Development of Two-Phase Dense Fluid Expander for Advanced Cryogenic Air Separation and Low-Grade Heat Recovery

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Project Goals and Objectives

- The first objective is to better understand the limitations associated with two-phase dense fluid expansion from aerodynamic, thermodynamic, and mechanical perspectives.

- The second objective is to apply this knowledge to construct a prototype device to further explore the basic properties of two-phase dense fluid expansion.
Presentation Outline

• Background
• Methods
• Results
• Future Testing
Background
Background

• Cryogenic air separation is the state of the art technology used to supply the vast amounts of oxygen required for coal gasification

• Power needed to drive the main air compressor (MAC) in a typical air separation unit (ASU) represents approximately 70-90% of ongoing operating cost for the entire ASU

• Usage of a dense fluid expander (DFE) within an ASU allows for more efficient plant operation, and therefore less power is required to produce an equivalent amount of oxygen product

• Typically 1HP refrigeration power created by the DFE equates to 5-6HP of electrical power savings
Air Products Model ETAGG-3DF

State-of-the-art, single-phase Dense Fluid Expander (DFE)
State of the art cryogenic dense fluid expanders used in air separation are typically limited to single-phase flow (liquid in, liquid out).

A single-phase DFE design with only liquid in the discharge typically experiences very little volume change upon expansion.

A two-phase DFE may experience volume increases of up to 10 times upon expansion.

The large volume difference between vapor and liquid poses challenges to designing equipment as it relates to machine efficiency, durability, erosion, stable operation, and other performance criteria.
Background
Opportunities for Additional DFEs in ASU Applications

Pumped-LOX Cycle

- N2
- Air
- O2
- HPCOL 5.5 bar
- LPCOL 1.2 bar
- LIN Reflux
- Crude LOX

Note: Argon splits between O₂ and N₂, depending on the cycle.

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Background

- Developing a successful two-phase dense fluid expander for cryogenic air separation will open doors for additional DFE applications and overall ASU plant efficiency improvement:

  1. Run traditional DFE applications two phase leading to more efficient plant operation. Current DFE’s are back-pressured to keep discharge flow single phase.
     - Savings equal to ~0.3% of MAC electrical power = 130HP*

  2. Replacement of letdown valves with DFE’s (3-6 valves per typical ASU)
     - Savings equal to ~1% of MAC electrical power = 450HP*

  3. Waste heat recovery cycles requiring two phase DFE’s
     - Savings equal to ~5% of MAC electrical power = 2,250HP*

*varies based on plant size, numbers above reflect a 45,000HP MAC
Methods
Expander Stage Layout

- Inlet
- Scrolls
- Nozzles
- Impeller
CFD Mesh
Flow Conditions

- **Inlet**
  - Total Pressure: 1226 psia
  - Total Temperature: -275 F

- **Outlet**
  - Total Pressure: 70-200 psia

- **Rotor**
  - Spinning frequency: 19500 RPM

- **Impeller-Nozzle Interface**
  - Mixing plane

- **Energy Equation**
  - Total Energy
Modeling Techniques

Three different ways to model:

1. Incompressible flow models

2. Real gas cubic equation of state
   (Redlich Kwong, Peng Robinson, etc.)

3. Variable density and specific heat from in house thermodynamic models
1. Separate equation for density as a function of pressure for vapor and liquid phases

2. For liquid phase:
   \[0.0016 \times \text{pressure} + 46.804\]

3. For vapor phase:
   \[0.0183 \times \text{pressure} - 0.1333\]
Cavitation Model Used

- Homogenous multi-phase model
  - Both vapor and liquid phase velocity fields are same

- Interface mass transfer - Rayleigh Plesset Model
  - Saturation pressure expression as function of temperature

Rayleigh Plesset Model

Temperature vs sat pressure

Saturation Pressure (psi)

Temperature (R)
Results
## Two-Phase Flow with Cavitation

<table>
<thead>
<tr>
<th>Case</th>
<th>Total Inlet pressure (psi)</th>
<th>Total Inlet Temperature (R)</th>
<th>Total Inlet Temperature (°F)</th>
<th>Vapor Fraction (%)</th>
<th>Discharge Static Pressure (psi)</th>
<th>Total Discharge Temperature (°R)</th>
<th>Total Discharge Temperature (°F)</th>
<th>Discharge Vapor Fraction (%)</th>
<th>Isentropic Discharge Temperature (°F)</th>
<th>Isentropic Efficiency (%)</th>
<th>Isentropic Enthalpy Drop (Btu/lb)</th>
<th>Actual Enthalpy Drop (Btu/lb)</th>
<th>Massflow (lb-mole/hr)</th>
<th>Power (HP)</th>
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<td>1</td>
<td>1226</td>
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<td>200</td>
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<td>179.74</td>
<td>0.00%</td>
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<td>100</td>
<td>179.72</td>
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<td>1.32%</td>
<td>-281</td>
<td>82.50%</td>
<td>4.3</td>
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<td>11414.3</td>
<td>460.7682</td>
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<td>-282.8</td>
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<td>178.3212</td>
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<td>-287.4</td>
<td>51.20%</td>
<td>4.47</td>
<td>2.29</td>
<td>11414.3</td>
<td>297.2607</td>
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Results

Discharge Pressure vs Vapor Fraction

Discharge pressure vs Delta hs, Delta ha

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Results

Discharge Pressure vs Power

<table>
<thead>
<tr>
<th>Power (HP)</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (psi)</td>
<td>0</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>200</td>
<td>250</td>
</tr>
</tbody>
</table>

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Axial Impulse Dense Fluid Expander

- An axial impulse design has been selected for crude liquid oxygen (LOX) letdown conditions.

- Axial impulse designs have been applied in industry to various two-phase designs (steam, refrigerants), but no published information found for ASU-related cryogens.

- An expander sizing tool has been developed. The program has been tested and correlates well with published data on other two-phase designs.

- This program will be used as the basis for sizing and design of the axial impulse stage along with other established criteria for axial impulse turbine designs.
### Axial Impulse Turbine Sizing

#### Lancaster LIN Study 3600 RPM DOE 2 Phase DFE Project

**Fluid: LIN**

<table>
<thead>
<tr>
<th>Generator speed RPM</th>
<th>P1 psia</th>
<th>T1 deg F</th>
<th>P2 psia</th>
<th>T2 (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3650</td>
<td>107.5</td>
<td>-281</td>
<td>35</td>
<td>82.4</td>
</tr>
</tbody>
</table>

**Nozzle velocity =**

\[ V = \frac{\sqrt{P_{noz}}}{\sqrt{\gamma}} \]

**Discharge sizing**

\[ A = \frac{\sqrt{P_{noz}}}{\sqrt{\gamma}} \]

**Efficiency**

\[ \eta = \frac{P_{out}}{P_{in}} \]

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**Notes:**
- All data is based on ideal inlet and discharge conditions.
- Lexit is calculated using the inlet and discharge pressures.
- Thrust and power are calculated for both inlet and discharge conditions.

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**Axial Impulse Dense Fluid Expander**

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Axial Impulse 101
Axial impulse design is attractive for various reasons:

- High tolerance to two-phase mixtures both at inlet and discharge
- Slower rotor speeds – improved reliability, lower cost
- Simple and inexpensive to manufacture relative to radial inflow designs
- Low-cost installation (no lubrication system, limited monitoring/controls)
- Significant turndown achievable with impulse design through partial admission
- Ability to use off-the-shelf induction motor as basis for the unit for our application
- Potential stepping stone for multistage and axial reaction turbine stages for other applications
Axial Impulse Dense Fluid Expander

- Expected to have limited applications due to a small “sweet spot” for direct drive devices (based on Ns and Ds)

It may be possible to overcome this using high-speed generator technology and variable-speed inverters for power recovery, or dissipate electricity in its generated form and simply use as a load/brake.

- Sharp-peaked efficiency curve associated with axial impulse design means efficient turndown only through step changes in partial admission (must keep nozzle exit velocities proper to maintain relative fluid and impeller velocities).
## Results

<table>
<thead>
<tr>
<th>Application</th>
<th>Machinery Device Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste Heat Recovery from Main Air Compressor Intercooler</td>
<td>Centrifugal Expander</td>
</tr>
<tr>
<td>Crude Liquid Oxygen Letdown</td>
<td>Axial Impulse Turbine</td>
</tr>
<tr>
<td>Traditional Dense Fluid Expander in Two-Phase Operation</td>
<td>Centrifugal Expander</td>
</tr>
</tbody>
</table>
Future Testing
Centrifugal DFE Testing

- Perform full-scale testing on an existing centrifugal DFE asset located in the US (LaSalle, IL)
- Upgrade instrumentation at site to be able to accurately quantify performance of unit

Actual unit to be tested was recently at CMD for refurbishment
Centrifugal DFE Testing

Three stages of testing planned:

Stage 1 - Test the existing unit as it is currently built by moving the process into two-phase flow

Stage 2 – Test the unit with newly designed impeller, shroud, and nozzles specifically for two-phase flow using newly developed CFD model

Stage 3 – Test unit with a more significantly modified aerodynamic stage including new larger OD impeller, shroud, and new nozzle geometry using newly developed CFD model
Axial Impulse Dense Fluid Expander

- Prototype Layout Completed
  - Major components detailed and budgetary quotes received
  - Basic mechanical analysis performed

- Final aero sizing/design required
  - Finalize detailed components
  - Final mechanical analysis

- Fabrication
  - Release of components for manufacturing
  - Assembly of unit
Axial Impulse Dense Fluid Expander

Cryo Test Diagram

Express Services Pumper Truck
Controls Inlet P, T and Flow
Tank liquid capacity 3000 gal (pumper) 6000 gal (tanker)
Approx Supply Range: LIN to 700 F, 20-1500 psia,
2-85 GPM (10,000 to 490,000 SCF/Hr)

Quadrant valves allowing shut-off of 2 nozzles feeding the impeller. Allows basic capacity of expander to be adjusted in 25% increments. Due to impulse design, running in full or partial admission modes should only have a small effect on efficiency of unit.

Motor generator electrically connected to grid. Ideally may be through a 4 quadrant VFD (allows both consuming/generating operation). VFD would allow shifts in speed to explore any mismatches in velocities at nozzle and impeller interface.

Measure output power (amps)
Acknowledgement

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