# On small disturbance ascent vent behavior

MICHAEL WORONOWICZ, SGT INC.

2015 CONTAMINATION, COATINGS, MATERIALS, AND PLANETARY PROTECTION WORKSHOP
NASA GODDARD SPACE FLIGHT CENTER
29-31 JULY 2015

Stinger Ghaffarian Technologies

# Outline

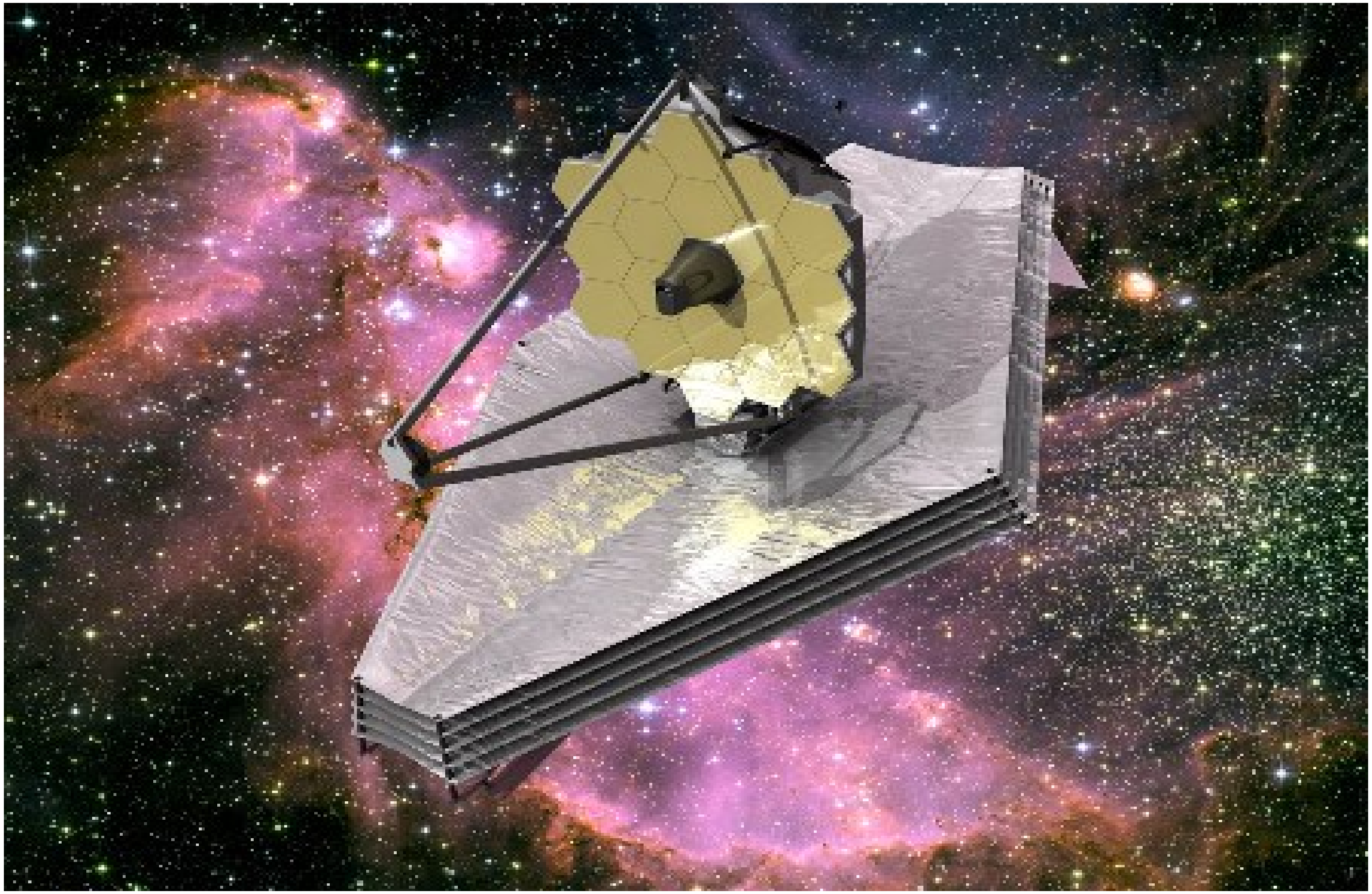


- Introduction
- Objective
- Math Model Development
  - Mass Conservation
  - Conductance
  - Small Disturbance Expressions
- Limit Case Overpressure Solutions
  - Observations
- Concluding Remarks

Stinger Ghaffarian Technologies

# JWST Observatory







MSW

Stinger Ghaffarian Technologies

# Introduction



- James Webb Space Telescope (JWST)
  - Contains four large instruments within an enclosure incorporating some blanketed walls
    - Only vents through small aperture during ascent
    - Other venting would risk light leaks
    - Blankets limit allowable overpressure
  - Electronics compartment on shadowed side also requires limited overpressure due to multi-layer insulation blankets
- Useful to develop expressions in this limit to help design process

# Objective



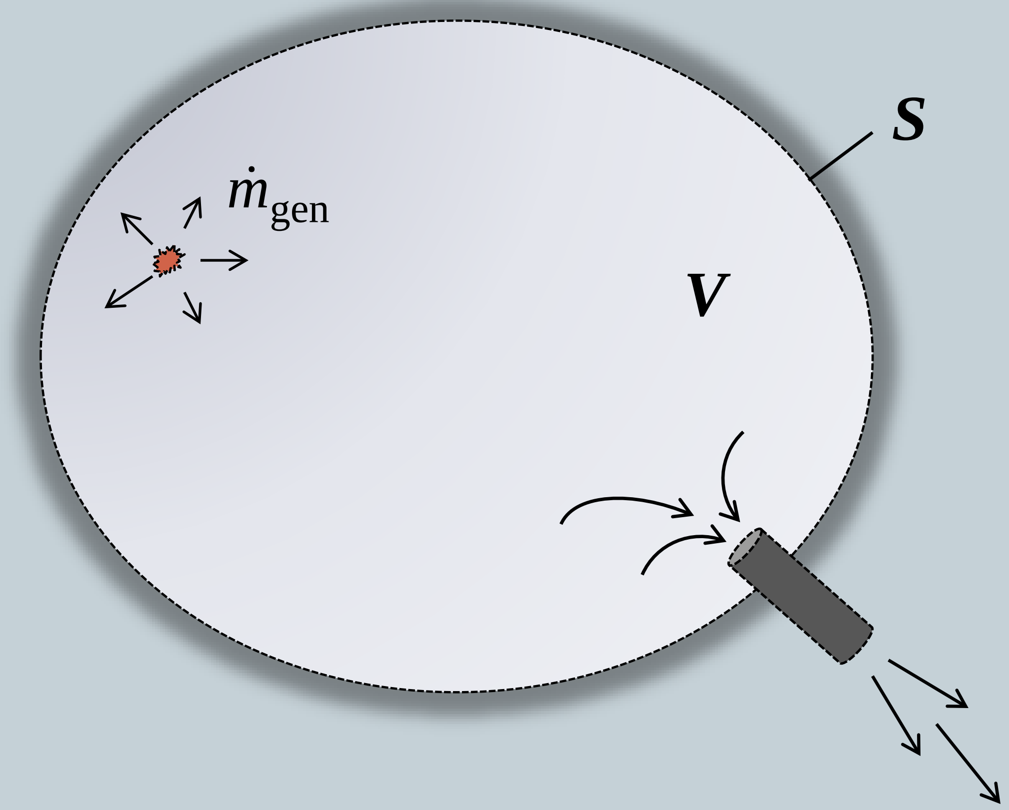
- Develop expressions in small disturbance limit for simple venting systems
  - Common conductance elements
    - Orifices
    - Ducts
  - Mass conservation statement
- Explore some limits for practical application

# Mass Conservation Statement



- Mass accumulation rate
  - Mass generation rate within volume rigid *V*
  - Net rate vented across bounding surface *S*

$$\frac{d}{dt}\iiint_V \rho\, dV = \dot{m}_{\text{gen}} - \oiint_S \rho \mathbf{u}\cdot \mathbf{dS}$$



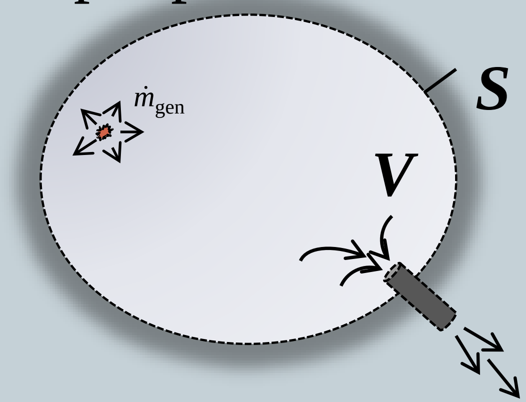



MSW

# Mass Conservation Development



- Assume isothermal, ideal gas with constant properties throughout $V$
  - Recast statement in terms of gas load $Q$




$$V\frac{dp}{dt} = \dot{m}_{\text{gen}}RT - \oint\!\!\oint_S p\mathbf{u}\cdot d\mathbf{S}$$

- In this case, can say venting occurs across a discrete set of elements $K$, define conductance $F$

$$F_{1-2} \equiv \frac{Q}{p_1 - p_2} = \frac{\dot{m}RT}{p_1 - p_2}$$

$$V\frac{dp_1}{dt} = \dot{m}_{\text{gen}}RT - \sum_k^K F_k\left(p_1 - p_2\right)$$

Stinger Ghaffarian Technologies

# Orifice Conductance



- For a calorically perfect gas in continuum flow

$$F_{\text{orifice}} = \sqrt{\frac{2\gamma RT}{(\gamma-1)}}\frac{A}{1-p_2/p_1}\left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}}\sqrt{1-\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}}$$

- Rewrite in terms of fairing pressure $p_2$ and pressure differential

$$F_{\text{orifice}} = \sqrt{\frac{2\gamma RT}{(\gamma-1)}}\frac{A}{1-\frac{1}{1+\frac{\Delta p}{p_2}}}\left(\frac{1}{1+\frac{\Delta p}{p_2}}\right)^{\frac{1}{\gamma}}\sqrt{1-\left(\frac{1}{1+\frac{\Delta p}{p_2}}\right)^{\frac{\gamma-1}{\gamma}}}$$

- For small pressure differentials:

$$F_{\text{ori,sm}} \equiv F_{\text{orifice}}(\Delta p << p_2) \approx A\sqrt{2RT\frac{p_2}{\Delta p}}\left(1-\frac{1}{\gamma}\frac{\Delta p}{p_2}\right) \approx A\sqrt{2RT\frac{p_2}{\Delta p}}$$

# Circular Duct Conductance



- Begin with Hagen-Poiseuille solution for average velocity in fully-developed, laminar flow

$$\bar{u} = \frac{A}{8\pi\mu}\left(\frac{p_1 - p_2}{\ell}\right)$$

$$F_{\text{duct}} = \frac{\dot{m}RT}{(p_1 - p_2)} = \frac{\bar{\rho}\bar{u}ART}{(p_1 - p_2)} = \frac{\bar{p}\bar{u}A}{(p_1 - p_2)} = \frac{A^2}{16\pi\mu\ell}(p_1 + p_2)$$

$$F_{\text{duct, sm}} = \frac{A^2}{16\pi\mu\ell} p_2 \left(2 + \frac{\Delta p}{p_2}\right) \approx \frac{A^2}{8\pi\mu\ell} p_2$$

# Conductance Comparisons



$$F_{\text{ori, sm}} \approx A\sqrt{2RT\frac{p_2}{\Delta p}}$$

$$F_{\text{duct, sm}} \approx \frac{A^2}{8\pi\mu\ell}p_2$$

# Small Disturbance Solution



- For a single venting element

$$V\frac{dp_1}{dt} = -F_{1-2}\left(p_1 - p_2(t)\right)$$

  - If conductance not a function of pressure, would identify a time constant $\tau = V/F$

- In terms of $\Delta p$, $p_2$

$$\frac{dp_2}{dt} + \frac{d\Delta p}{dt} = -\frac{F_{1-2}}{V}\Delta p.$$

- Since $p_1$ is close to $p_2$ over all time, can neglect second time derivative

# Small Disturbance Solution



- Grouping known quantities together

$$F_{1-2}\Delta p \approx -V\frac{dp_2}{dt}.$$

- What was a first-order differential equation has been reduced to an algebraic expression!
- Find solutions for $\Delta p$ using orifice and duct behavior

Stinger Ghaffarian Technologies

# Limiting Orifice Behavior



- Substitute small disturbance equation for orifice
- Solving for $\Delta p$

$$\Delta p_{\mathrm{ori,\,sm}}(t) = \frac{1}{2RT}\left(\frac{V}{A}\right)^2 \frac{\left(\frac{dp_2}{dt}\right)^2}{p_2}.$$

- Identical to solution developed intuitively by Scialdone!
- Highest value occurs where last term is maximized
  - Usually occurs during transonic disturbance period

# Comments on Scialdone Formula



- Scialdone modified the orifice area by using a discharge coefficient
  - Based on what was originally an ASTM description for orifice plates within pipes
  - This author has not found this coefficient to be necessary when comparing against test data
- Original development recognized use of small disturbance assumptions, but created a time constant based on molecular flow and sonic conditions
  - Sonic conditions definitely violate small disturbance limit
  - Assumptions lead to minimum critical areas that are too large
    - Run up against thermal, optical, high-voltage restrictions

# Limiting Duct Behavior



- Circular duct solution

$$\Delta p_{\mathrm{duct,\,sm}}(t) \approx -8\pi\mu \frac{V\ell}{A^2} \frac{\frac{dp_2}{dt}}{p_2} = -8\pi\mu \frac{V\ell}{A^2} \frac{d \ln p_2}{dt}.$$

- Note differences from orifice solution
  - Difference dependence on fairing depressurization rate
  - Lower dependence on volume
  - Presence of dynamic viscosity, duct length emphasize viscous rather than gasdynamic effects

# Critical Reynolds Number



- Laminar flow condition violated when duct Re > 2000 – 4000
- Work with definition of Reynolds number and duct mass flow expression in small pressure disturbance limit to find

$$\Delta p(\text{laminar}) < \frac{32\,\text{Re}_{\text{crit}}\,\mu^2 \ell RT}{d^3 p_2}.$$

  - Stubby ducts allow higher flow rates at constant diameter, but may also lead to turbulent conditions
    - If aspect ratio is stubby enough, the element may behave more like an orifice instead!

Stinger Ghaffarian Technologies

# Concluding Remarks



- Overpressure model developed for isothermal, constant temperature venting of an ideal calorically perfect gas for a rigid volume in the presence of an external driving pressure, in the limit of small $\Delta p$
- Limiting expressions for $\Delta p$ were developed for venting across orifices and circular ducts in fully developed, laminar flow
  - Orifice equation identical to Scialdone's, discussed how limits should be understood
  - Duct equation exhibits viscous effects, different dependence on driving pressure profile, found limit on validity based on critical Reynolds number