Supercritical Xe as Propellant in Satellite Electric Propulsion System: Experimental Study on Thermal Physical Properties

Yueshuai Zhao, Lichen Sun, Xinfa Yu and Wei Sun
Department of Vacuum and Leak Detection, Beijing Institute of Spacecraft Environment Engineering, Beijing 100094, China
Email: zhaoyueshuai@163.com

Abstract. Supercritical Xenon was used in satellite electric propulsion system as propellant. The supercritical physical properties of Xenon have a great influence on the pressure-temperature relationship during filling and storage. The Burnett isochoric coupling method was used to test the PvT data of Xenon in this paper. A test system was established to obtain the critical test data for Xeon. Near the critical temperature, the calculation results by REFPROP are significantly larger than the experimental results in this work, up to 6 kPa. The reliability and high precision of the experimental data in this work are verified by the data from literature and the data calculated by NIST’s REFPROP software.

1. Introduction
Satellite electric propulsion technology is an advanced propulsion technology with higher specific impulse and lower propulsive force. A separate Xenon supply system with high precision pressure regulation and flow control function was used in this system. In the storage subsystem, Xenon is in a supercritical state. The supercritical physical properties of Xenon have a great influence on the pressure-temperature relationship during filling and storage. It is necessary to study the precise thermophysical properties of Xeon in the supercritical state.

The critical parameter is one of the most important thermophysical parameters of a substance. In the critical state, the density of the liquid phase of the substance is the same as the density of the gas phase, and the gas-liquid interface disappears. The research on the thermophysical properties of Xeon can be traced back to the work of Patterson et al[1], in 1912. The critical temperature of Xeon is 289.75 K and the critical density is 1.155 g/cm³ in Patterson’s work. Gillis et al. [2](NIST)measured the expansion of the critical parameters of Xeon in 2004, and get the critical temperature is 289.733 K. Lemmon (NIST) and Span ( Paderborn University)[3] measured a critical density of 8.4 mol/dm³ for Xeon in 2006. However, high-precision experimental research on the Xenon supercritical region for the filling process of satellite electric propulsion system was not yet available.

In this paper, thermophysical properties of supercritical Xeon were studied by experimental methods. A test system was established to obtain the critical test data for Xeon. The test data was compared with the data test by other research institutions.

2. Test Method and Procedure
The Burnett isochoric coupling method[4,5] was used to test the PvT date of Xenon. The schematic diagram of the Burnett isochoric coupling method experimental apparatus is shown in Fig.1. The body consists of two cells, the main cell volume is V₁, and the volume of the expansion cell is V₂. The two
cells are connected by valves through small diameter pipes, and the whole apparatus is in the same constant temperature environment.

![Figure 1. The schematic diagram of the Burnett isochoric coupling method](image)

First, The two cells were evacuated separately, and the expansion valve between the two cells was closed. Filling the cell 1 with experimental fluid, after stabilization, record the pressure $p_0$, the temperature $T_0$. Second, open the expansion valve, the experimental fluid expanded from cell 1 to cell 2 (which has been evacuated), after stabilization, close the expansion valve, record the pressure $p_1$, and the temperature $T_1$ in cell 1, repeat this process until the expansion pressure is low enough, and get the pressure and the temperature $(p_2, T_2)$, $(p_3, T_3)$…$(p_i, T_i)$.

The densities were calculated as:

$$\rho_i = \frac{p_i}{Z_iRT} = \frac{1}{N_iART}$$

(1)

Where, $p_i$ is the pressure, $\rho_i$ is the molar density, $T$ is the temperature, $R$ is the universal gas constant, $i$ is the expansion number, $N_i$ is the cell constant, $Z_i$ is the compressibility factor.

Define $N_i$ as:

$$N_i = \frac{V_1 + V_2}{V_1}$$

(2)

Where, $V_1$ is the volume of cell 1, and $V_2$ is the volume of cell 2.

A is the gas-filled constant:

$$\frac{1}{A} = \lim_{p \to 0} p_i N_i$$

(3)

The cell constant $N_i$ is a function of pressure and temperature. Since the experimental apparatus are made of same stainless steel, the cell constant is independent of temperature, and can be calculated by:

$$N_i(p_{i-1}, p_i) = N_0 \frac{1 + mp_i}{1 + mp_{i-1}}$$

(4)

where, $N_0$ is the cell constant when the pressure is 0, $m$ is a constant calculated from the mechanical properties.

3. Experimental System

The Burnett test system as shown in Fig.2 including 2 cells (cell 1 and cell 2), the volume of cell 1 is 500 cm$^3$ and the volume of cell 2 is 200 cm$^3$, the experimental fluid was expanded in cell 1.
The Constant Temperature Environment was provided by a cryostat (±3.4 mK uncertainty), the working medium is industrial alcohol, cooled by a two-stage cascade refrigeration system. The PID technology is used in temperature control system, the temperature fluctuation was controlled within ±3 mK.

The temperature measurement system, including: the platinum resistance thermometer (±2 mK uncertainty), the thermometer bridge (MI 6242T, ±0.3 mK uncertainty) and the Super Thermometer (HART 1590, ±1 mK uncertainty). The overall temperature uncertainty was less than 5 mK.

The pressure measurement system, including one absolute digital manometer (MT 210: 0~130 kPa, ±20 Pa uncertainty), two gauge pressure digital manometers (MT 210: -80~3000 kPa, ±80 Pa uncertainty; GE 7050i: 0~10 MPa, ±300 Pa uncertainty) and one sensitive diaphragm pressure transducer (Rosemount 3051S: 0~16 kPa, ±0.1% uncertainty).

A turbo-molecular pump was used to provide the vacuum for the experiment system.

4. Results and Discussion

4.1. Test for the Cell Constant $N_0$

The cell constant $N_0$ is the key parameter of the Burnett isochoric coupling method. The cell constant is independent of the experimental fluid, and could be determined from eq.(2) by an isothermal expansion experiment of Xenon at 100°C. As shown in Fig.3. ($N_0 = 1.378096225$)
4.2. Test for the Gas-Filled Constant $A$

The gas-filled constant $A$ was determined from eq.(3), and can be fitted by a polynomial in the form of eq(5):

$$p_i N_i = \frac{1}{A} + a_1 p_i + a_2 p_i^2 + a_3 p_i^3 + \cdots$$  \hspace{1cm} (5)

In fact, the number of terms was not the more the better. According to the test result of the isothermal expansion experiment of Xenon at 100°C, the gas-filled constant $A$ was calculated as Table 1.

| Max. power exponent | $1/A$          | $R^2$     |
|---------------------|----------------|-----------|
| 2                   | 11608.92650062 | 0.999983  |
| 3                   | 11600.92308053 | 0.999998  |
| 4                   | 11604.99653339 | 0.99999961|
| 5                   | 11605.30580183 | 0.99999954|

It can be found that when the Max. power exponent is 4, $R_2$ is the largest. $1/A=11604.99653339$ is taken to calculate the density of Xenon.

4.3. Test Result for the Supercritical Xeon

A total of 130 $PvT$ data points for the Xenon were obtained in supercritical state with temperature from 289 to 373K. As shown in Fig.4.

![Figure 4. Experimentation data of xenon in supercritical state](image)

The measurement results in this work, the data from literature[6-11] and the data calculated by NIST's REFPROP software are shown in Figure 5-8. It can be seen that the measurement results in this work are in good agreement with the high-precision experimental data such as Hurly. Near the critical temperature, the calculation results by REFPROP are significantly larger than the experimental results in this work, up to 6 kPa; in the range of 250-280 K, there is a certain negative deviation, which is lower than the measurement result of about 1 kPa.
Figure 5. Relative deviations between the experimental density data in this work and the density data calculated from the NIST's REFPROP software.

Figure 6. Absolute deviations between the experimental density data in this work and the density data calculated from the NIST's REFPROP software.

Figure 7. Relative deviations between the experimental pressure data in this work and the pressure data calculated from the NIST's REFPROP software.
Figure 8. Absolute deviations between the experimental pressure data in this work and the pressure data calculated from the NIST's REFPROP software

5. Conclusion
In this paper, the thermophysical properties of the supercritical Xenon of the satellite electric propulsion system are tested. Near the critical temperature, the calculation results by REFPROP are significantly larger than the experimental results in this work, up to 6 kPa. The reliability and high precision of the experimental data in this work are verified by the data from literature and the data calculated by NIST's REFPROP software.

6. Reference
[1] Patterson H S, Crips R S, Whytlaw-Gray R. The Critical Constants and Orthobaric Densities of Xenon. Proc. R. Soc. Lond. 1912, 86: 579-590.
[2] Gillis K A, Shinder I I, Moldover M R. Thermoacoustic boundary layers near the liquid-vapor critical point. Phys. Rev. E. 2004, 70(2): 021201.
[3] Lemmon E W, Span R. Short fundamental equations of state for 20 industrial fluids. J. Chem. Eng. Data. 2006, 51(3): 785-850.
[4] Michels A, Wassenaar T. Vapour Pressure of Liquid Xenon. Physica. 1950, 16(3): 253-256.
[5] Hurly J J, Schmidt J W, Boyes S W, Moldover M R. Virial equation of state of helium, xenon, and helium-xenon mixtures from speed-of-sound and Burnett PpT measurements. Int. J. Thermophys. 1997, 18(3): 579-634.
[6] Habgood H W, Schneider W G. PVT measurements in the critical region of xenon. Can. J. Chem. 1954, 32(2): 98-112.
[7] Bowman D H, Aziz R A, Lim C C. Vapor pressure of liquid argon, krypton, and xenon. Can. J. Phys. 1969, 47(3): 267-273.
[8] Theeuwes F, Bearman R J. The p, V, T behavior of dense fluids V. The vapor pressure and saturated liquid density of xenon. J. Chem. Thermodyn. 1970, 2(4): 507-512.
[9] Nunes da Ponte M, Chokappa D, Calado J C, Clancy P, Streett W B. Vapor-liquid equilibrium in the xenon + ethane system. J. Phys. Chem. 1985, 89: 2746-2751.
[10] Dias L M B, Filipe E J M, McCabe C, Cordeiro T, Calado J C G. Liquid mixtures of xenon with fluorinated species: xenon + sulfur hexafluoride. J. Phys. Chem. B. 2007, 111(19), 5284-5289.
[11] Leadbetter A J, Thomas H E. Density and surface tension of liquid xenon and theory of corresponding states for the inert gas. Trans. Faraday Soc. 1965, 61: 10-19.