Analyzing Cryogenic Recovery Parameters for the XENON1T Experiment

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August 7th, 2014
Overview

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Introduction: what is dark matter?

- Originally postulated by Zwicky in 1933 to explain unseen mass in the Coma cluster.
- Major evidence in galaxy velocity distributions discovered by Rubin in 1970.
- Observational evidence at all scales (galactic velocity dispersions, gravitational lensing, cosmic background, etc.)
- Electromagnetically neutral, hence “dark”; interacts mostly through gravitation.

What is dark matter, cont.

- Probable model is a weakly-interacting massive particle (WIMP); only interacts with the weak force and gravity, mass in the GeV+ range.
- Particle physics theories independently predict WIMP-like particles (supersymmetry, Kaluza-Klein).
- “Cold” (non-relativistic) particle; expected to form halos around cosmic macrostructures, enabling direct detection.
Detection principle

- WIMP-nucleon elastic scattering deposits a small amount of energy in the target material/volume.
- Signal is very small, phenomenally rare and buried in enormous background.
- Detecting methods/materials can be selected to amplify or transduce the signal into a readable output.

Cross-sections larger than $10^{-45}$ cm$^2$ currently excluded!
The XENON1T detector

- Dual-phase xenon time-projection chamber located underground at LNGS.
- Xenon stopping power reduces background in internal “fiducial” volume (1 ton of liquid xenon for XENON1T), target volume “self-shields”.
- Ionization electrons generate post-scattering scintillation; ratio of the two signals discriminates background further.

![Diagram of XENON1T detector](image)
The ReStoX system

- A sophisticated cryogenic storage and recovery system for the xenon used in the XENON1T.
- Can keep up to 6 tons of xenon liquid via built-in cryogenics, can also store in gaseous phase in case of power failure.
- Can also continuously radio-purify xenon held in storage.
The ReStoX recovery line

- The entire line consists of approximately 21 meters of pipe.
- Sections entering and leading out of the main cryogenics system are inclined at 5 degree angles.
- Piping inside of the cryostat modeled as going straight down.
- Various bends and cross-section changes present.
Project emphasis

• During an emergency failure, pressure-driven flow drives xenon into the storage sphere from the detector cryostat.
• Recovery characteristics determine the cooling parameters for the sphere.
• Important to know relevant thermo-fluidic phenomena inside of the recovery line to ensure safe operation and improve performance.
Physical phenomena

- Pressure gradients in the cryoline induce xenon flash evaporation & dual-phase flow.
- The density reduction generates a convective velocity gradient to preserve a constant mass flow rate.
- The increased velocity creates larger pressure losses towards the end of the pipe, inducing steeper pressure gradients.
Solving methodology

- Highly turbulent dual-phase flow with large calculation complexities.
- Coupled-field thermo-fluidics problem; considerably better to create original hand-coded model instead of using pre-made suites (COMSOL).
- This kind of model is exceptionally time-efficient and can properly model “minor” pressure losses.

\[
\frac{1}{\sqrt{f}} = -2 \log_{10} \left( \frac{\varepsilon}{3.7D} + \frac{2.51 \rho v D}{\mu} \sqrt{f} \right)
\]

Turbulent friction factor is both implicit and a function of velocity!
Preliminary models

- The first preliminary model solves for the velocity with a simple Bernoulli analysis as a function of the pressure difference, and using constant liquid xenon properties.
- Used to get basic order-of-magnitude estimates for future model validation, and to see the relative magnitude of loss sources (friction, valve, geometry)
First preliminary model

Mass flow rate as a function of pressure difference between ReStoX and cryostat

Pressure loss due to various sources vs. pressure difference

- Friction
- Valve
- Geometry
Preliminary models, pt. 2

- The second preliminary model takes into consideration evaporation in the recovery line, and different physical approximations were used to calculate average pressure losses in the line.

- High variations in the results for slightly different physical assumptions are indicative of this model being too coarse for predictive use.
Second preliminary model

Using mean thermodynamic state

Using mean thermodynamic properties

~70% increase!
Finite-difference model

• Discrete finite-difference model calculates the thermodynamic properties of the xenon as it flows through the pipe by solving the Bernoulli equation between nodes.

• Lagrangian model, assumes a homogeneously mixed dual-phase flow which evolves isenthalpically.

• Can calculate pressure losses to an arbitrary precision.

• Requires solving implicit equations at every node; can take enormous amounts of time to solve for small node distances.
Finite-difference model, pt. 2

Initial thermodynamic state defined

Trial inlet velocity selected

\[ P_{\text{next}} = P_{\text{previous}} + \Delta \rho g h - \Delta P_{\text{loss}} \]

\[ \chi_{\text{next}} = \frac{\chi h_v + (1 - \chi) h_l - h_{l,\text{next}}^{\text{next}}}{h_v^{\text{next}} - h_{l,\text{next}}^{\text{next}}} \]

New density & viscosity calculated

New velocity calculated, \( \rho v A = \text{constant} \)

\[ P_{\text{end}} = \frac{P_{\text{end}}}{P_{\text{sphere}}} \text{?} \]

Yes

Output data

No

Next node
Results

- Absolute pressure (bar)
- Gaseous volume fraction (%)
- Mean density (kg/m³)
- Velocity (m/s)

Valve drop
Cross-section drop
Results

Mass flow rate as a function of cryostat pressure, $P_{\text{sphere}} = 0.9$ bar

Recovery time for 3 tons of Xe as a function of cryostat pressure
Results

Recovery mass flow rate as a function of pressure in the ReStoX sphere, $P_{\text{cryostat}} = 3.2$ bar

Very high flow rates at low pressure differences!
Results

Mass flow rate as a function of cryostat pressure for constant $\Delta P = 1$ bar

The flow rate depends strongly on the beginning/end states!
Conclusions

• We can guarantee recovery between 2.25 and 3.25 hours at a ReStoX sphere pressure of 0.9 bar.
• Valve contributes heavily to thermo-fluidic phenomena in the pipe.
• Linear relationship between flow rate and pressure allows excellent recovery predictions for arbitrary cryostat pressure variations.
• Mach numbers well clear of subsonic range ($M_{max} = 0.21$)
• Gaseous volume fraction evolution indicates xenon rapidly turns into mist.
• High flow rates even at high ReStoX pressures due to nonlinearity between pressure gradient and flow velocity.
Future Work

• Validate model results with in-situ testing.
• Include pre-evaporation single-phase flow into the current model.
• Incorporate outward heat loss (remove isenthalpic assumption).
• Include initial transient phenomena into the model.
• Optimize calculation by removing homogeneous flow assumption.
Acknowledgements

• Prof. Aprile for giving me this wonderful opportunity to participate in cutting-edge dark matter detection research with an international collaboration.

• Grazie mille a Jean-Marie e Luca per tutto l'aiuto riguardo il funzionamento di ReStoX e con tutti i conti che ho dovuto fare.

• Alfio, Yun, Guillaume, Ranny, Marcello, and everyone in the collaboration for all the help with my work, around the lab, and with life in Paganica.

• The Nevis REU program/administrators, Columbia University, and the NSF for making this kind of research opportunity possible.
Questions?