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

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2017 NETL Gasification Systems Portfolio Review

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Period of Performance: October 1, 2015 – September 30, 2017

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

ID	Task Name	Start	Finish
1	**Project Kickoff**	Thu 10/1/15	Thu 10/1/15
2	1.0 Update Project Management Plan	Fri 10/2/15	Fri 11/6/15
3	2.0 Aerodynamic and Thermodynamic Analysis	Mon 1/4/16	Mon 2/22/16
7	3.0 Technical Evalution of Machinery Options	Mon 1/4/16	Mon 2/22/16
11	4.0 Equipment and Application Selection	Tue 2/23/16	Mon 3/14/16
12	5.0 Identify Potential Technical Risk Issues of Selected Device/Application Combinations	Tue 3/15/16	Mon 4/4/16
15	6.0 Aerodynamic Analysis of Two Phase Applications	Tue 2/23/16	Fri 6/3/16
17	7.0 Final Machinery Selection and Conceptual Device Design	Mon 6/6/16	Fri 9/2/16
22	**Interim Report**	Mon 9/5/16	Mon 9/5/16
23	**Decision Point**	Mon 9/5/16	Mon 12/5/16
24	8.0 Demonstration Device Design	Tue 12/6/16	Mon 3/27/17
27	9.0 Prototype Device Manufacturing and Assembly	Tue 12/6/16	Mon 7/3/17
30	10.0 Design and Construction of Testing System	Tue 3/28/17	Mon 7/3/17
33	11.0 Prototype Device Testing and Performance Evaluation	Tue 7/4/17	Fri 9/29/17
36	**Final Report**	Fri 9/29/17	Fri 9/29/17

Presentation Outline

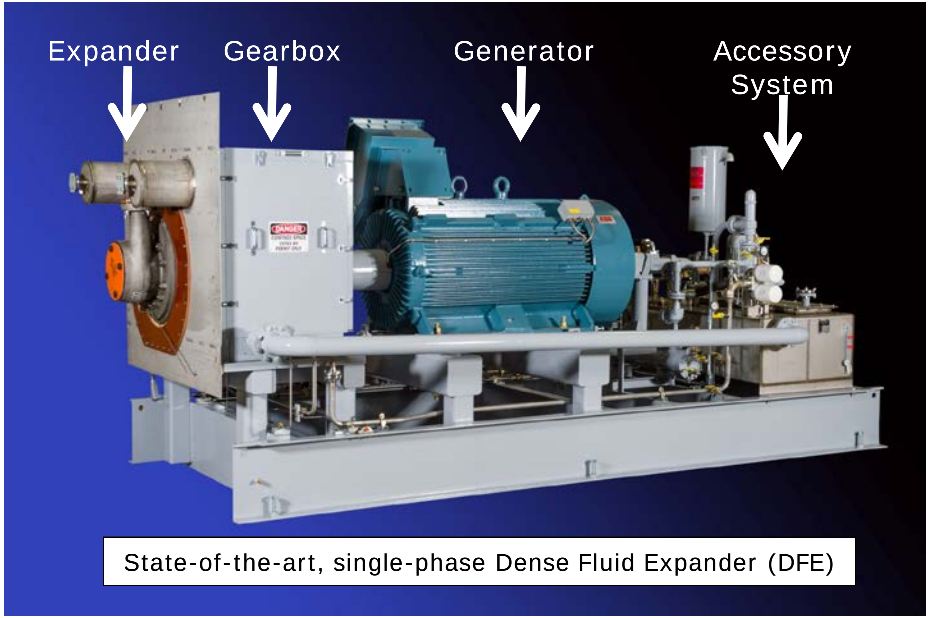
- Background
- Methods
- Results
- Future Testing

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

Background



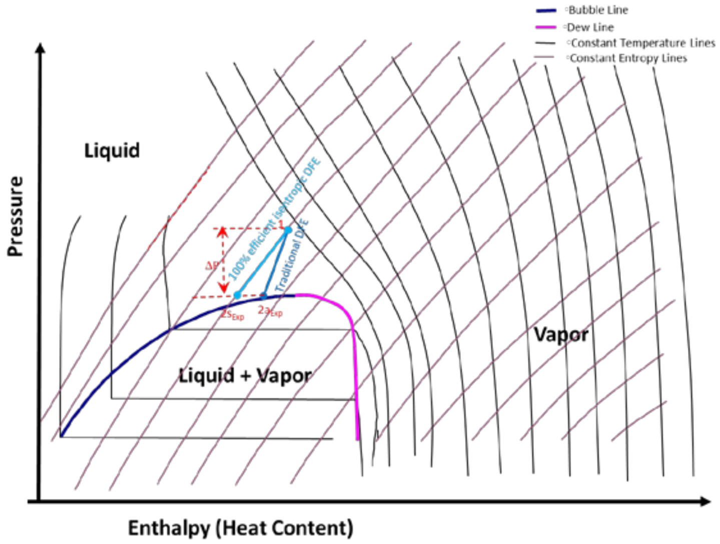
Air Products Model **ETAGG-3DF**

Background

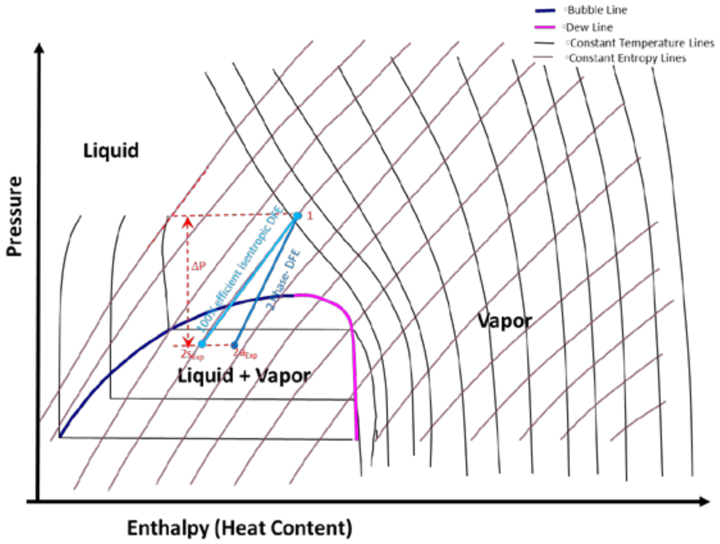
- State of the art cryogenic dense fluid expanders used in air separation are typically limited to single-phase flow (liquid in, liquid out)
- A single-phase DFE design with only liquid in the discharge typically experiences very little volume change upon expansion
- A two-phase DFE may experience volume 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

Single-Phase DFE

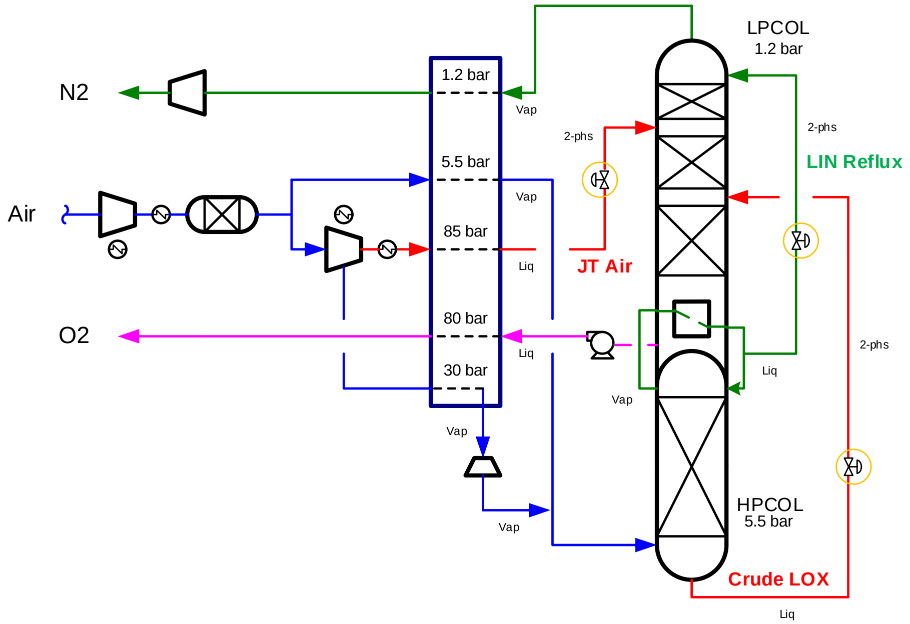


Two-Phase DFE



Opportunities for Additional DFEs in ASU Applications

Pumped-LOX Cycle



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Background

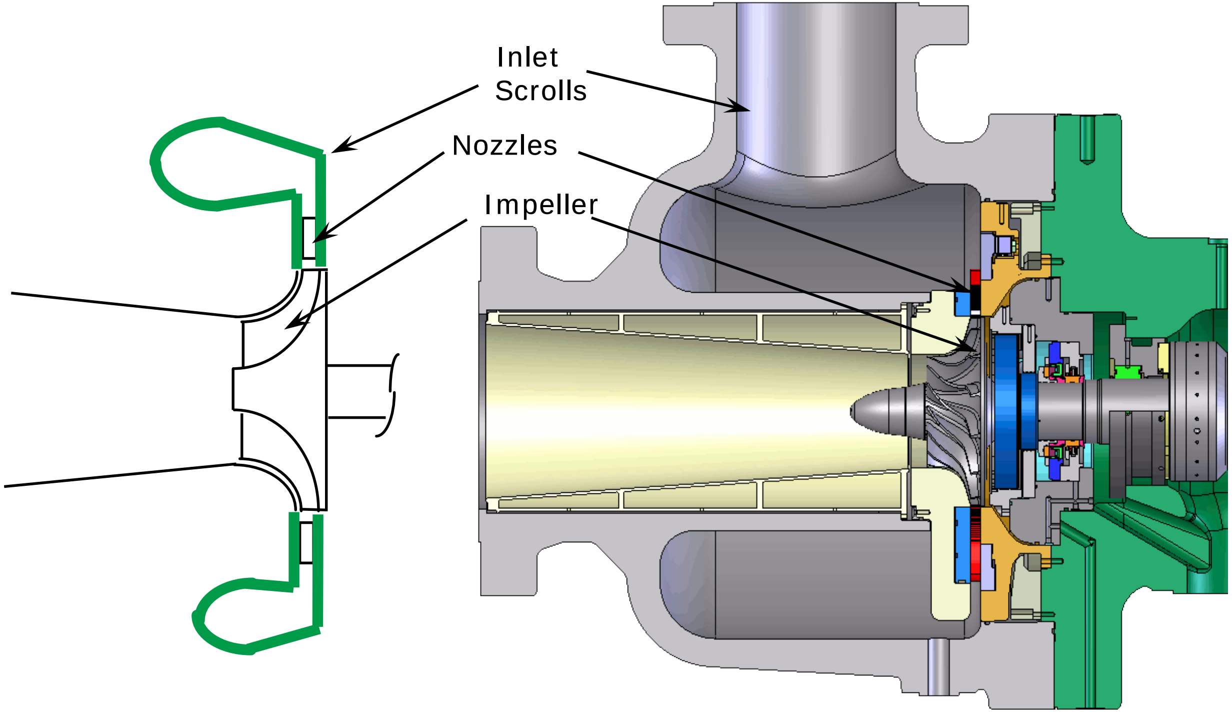
- Developing a successful two-phase dense fluid expander for cryogenic air separation will open doors for additional DFE applications and overall ASU plant efficiency improvement:

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*

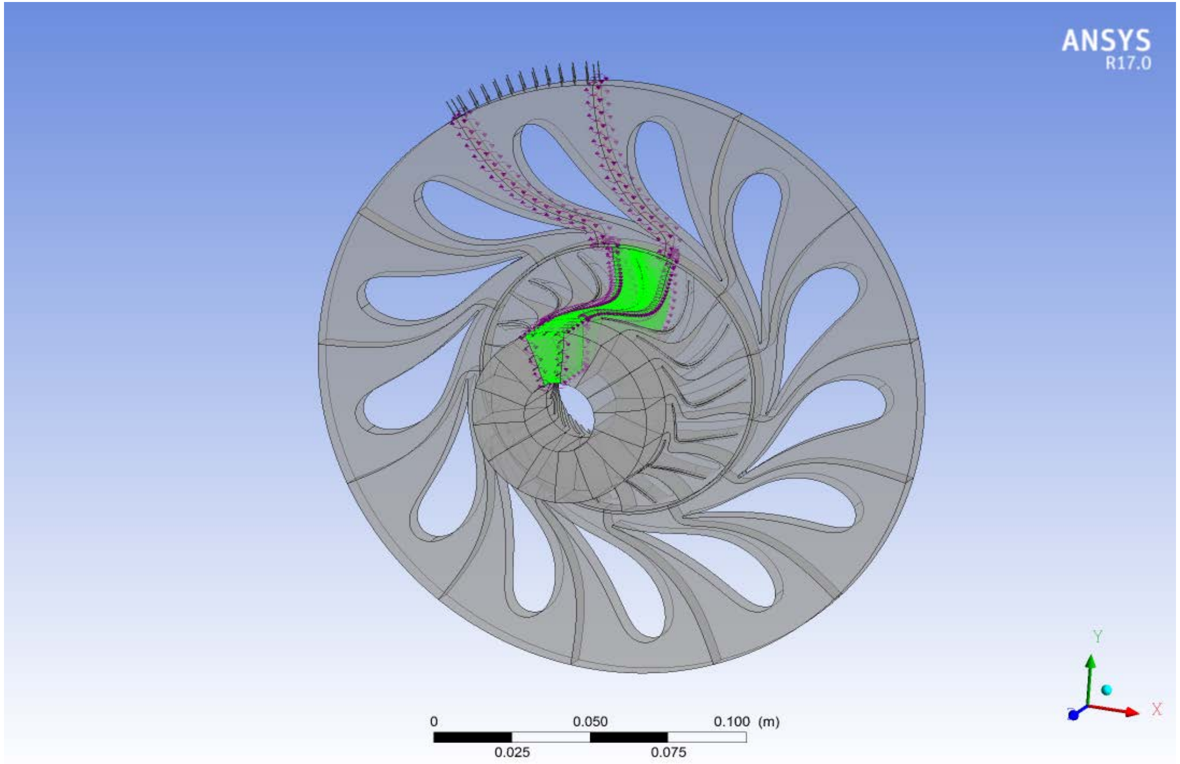
*varies based on plant size, numbers above reflect a 45,000HP MAC

Methods

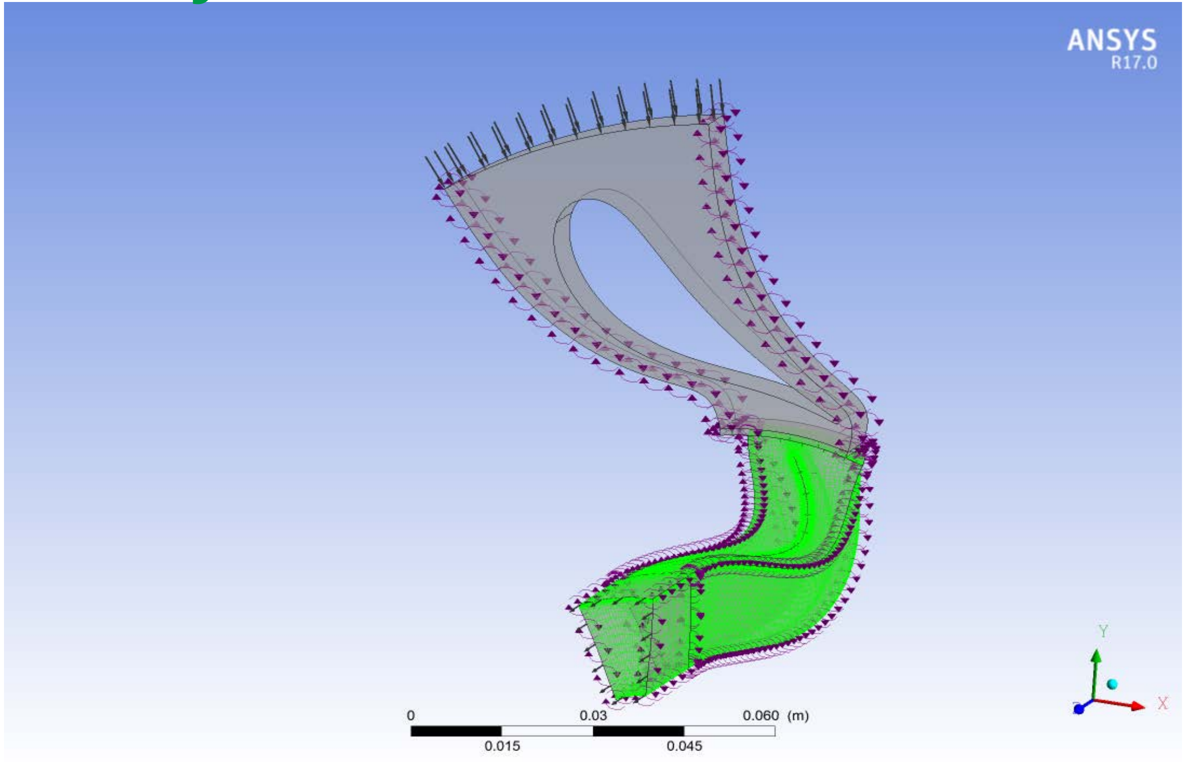
Expander Stage Layout



CFD Mesh



Sector-only



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

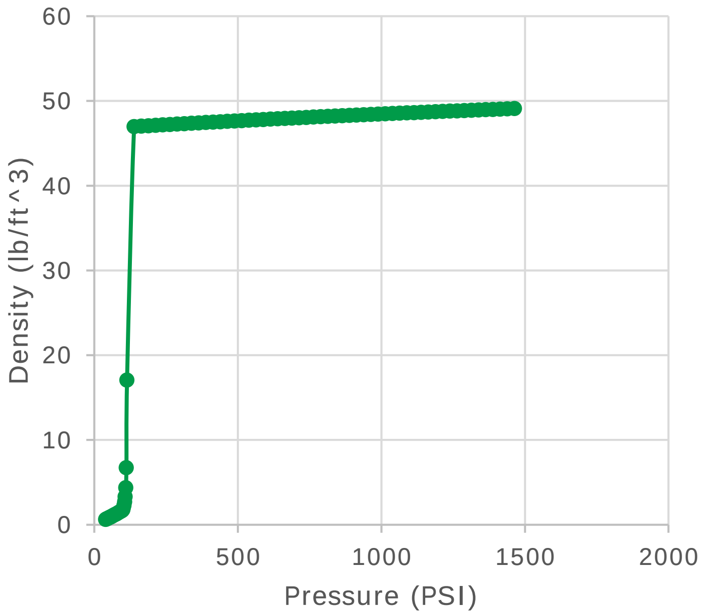
Three different ways to model:

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**

Modeling Techniques



1. Separate equation for density as a function of pressure for vapor and liquid phases

2. For liquid phase:

   0.0016*pressure + 46.804

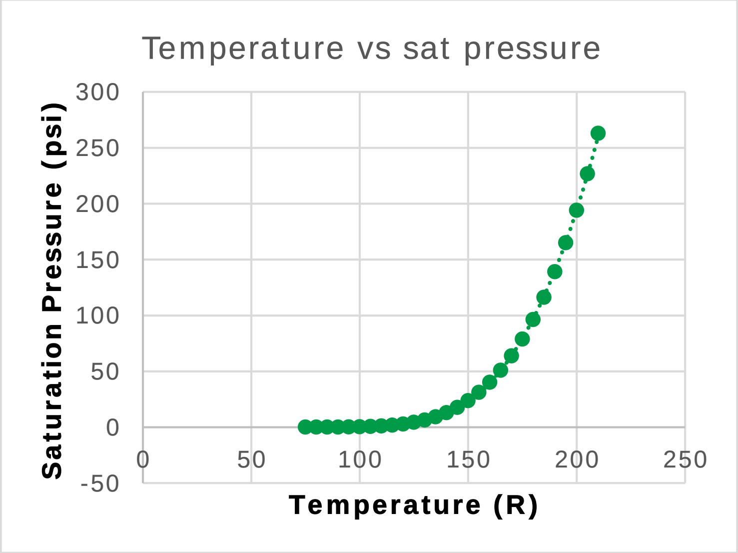
3. For vapor phase:

   0.0183*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

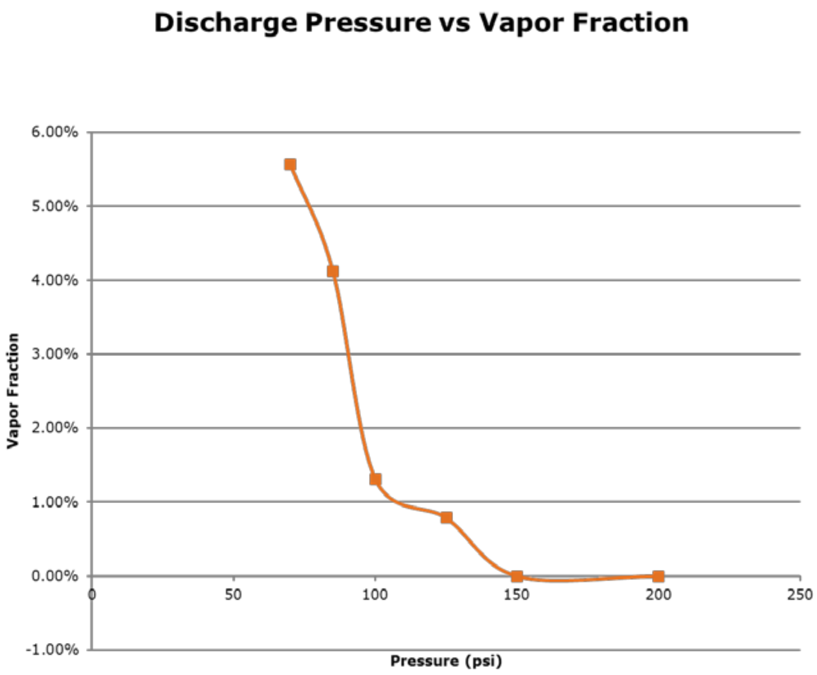


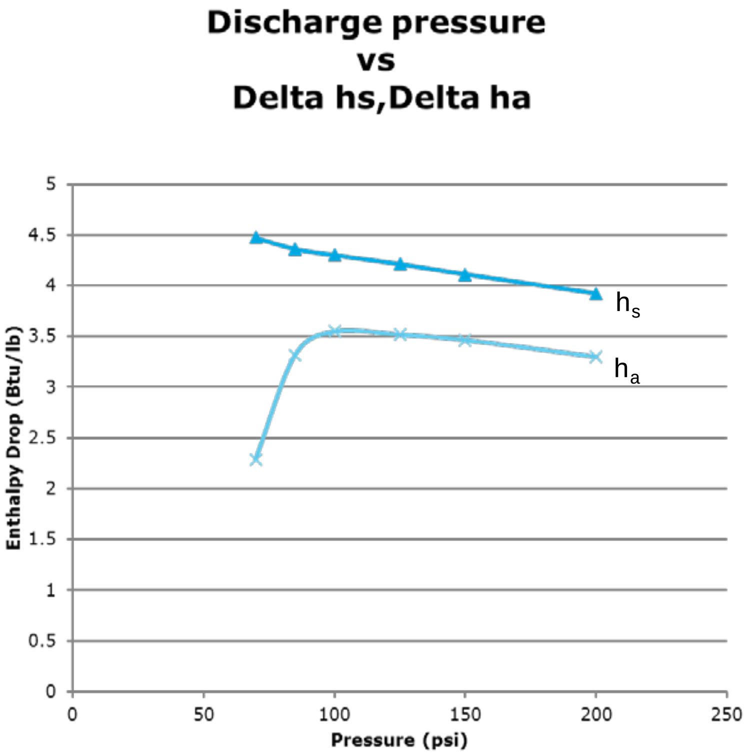
Results

Two-Phase Flow with Cavitation

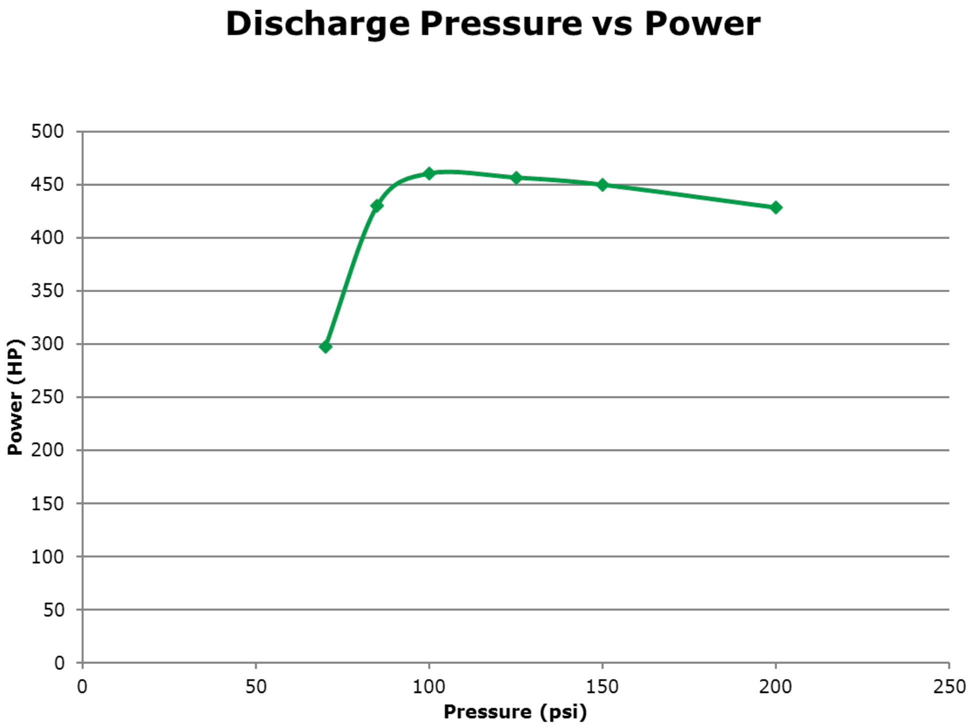
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Total Inlet pressure	psi	1226	1226	1226	1226	1226	1226
Total Inlet Temperature	R	184.67	184.67	184.67	184.67	184.67	184.67
Total Inlet Temperature	F	-275	-275	-275	-275	-275	-275
Vapor Fraction		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Discharge Static Pressure	psi	200	150	125	100	85	70
Total Discharge Temperature	R	180.04	179.78	179.74	179.72	178.74	178.3212
Total Discharge Temperature	F	-279.63	-279.89	-279.93	-279.95	-280.93	-281.349
Discharge Vapor fraction		0.00%	0.00%	0.79%	1.32%	4.13%	5.57%
Isentropic Discharge Temperature	F	-280.5	-280.8	-280.9	-281	-282.8	-287.4
Isentropic Efficiency		84.18%	84.31%	83.56%	82.50%	76.03%	51.20%
Isentropic Enthalpy Drop	Btu/lb	3.92	4.11	4.21	4.3	4.36	4.47
Actual Enthlapy Drop	Btu/lb	3.30	3.47	3.52	3.55	3.31	2.29
Massflow	lb-mole/hr	11414.3	11414.3	11414.3	11414.3	11414.3	11414.3
Power	HP	428.6121	450.0728	456.9167	460.7682	430.5332	297.2607

Results


Discharge Pressure vs Vapor Fraction
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
-1.00%
Vapor Fraction
0
50
100
150
200
250
Pressure (psi)


Discharge pressure
vs
Delta hs,Delta ha
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Enthalpy Drop (Btu/lb)
0
50
100
150
200
250
Pressure (psi)
h_s
h_a

Results


Discharge Pressure vs Power
Power (HP)
500
450
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
Pressure (psi)

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 Dense Fluid Expander

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Axial Impulse Turbine Sizing

CMD-XXXXx
Revision p1
6-Apr-16

Reference CMD-XXXX

AUTHORIZED BY:

SUBJECT MATTER EXPERT: Robert Benton

Lancaster LIN Study 3600 RPM DOE 2 Phase DFE Project
Fluid: LIN

By: R Benton Date: 20-Sep-16

					Generator speed	RPM	3650		P1	psia	107.5			
									T1	deg F	-281	-317.74		
P1	107.5	psia				Nozzle speed/blade speed	2		s1		22.44034			
T1	-281	F							P2	psia	35			
d1	43.24995328	lb/ft^3			Impeller Mean Line Diameter	inches	7		T2 ((a)diabati	deg F	-305.646			
h1	-165.456397	btu/lb			U	FPS	111.4829							
Pnoz	35	psia			flow	ft^3/s	1.881079		Mw	--	28.014		Inlet sizing	
Tnoz		F			nozzle #		8		Flow	#mole/hr	1000		647.7232	ft^3/hr
dnoz	4.136810791	lb/ft^3			α1	degrees	20		Density1	lbm/ft^3	43.24995		2	pipe dia (in)
hnoz	-165.456397	btu/lb							DensityNoz	lbm/ft^3	4.136811		8.247068	velocity (fps
Prot	35	psia		required nozzle velocity =			237.275		Density2	lbm/ft^3	0.645298			
Trot		F			Vai	FPS	237.275		enthalpy1	btu/lbmol	-4635.1		Discharge sizing	
drot	0.645298355	lbm/ft^3				Nozzle size for this velocity			enthalpy2s	btu/lbmol	-4669.2		43412.48	ft^3/hr
hrot	-166.673883	btu/lb			area	ft^2	0.001						4	pipe dia (in)
dh	1.217485722	btu/lb			area	in^2	0.143						138.1862	velocity (fps
mdot	7.781666667	lbm/s			diameter	in	0.426		Fluid	%				
dProt	0	psid			nozzle ellipse length	in	1.246		N2	100				
speed	3650	RPM			ellipse circumference	in	9.970		O2	0				
#noz	8				actual circumference	in	21.991	**OK**	AR	0				
α1	20	degrees												
β1	38	degrees		36.05238873	ideal inlet blade angle									
Vai	237.3	ft/s												
Vri	137.9	ft/s	ns	107.5681281										
Vre	128.2	ft/s	ds	1.529857182										
Fbld	50.7	lbf												
Pbld	5655.3	ft-lbf/s	power	5731.45	ft-lbf/s									
HPbld	10.3	Hp		10.42	Hp									
HPs	12.5	Hp												
Drot	7	inch												
EFFnoz	0.9585													
BladeLoss	0.93													
BladeEff	0.792			Inlet				Discharge						
Vexit	1.123981051	lbm/s		Cp_vapor	0.0000	Cv_vapor	0.0000	Cp_vapor	0.2956	Cv_vapor	0.1950			
Lexit	6.657685616	lbm/s		Cp_liquid_1	0.5488	Cv_liquid	0.1784	Cp_liquid_1	0.4962	Cv_liquid	0.1686			
TOTexit	7.781666667	lbm/s												
Thrust	0.53	lbf		gamma	3.07550989			gamma	2.710036567					

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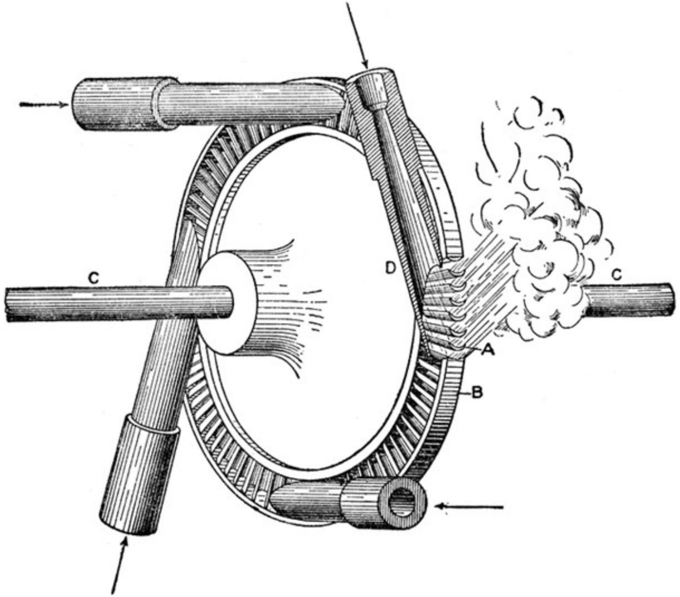
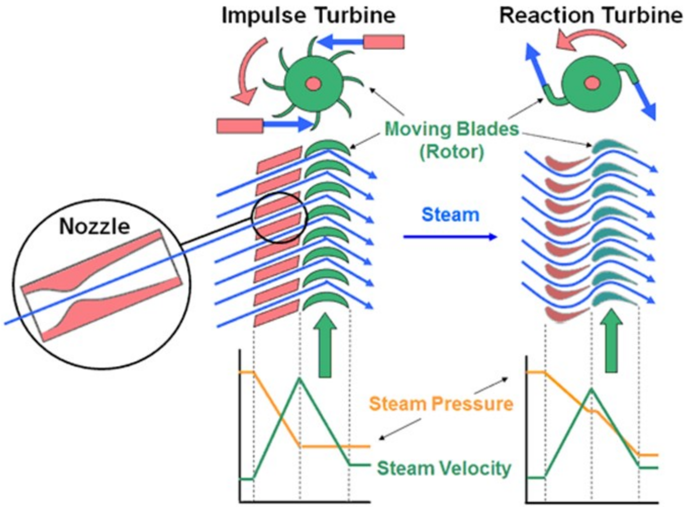
Axial Impulse 101





Axial Impulse Dense Fluid Expander

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

Application	Machinery Device Selected
Waste Heat Recovery from Main Air Compressor Intercooler	Centrifugal Expander
Crude Liquid Oxygen Letdown	Axial Impulse Turbine
Traditional Dense Fluid Expander in Two-Phase Operation	Centrifugal Expander

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 able to accurately quantify performance of unit

Actual unit to be tested was recently at CMD for refurbishment

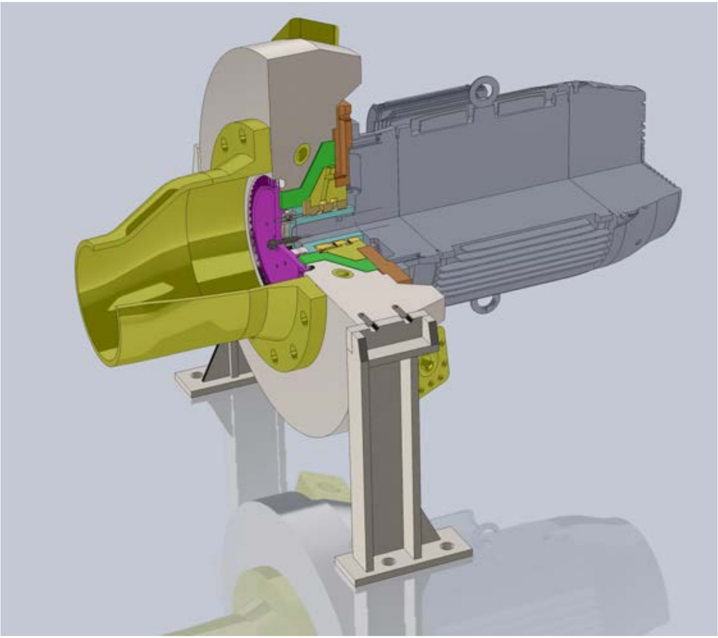
Centrifugal DFE Testing

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



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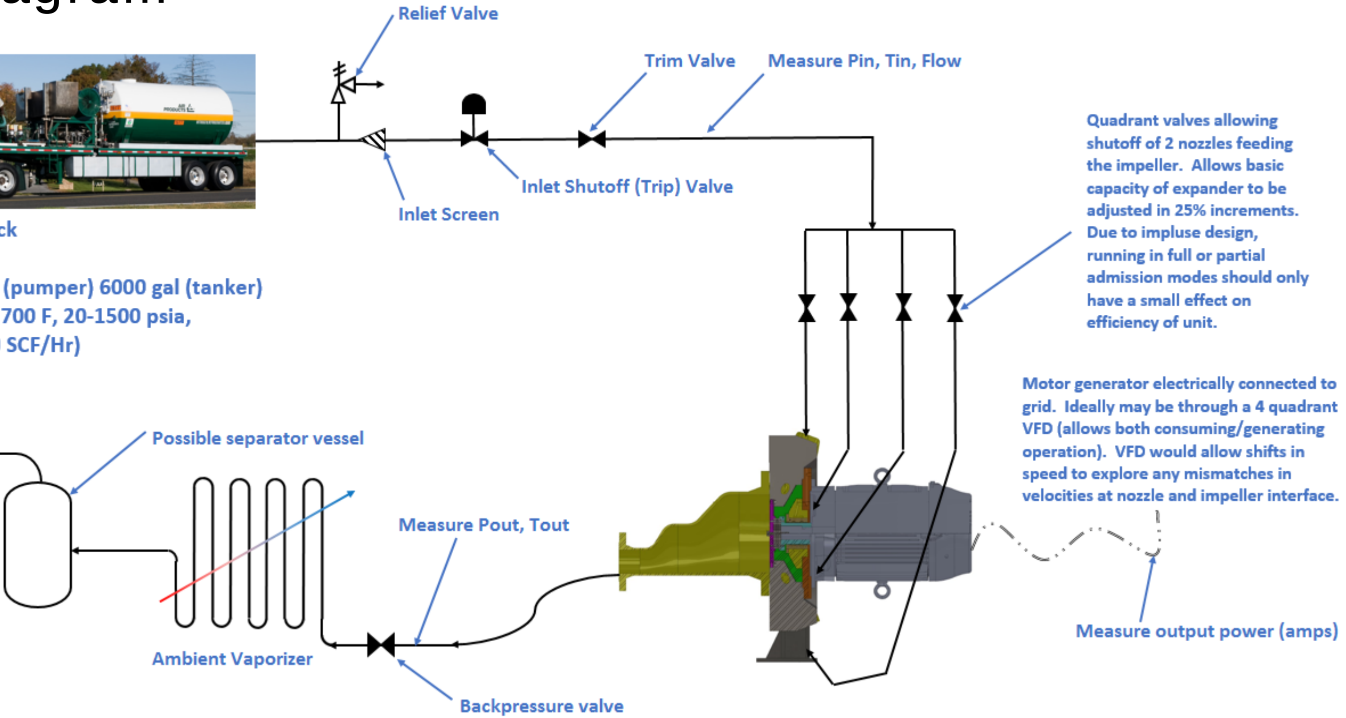
Axial Impulse Dense Fluid Expander

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)



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