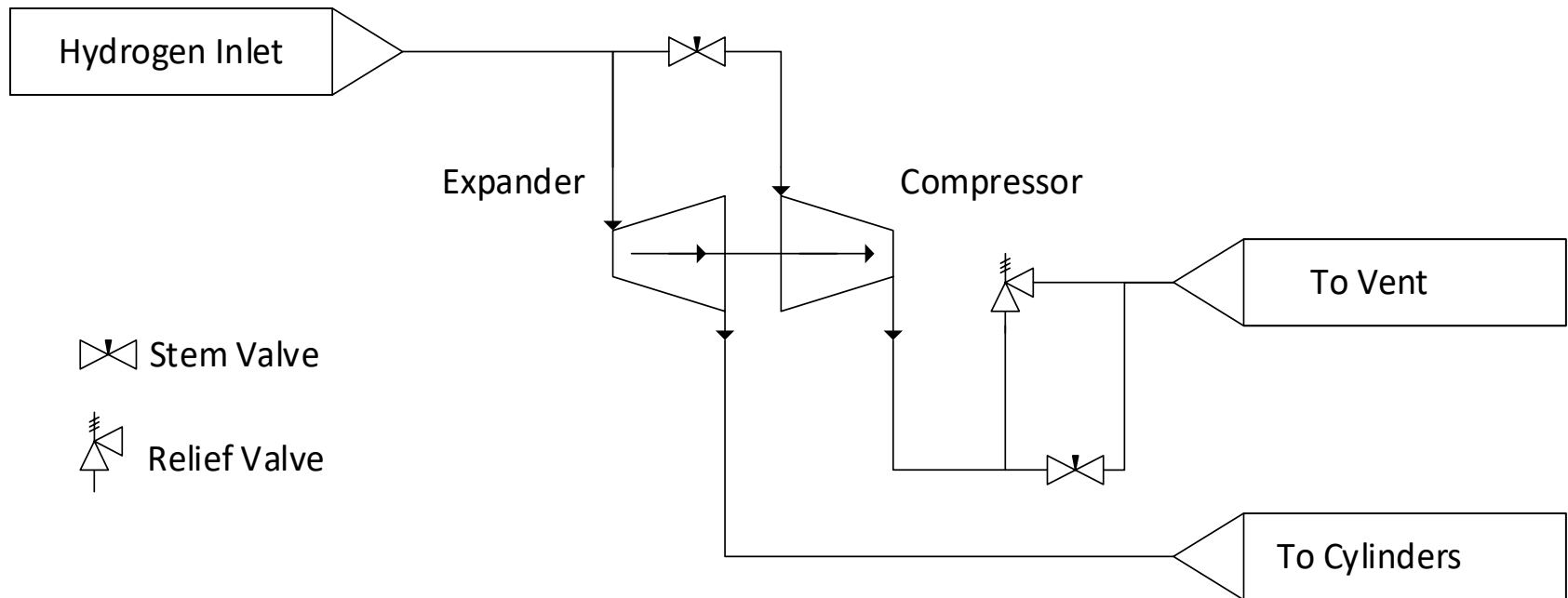
- This project was not previously reviewed.

Collaboration and Coordination

Institution	Role
<u>National Renewable Energy Laboratory</u> Matthew Post, Daniel Leighton	Project coordination, design/build and modeling of a turboexpander device, and testing the device
<u>Toyota Motor Company</u>	Cost share partner for the design/build portion of the project
<u>Honda R&D Americas, Inc.</u>	Cost share partner for the modeling portion of the project

Future Work: Test Installation

- The turboexpander device will use a compressor wheel on the same shaft as the turboexpander to supply a load.
- Both the expander and compressor sides of the device will be supplied with the same pressure to minimize cross flow of hydrogen.
- Valves on the outlet of the compressor side will control the load applied to the turboexpander and can be varied for testing.



Future Work: Test Installation

- NREL will test performance of the turboexpander using the Flow Meter Benchmarking Apparatus.
- Equipment is rated for dispenser pressure and has pressure control valves found in dispensers.
- Test stand has temperature and pressure measurement at four points in the flow path.
- The cooled hydrogen fills into cylinders with temperature and pressure measurement capability.



Summary

- A turboexpander is capable of cooling pressurized hydrogen gas as it drops in pressure from the station supply
- NREL was awarded a project under the DOE CRADA Call to investigate the performance of a turboexpander device
- NREL has designed and is building a proof of concept device
- A drag turbine will be used in this project
- Test results will be published and will be used in future projects
- A successful project will bring the technology to TRL 2 or 3
- Separate FOA Project Awarded:
 - NREL and SNL have partnered with Creare LLC for the design/build of a lab scale system validation device
 - NREL will test the device and report on the results
 - A successful project will bring the technology to TRL 4 or 5

Thank You

www.nrel.gov

NREL/PR-5400-73527

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Technical Back-Up Slides

Concurrent Projects: Project Objectives

CRADA Call Project

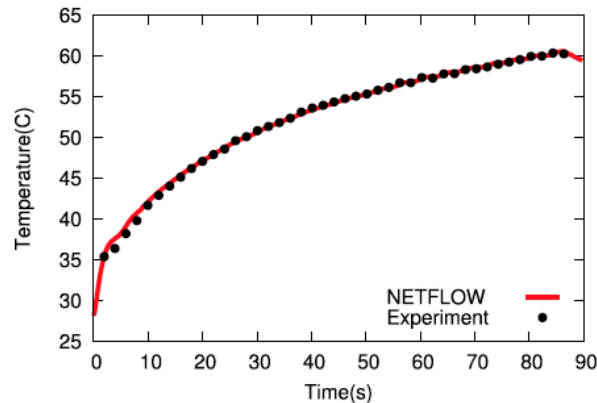
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- Modeling at NREL will focus on system level integration

FOA Project

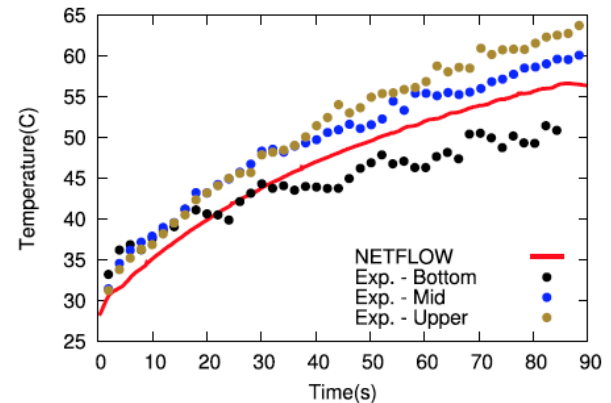
- Laboratory scale system validation
- TRL 4 or 5
- Turbine type to be determined
- Efficiency can approach 70%
- Gas temperature can be much lower than -40°C
- Device is more complex
- Device will address issues of dispenser installation
- Built at Creare and tested at NREL
- Modeling at Sandia will focus on ultimate heating of the cylinder

Concurrent FOA Project: Sandia Modeling

MassTran, developed at Sandia National Laboratories, will be used to model the tank filling and will inform the turboexpander design efforts.



*Left: Comparison of measured and computed gas mass-average temperatures.
Right: Comparison of measured and computed interior wall temperatures.*

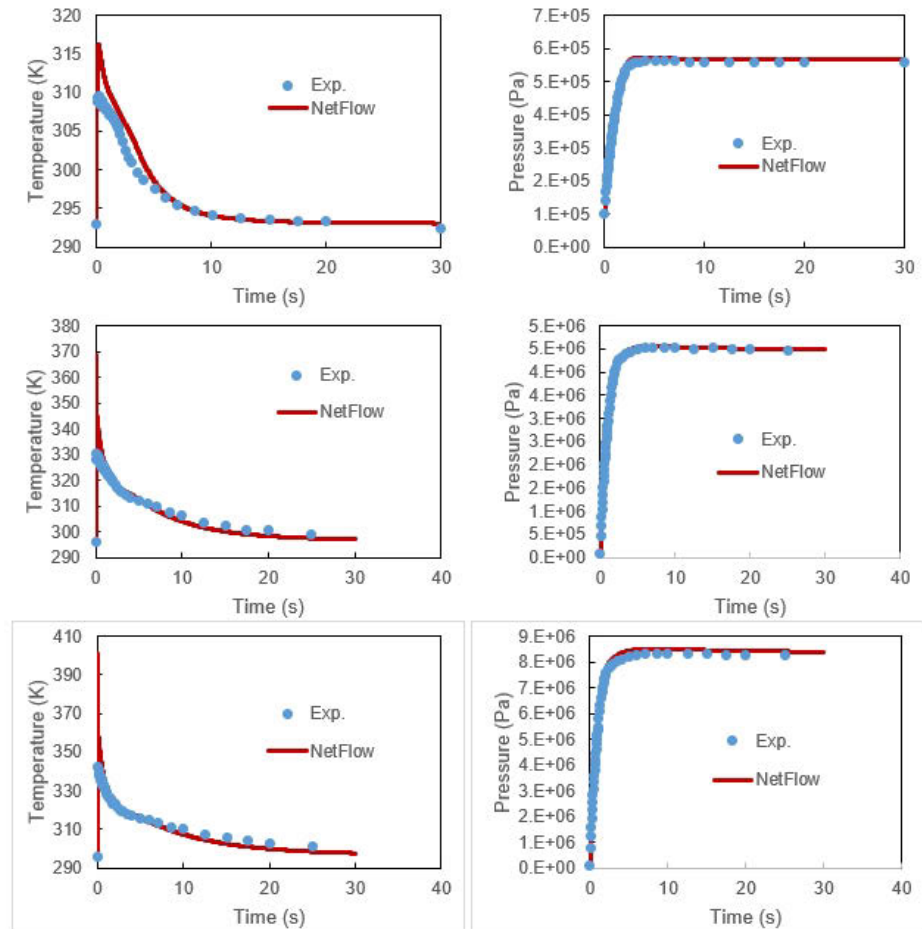


- MassTran tank filling model and previous validation efforts were reviewed
- Validation needs were assessed and it was determined that the NetFlow wall conduction model needs to be added to MassTran

Concurrent FOA Project: Sandia Modeling

Next steps for Sandia turboexpander modeling

- Incorporate the wall heat transfer model into the MassTran package.
- Implement a method to select time steps needed to avoid temperature overshooting.
- Repeat validation scenarios to ensure models can be used for temperature predictions during fast fillings.
- Validate MassTran using HySTEP data, which consists of fast filling of hydrogen tanks.
- Simulate tank heating for turboexpander supplied hydrogen (transient temperature and pressure H₂ entering tank).



Comparison of measured and computed temperature (left) and pressure (right) for a maximum pressure of 300 psi (top), 3000 psi (middle), and 6000 psi (bottom)