Approximating Fluid Flow from Ambient to Very Low Pressures – Modeling ISS Experiments that Vent to Vacuum.

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Background

- Two ISS experiment payloads will vent a volume of gas overboard via either the ISS Vacuum Exhaust System or the Vacuum Resource System. A system of ducts, valves and sensors, under design, will connect the experiments to the ISS systems.
Background
The Task

- Create an analysis tool that will verify the rack vacuum system design with respect to design requirements, more specifically approximate pressure at given locations within the vacuum systems.
- Determine the vent duration required to achieve desired pressure within the experiment modules.
- Update the analysis as systems and operations definitions mature.
Unknowns

- Final configuration of rack based vacuum system.
- Some material specific characteristics of the ISS vacuum system, particularly off-gas rates for components with company proprietary material specifications.
- Gas to be vented.
- Gas temperature, pressure and volume.
- Operations scenarios which could impact pressure and temperature of downstream systems.
Known

- Final Configurations of ISS Vacuum Exhaust and Vacuum Resource Systems.
- At some point, in all operations scenarios, there will be a venting of an experiment chamber from ambient to very low pressure.
- Pressure outside ISS is \( \sim 1.2 \times 10^{-7} \) torr.
- Volume outside ISS is infinite.
Three Regimes of Fluid Flow

- Continuum (viscous) flow can be laminar or turbulent, and can be predicted by the laws of conservation of mass and energy.

- Transitional flow has characteristics of both molecular and continuum and is approximated with a conductance method.
Fluid Flow (Continued)

• Molecular flow can be characterized by the mean free path of the molecule ($\lambda$). The mean free path is the distance a molecule is predicted to travel without colliding with another molecule or vessel wall. Molecular flow occurs when $\lambda$ is relatively large so the likelihood that a molecule will collide with a vessel wall is greater than the likelihood that there will be intermolecular collisions. Molecular flow will be analyzed using a conductance method.
Determining Flow Regime

• Predicting flow regime is accomplished with Knudsen number (Kn).
  – A Knudsen number greater than zero and less than 0.01 indicates a continuum flow regime.
  – The transitional regime will occur where Kn is greater than or equal to 0.01 and less than or equal to 1.0.
  – A Knudsen number greater than 1.0 identifies the flow regime as molecular flow.
• Knudsen number is calculated by:
  – Kn=0.066/(D*P)
  – Derivation for this equation can be found in the paper.
Determining Pressure

- Two distinct methods of determining the change in pressure over time are employed in order to evaluate performance over all flow regimes
  - Pressure changes through the viscous flow regime are evaluated using the Generalized Fluid System Simulation Program (GFSSP).
  - Flow in the low continuum, transitional, and molecular regimes is predicted using a conductance method.
GFSSP

- Assumes a Newtonian, non-reacting and one-dimensional flow.
- Requires resolution of the system into nodes (internal and boundary) and branches.
- Pressures, temperatures, and concentrations of fluid species are specified at the boundary nodes.
- Flow rates are computed in the branches.
- Results are in English units.
Conductance Method

- Flow for the molecular and transitional regimes are predicted by measuring the ability of a gas to flow through a control volume, called conductance.
- In a manner similar to GFSSP analysis a conductance model is developed as a series of connected nodes.
- Control volumes are modeled in terms of pipe and orifice.
- Control volume conductances can be added, in a manner analogous to electrical resistance, so that systems with parallel or series branches can be simplified into single volumes.
Conductance Method (Continued)

\[
\dot{P}_j = \frac{1}{V_j} \left[ G_j + L_j + C_{ij} \cdot (P_i - P_j) - C_{jk} \cdot (P_j - P_k) \right]
\]

Where:  
\( \dot{P}_j \) = Change in pressure in control volume \( j \) (torr/sec) 
\( V \) = Volume (L) 
\( G \) = Off-gas rate (torr L/sec) 
\( L \) = Leak (torr L/sec) 
\( C \) = Conductance (L/sec) 
\( P \) = Pressure (torr) 
i and \( k \) are upstream and downstream respectively from \( j \).
Meshing the Models

- GFSSP output becomes the conductance model input file.
  - Design both models so node information mesh.
  - GFSSP calculates in English units, conductance code in SI, be sure to convert.
  - Expect a settling in period, the duration will depend on step size.
Helpful Assumptions for ISS Venting Approximations

- The experiment will either fly at ambient pressure to the station or at some point an on-orbit operation will fill an experiment chamber with station air. This allows for the following assumptions:
  - The gas to be vented is air.
  - Gas temperature and pressure are standard.
- If the valve configuration is under study, let valves open instantaneously.
- Station vacuum systems are vented from ambient pressure along with experiment modules.
Helpful Assumptions for ISS Venting Approximations

- Seals
  - All seals, within the system under design, will leak, the maximum allowable amount, per seal specification.
  - Seals leaking the maximum allowable amount, will not impact continuum pressures, i.e. GFSSP model.
  - Seals within Vacuum Exhaust and Vacuum Resource systems do not leak.
  - Other experiments connected to these vacuum systems do not leak.
Helpful Assumptions for ISS Venting Approximations

- Off-gassing is described by an exponential decay function.
  - Pressure must be low enough for the escape of entrained gases to be significant, which won’t occur to a noticeable degree in continuum regime.
  - When off-gassing rates are unavailable use a known rate for a material with chemical similarities.
Conclusions

When designing a new analysis tool:

• Gather information from system designers, operations planners, and principal investigators,
• Fill in the blanks with assumption,
• Create modular software,
• Share results,
• Iterate.