Benchmark performance metrics of a vane propellant management device for a 0.15 m^3 liquid hydrogen tank

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NASA

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HYPER: HYdrogen Properties for Energy Research Lab

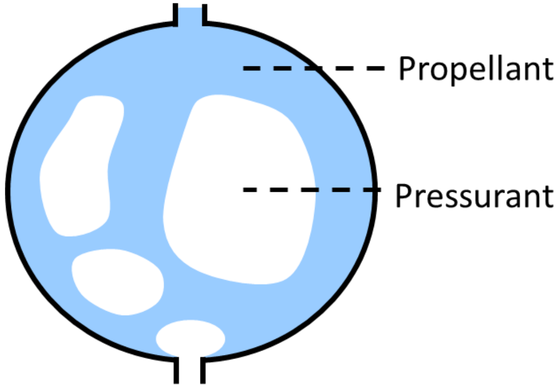
Motivation

The high specific impulses of cryogenic propellants (e.g. 450s for liquid hydrogen/liquid oxygen) will see their continued use in future long-duration manned in-space missions, but this brings challenges.

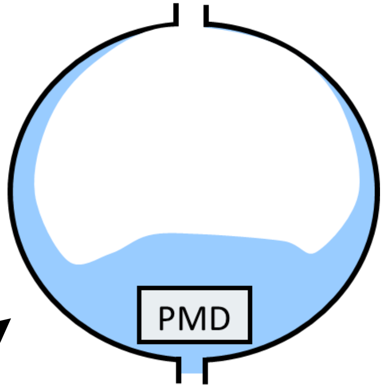
$$\text{Bo} = \frac{\Delta\rho g L^2}{\gamma} = \frac{\text{Gravitational forces}}{\text{Capillary forces}} \ll 1$$

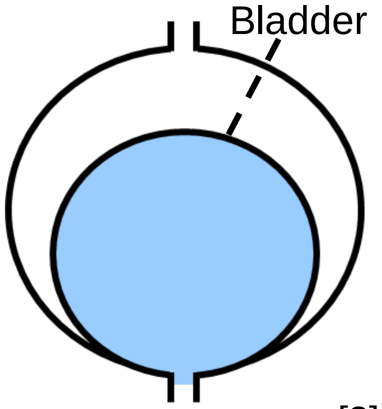
Exacerbated by the low surface tension of cryogens and complex transport processes.

Negligible body forces:



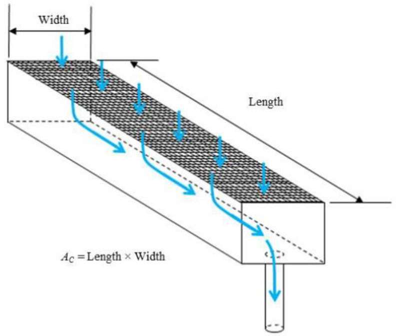
Corrected via:





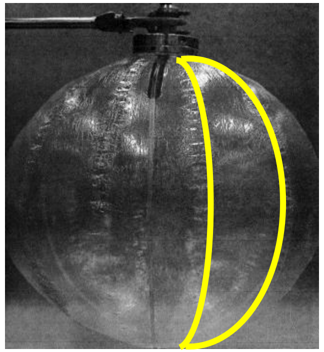
[1] Hartwig, J. W. 2017. DOI: 10.2514/1.A33750

Gallery Arms

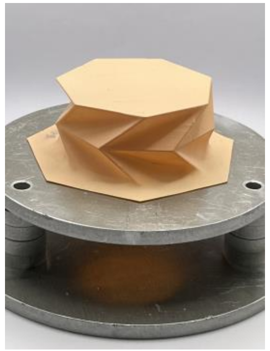


[2] Hartwig, J.W. 2016. DOI: 10.1016/C2014-0-03511-3

Bladder (traditional)



Bladder (compliant)



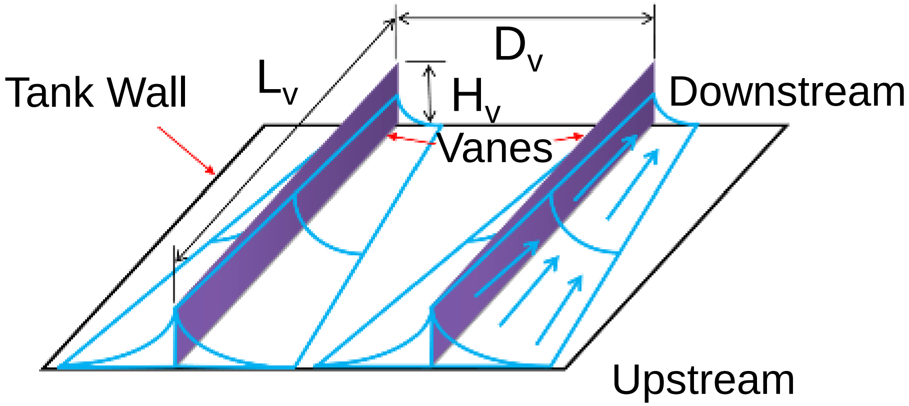
[3] Adapted from Weiderkamp, K. NASA-CR-72432, 1968.

Comparing performance

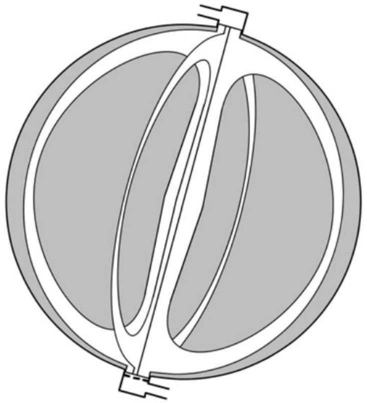
The complexities of these PMDs must be justified by three primary performance metrics.

1. PMD mass, m_{PMD}.
2. Expulsion flow rate, $\dot{m}$.
3. Expulsion efficiency, $EE = 1 - V_{residuals} / V_{tank}$.

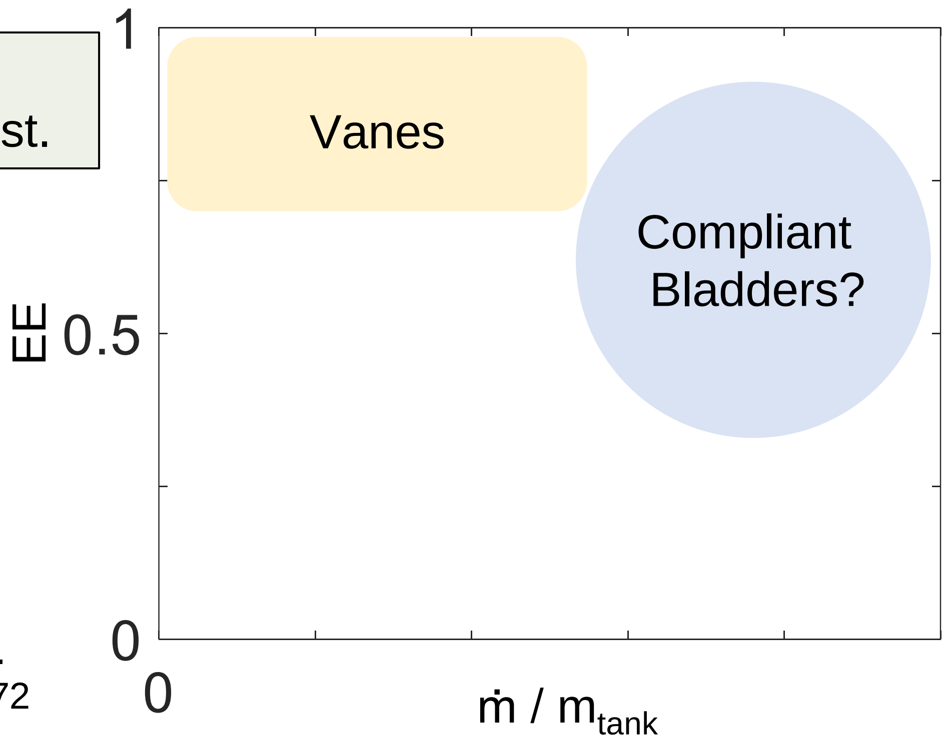
This study focuses on deriving benchmark performance metrics from orthodox vanes from which to compare against.



[2] Hartwig, J.W. 2016. DOI: 10.1016/C2014-0-03511-3



[4] Jaekle, D.E., Jr. 1991. DOI: 10.2514/6.1991-2172



Case study

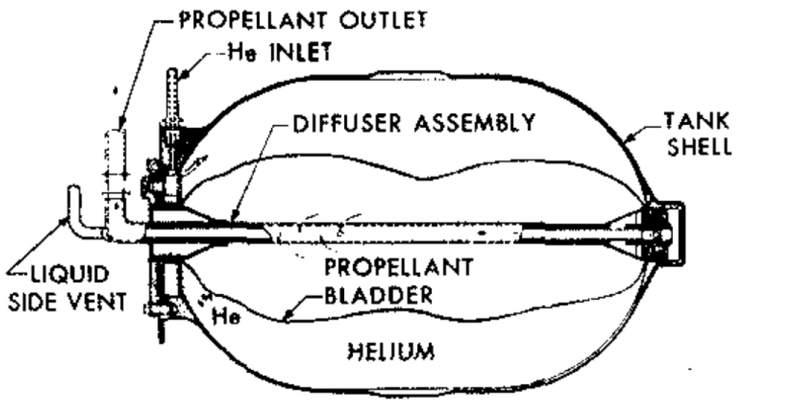


Figure 5. Apollo RCS Positive Expulsion Tank

[5] Stechman, R., & Sumpter, D. 1989. DOI: 10.2514/6.1989-2388.

Characteristic Size m (in.)	Geometry	Quantity	Associated Programs
0.24 (9.4)	Sphere	28	AEROS, IUS, SHUTTLE, etc .
0.328 (12.9)	Sphere	94	GPS, GEOSAT, etc.
0.391 (15.4)	Sphere	11	OTS
0.419 (16.5)	Sphere	219	PIONEER, NOVA, TITAN II, etc.
0.444 (17.5)	Sphere	9	ISPM, SAX
0.483 (19)	Sphere	3	EXOSAT
0.528 (20.8)	Sphere	53	IUS
0.561 (22.1)	Sphere	231	P-95, VIKING, CENTAUR, etc.
0.587 (23.1) x 0.653 (25.7)	Cylindrical	8	EURECA
0.71 (28)	Sphere	54	VOYAGER, SHUTTLE, CASSINI, etc.
0.91 (36) x 1.2 (47)	Cylindrical	5	GRO
1.0 (40)	Oblate Spheriod	28	TDRSS, COBE, EOS, etc.

Adapted from [6] Ballinger, I.A., Lay, D., and Tam, W.H. 1995. DOI: 10.2514/6.1995-2534.

RCS thrusters provide a relevant context from which to couch comparisons between PMDs.

Selected geometry:

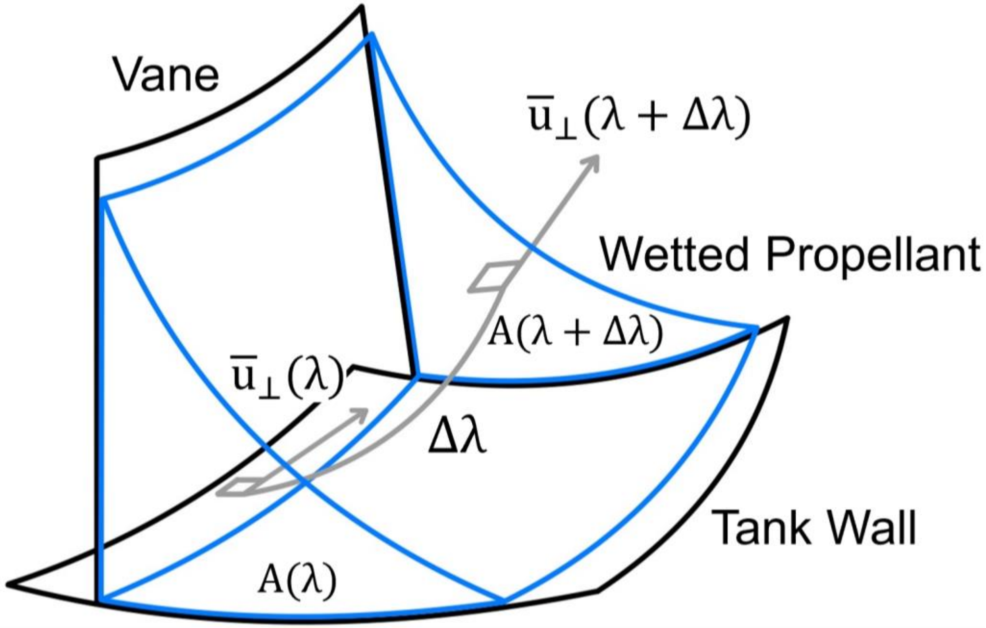
- Cylindrical tank w/ no domes.
  - L_{tank} = 0.75 m; D_{tank} = 0.5 m.

Selected test conditions:

T = 20.3 K; P = 101.3 kPa.

F_{ullage} = 0.05.

Model derivation



Navier-stokes equations:

$$\underline{\nabla} \cdot \underline{u} = 0$$

$$\rho \frac{D\underline{u}}{Dt} = -\underline{\nabla} p + \mu \nabla^2 \underline{u} + \rho \underline{F}$$

Pressure gradient across fillet:

$$dP = \gamma \, d(R^{-1}) = -\gamma R^{-2} dR$$

Assumptions:

- Incompressible.
- Steady-state.

- No body forces.
- No heat transfer.
- End-of-life configuration.

Governing equation:

$$\frac{dR}{d\lambda} = \frac{(FMU)\frac{2\upsilon}{Q}s^2}{\frac{dA}{dR} - (SF)\frac{\gamma_{LV}}{\rho}\frac{1}{Q^2}\frac{A^3}{R^2}} \quad \text{where } A = A(R(\lambda)).$$

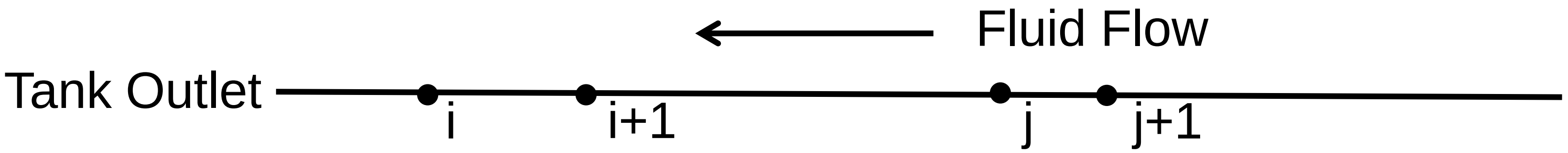
Post-processing:

$$V = N_V \int_0^{L_V} A(\lambda) d\lambda \qquad EE = 1 - V/V_{tank}$$

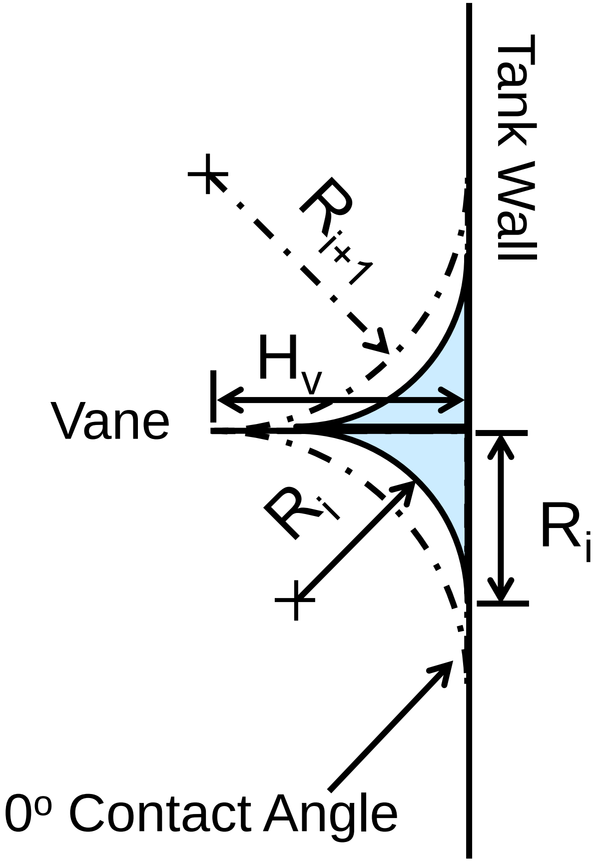
For a given **volumetric flow rate, Q, area, A(λ), and initial down stream radius, R(λ = L_V),** numerically solve for expulsion efficiency, EE.

[4] D. Jaekle, Jr. 1991. DOI: 10.2514/6.1991-2172.

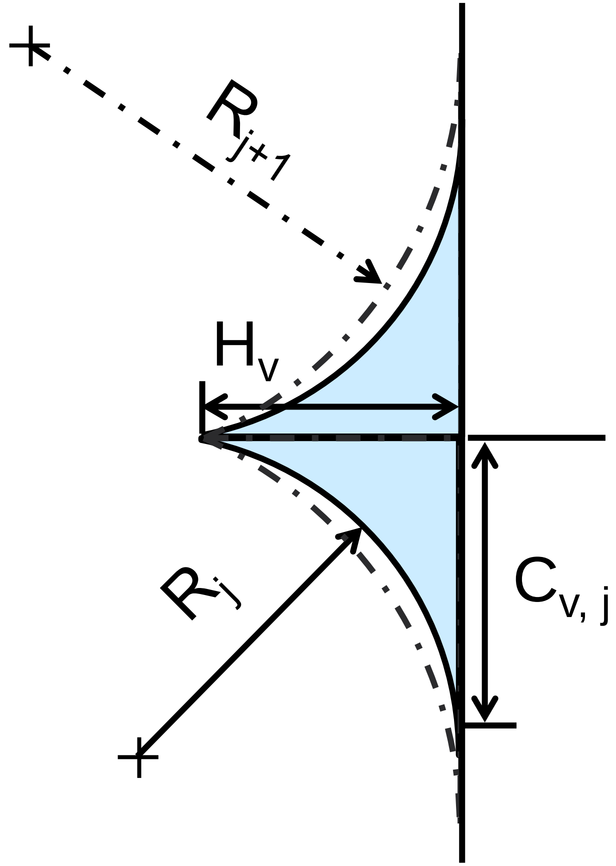
Defining cross-sectional geometry, A(λ)



Case 1: R ≤ H_V



Case 2: R > H_V



Case 1:

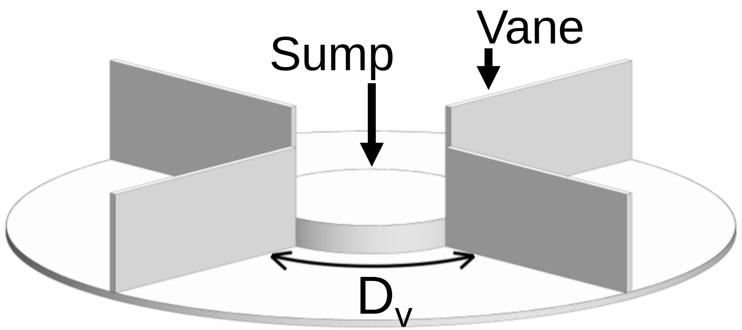
- $A_i = 2R_i^2(1 - 4^{-1}\pi)$

Case 2:

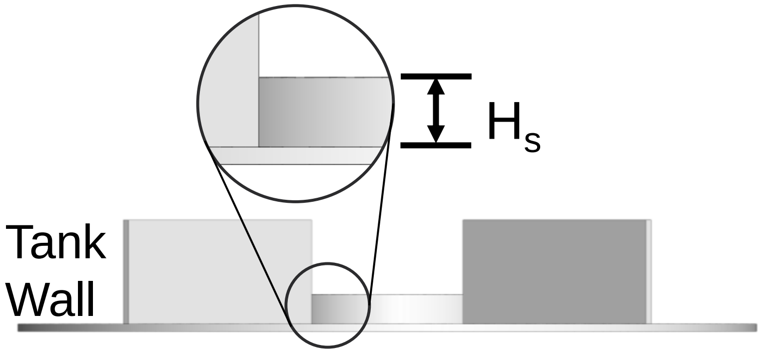
- $A_j = H_v C_{v,j} - R_j\left(R_j\theta_j - (R_j - H_v)\sin\theta_j\right)$
  - $\theta_j = \text{acos}(1 - R_j^{-1} H_v)$
  - $C_{V,j} = \sqrt{8\,H_v(R_j - 2^{-1}\,H_v)}$

Defining boundary condition, $R(\lambda = L_V)$

Sump must remain submerged.

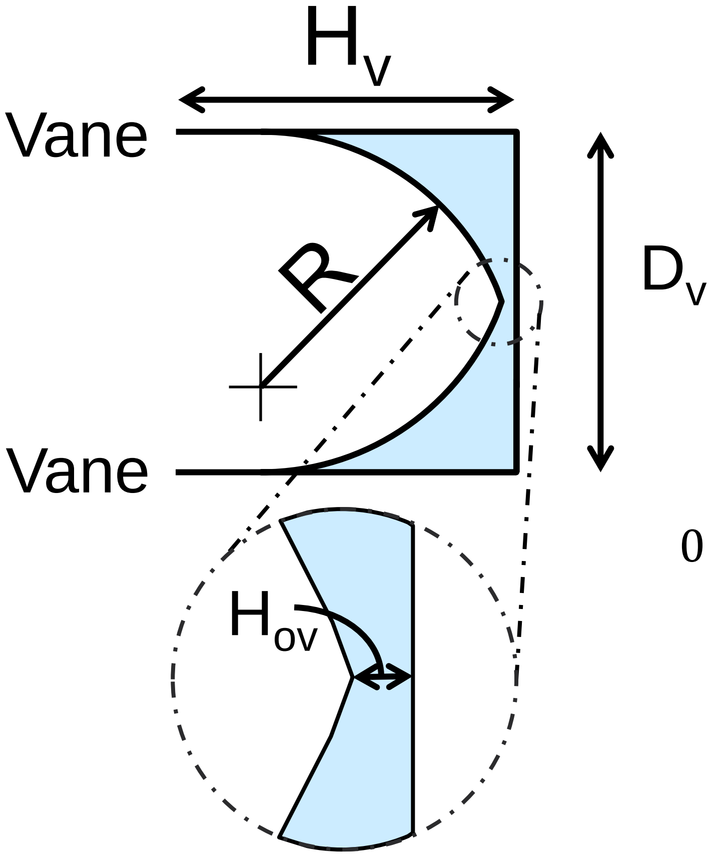


Tank Outlet - Diametric View



Tank Outlet - Side View

Accomplished with overlapping propellant.



Determine a minimum $R(\lambda = L_V)$ where $H_{OV} > H_s$.

Compare via chord lengths:

$$C(h) = \left(8h\left(R - 2^{-1}h\right)\right)^{0.5}$$

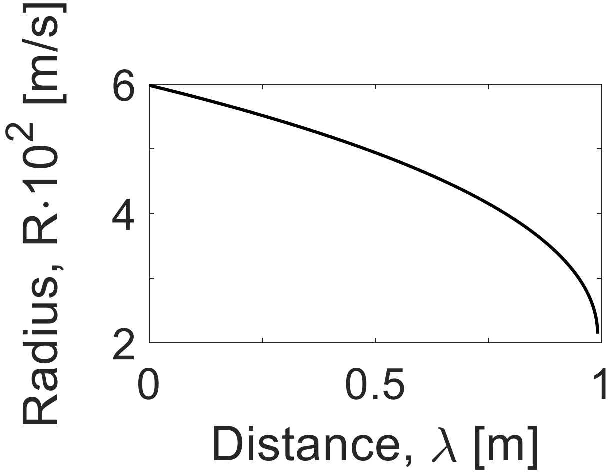
Find the root of:

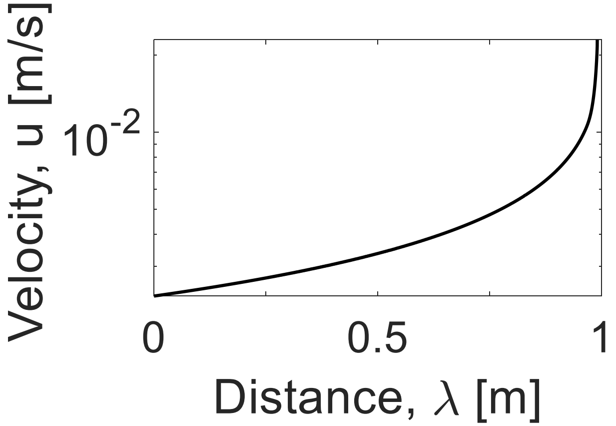
$$0 = \left(\left(C(h = H_{OV}) - C(h = H_s)\right) - Dv\right)^2$$

Studies – i.

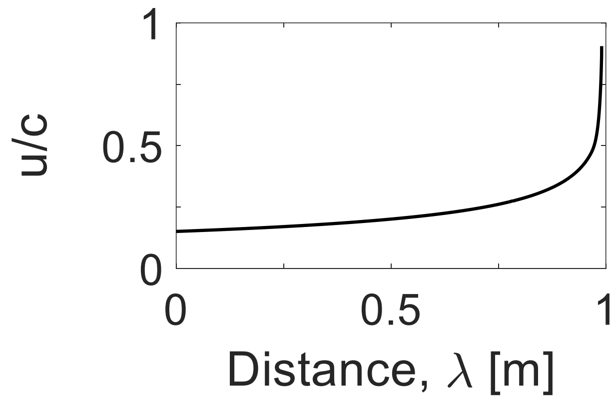
Results from 4 vanes with heights of 10 cm, subjected to 0.001 kg/s.

Implications of continuity eq.



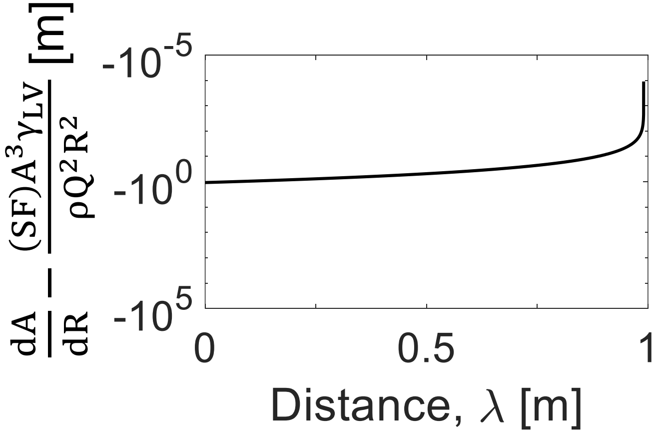


Proximity to choked flow.



Wave propagation speed

$$c = \sqrt{2^{-1}\gamma_{LV}\rho^{-1}R^{-1}}$$

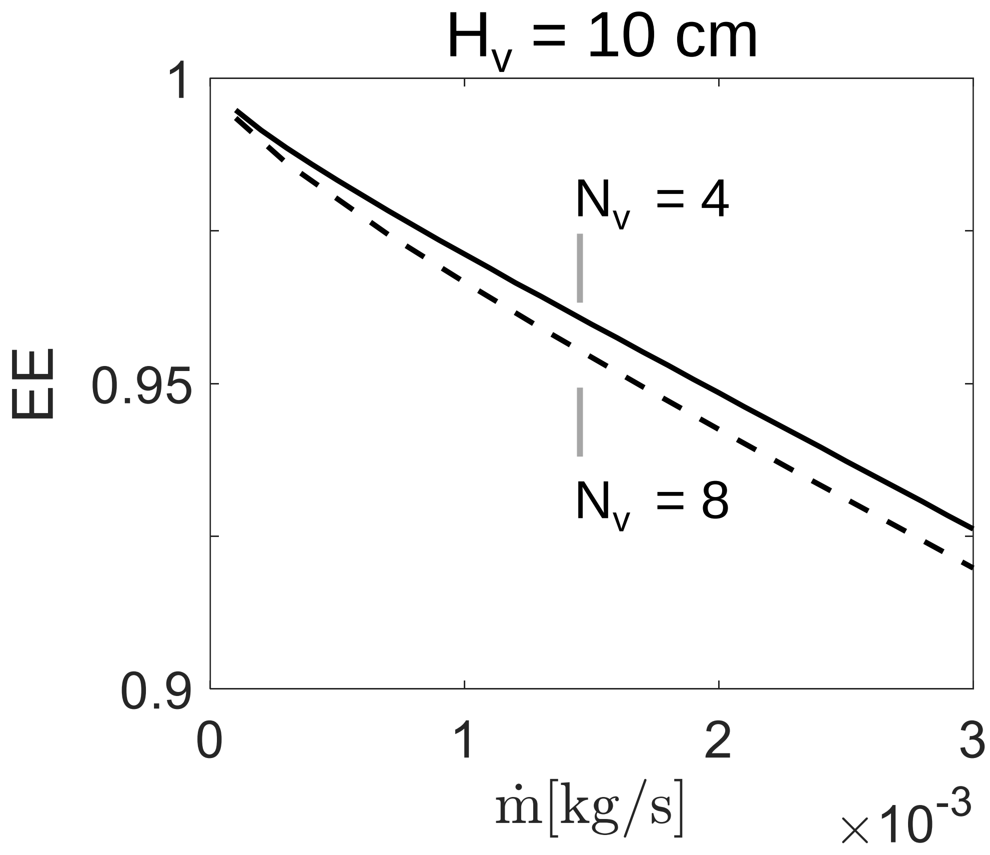


$$\frac{dR}{d\lambda} = \frac{(FMU)\frac{2\upsilon}{Q}s^2}{\frac{dA}{dR} - (SF)\frac{\gamma_{LV}}{\rho}\frac{1}{Q^2}\frac{A^3}{R^2}}$$

Studies – ii.

Parametrically varied number of vanes, N_v, and vane height, H_v, between 4 – 8 and 1 – 10 cm, respectively.

N_v	H_v (cm)	$\dot{m}$ (kg/s)	EE
4	1	0.0001	0.9964
8	1	0.0001	0.9951
	1	0.0003	0.9903
4	10	0.0001	0.9948
	10	0.0003	0.9886
	10	0.001	0.9712
8	10	0.0001	0.9935
	10	0.0003	0.9861
	10	0.001	0.9666



Conclusions and Future Work

- Defined a case study of a 1.5 m^3 LH_2 tank from which to calculate performance metrics of vanes, characterized by high EE and low $\dot{m}$.
- Future work will focus on constraining maximum expulsion flow rates of vanes with choked flow.
- This and future work will help carve out niches within the PMD design space.

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Thank You!