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ENGINEERING ESTIMATION METHOD FOR HELIUM VOLUME IN TETHERED AEROSTATS

YuFan Xie
AVIC Special Vehicle Research Institute, Jingmen 448001, Hubei, China.
Corresponding Email: 815199892@qq.com

Abstract: Addressing the engineering need for precise estimation of helium volume within the envelope of tethered aerostats during station-keeping, and to overcome the increased errors of traditional methods in complex environments, a high-precision and practical engineering estimation method is proposed through the construction of a multi-factor coupling model. Firstly, for single influencing factors, two helium volume estimation methods are presented: one based on ground temperature variations and another on atmospheric parameter changes. Further, considering multiple influencing factors during aerial tethering, a multi-factor coupling computational model is developed. This involves simplifying the force model of the tethered aerostat and establishing force balance equations to correlate helium volume with measurable parameters such as wind speed and temperature. Additionally, a wind speed-tension fitting relationship is proposed to correct wind disturbance errors. Validation against field test data demonstrates that the estimation error of this helium volume method is within 5%. The proposed engineering estimation method provides reliable technical support for managing envelope helium volume during the long-term station-keeping of tethered aerostats, exhibiting significant practical application value.
Keywords: Helium volume; Multi-factor coupling; Engineering estimation; Experimental verification

1 INTRODUCTION

Tethered aerostats are lighter-than-air vehicles constrained by a tether, typically comprising an envelope, a tether cable, and ground-based mooring facilities[1][2]. They achieve lift by being filled with a buoyant gas (lighter than ambient air). Lacking a propulsion system, they remain aloft via a tether connected to ground facilities[3]. With technological advancements, helium has largely replaced hydrogen as the buoyant gas, extending station-keeping duration, enhancing payload capacity and economic efficiency. Consequently, tethered aerostats are increasingly deployed for applications such as Earth observation, early warning and detection, communication relay, disaster prevention and mitigation, environmental monitoring, and network coverage in both civil and military domains, becoming a focus of development for many nations[4][6].

The envelope, a critical component, houses the helium whose volume determines the aerostat's buoyancy performance. During station-keeping, the helium volume continuously fluctuates due to the influence of surrounding atmospheric temperature, pressure, and other factors. Furthermore, as deployment scenarios expand[7][9]—spanning plains, plateaus, oceans, and diverse latitudes, longitudes, and altitudes—accurately estimating the in-envelope helium volume based on actual measurement parameters becomes crucial for optimal operational performance. This study investigates helium volume estimation methods, providing a reference for engineering applications.

2 HELIUM VOLUME ESTIMATION METHODS BASED ON SINGLE FACTOR ANALYSIS

2.1 Method Based on Ground Temperature Variation

Assuming constant ground atmospheric pressure, the ideal gas law dictates that helium volume (V_{he}) is proportional to ground temperature (T). Thus, volume increases with rising temperature and decreases with falling temperature. This yields Equation 1:

$$V_{he} = V_{he}^* \frac{T}{T^*} \tag{1}$$

Where:

T^* is the atmospheric temperature at the initial ground state;

T is the atmospheric temperature at the real-time or future ground state;

V_{he}^* is the helium volume at the initial ground state;

V_{he} is the helium volume at the real-time or future ground state.

Given initial ground temperature and helium volume, Equation 1 estimates volume under temperature changes. This method aids in predicting if the ballonet volume reaches its limit during cooling, informing helium replenishment operations.

Comparisons between helium volumes calculated using this ground-temperature-based method and the ground test data, along with error curves, are shown in Figure **1** and Figure **2**. The results indicate minor discrepancies, validating the method's high precision for ground-level helium volume estimation.

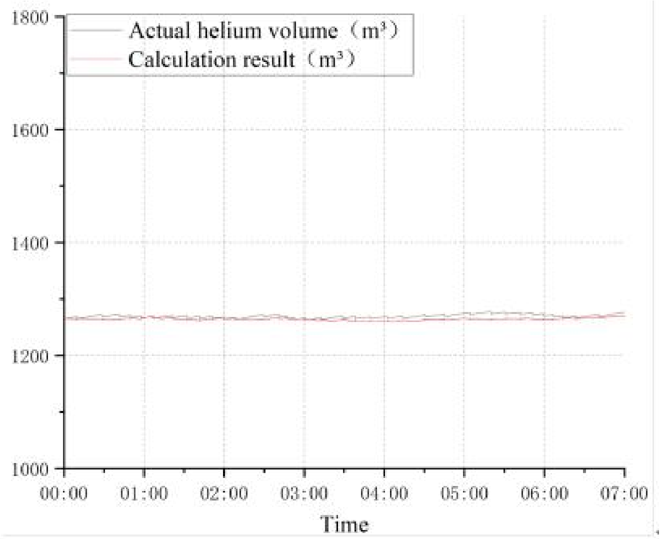

Figure 1 Comparison of Estimated Helium Volume Data and Test Data

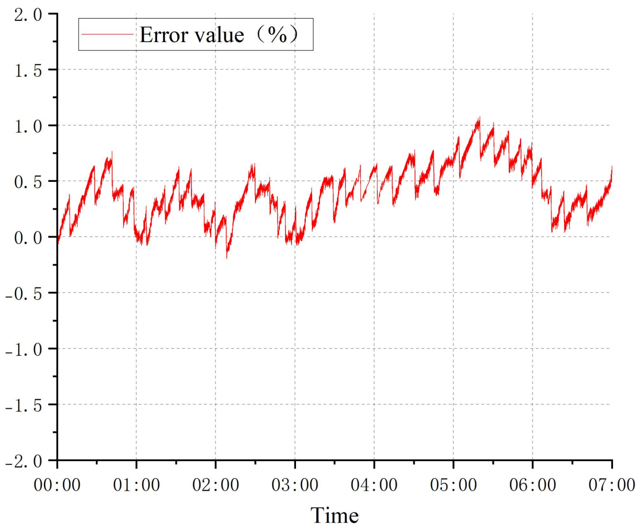

Figure 2 Helium Volume Estimation Error Curve

2.2 Method Based on Atmospheric Parameter Variation

During actual aerostat ascent and recovery, atmospheric temperature and pressure change significantly with altitude compared to the ground-moored state, substantially impacting helium volume. Based on the ideal gas law and standard atmospheric models, expressions for atmospheric temperature and pressure at different altitudes are given by Equation 2 and Equation 3. Considering the combined effect of pressure and temperature on volume, the expression for helium volume at different altitudes is derived as Equation 4:

$$T = T_0 + L \times H \tag{2}$$

$$P = P_0 \times (1 - 2.25577 \times 10^{-5} \times H)^{5.25588} \tag{3}$$

$$V_{he} = V_{he}^{*} \frac{P_0 T}{P T_0} \tag{4}$$

Where:
P is the atmospheric pressure at the current state;
T is the atmospheric temperature at the current state;
P_0 is the atmospheric pressure at the initial altitude state;
T_0 is the atmospheric temperature at the initial altitude state;
L is the temperature lapse rate, typically -0.0065 K/m;
H is the altitude.

2.3 Comparison and Analysis of the Two Estimation Methods

Both methods were used to estimate helium volume during actual ascent, and results were compared against test data. Method 1 used measured ground temperature data at different times with Equation 1. Method 2 used Equation 2 and Equation 3 to obtain atmospheric parameters at various ascent altitudes, then Equation 4 for volume estimation. Comparisons of estimated results against actual helium volumes derived from measured ballonet fullness, along with error curves, are shown in Figure 3 and Figure 4.

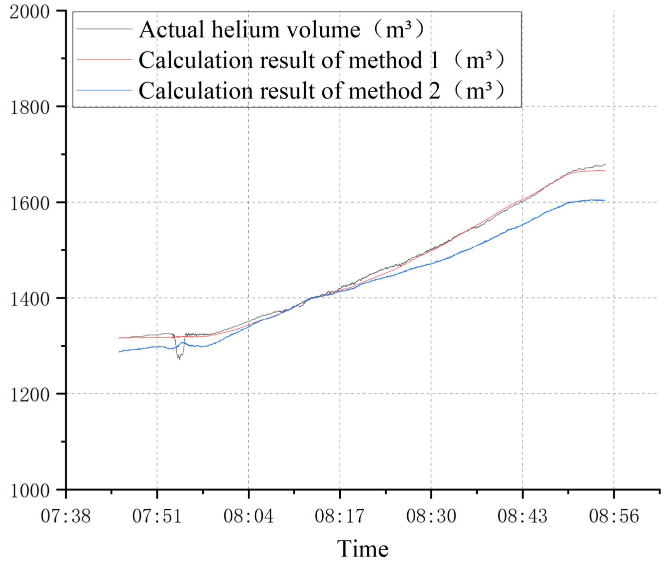

Figure 3 Comparison of Estimated Helium Volume Data and Test Data

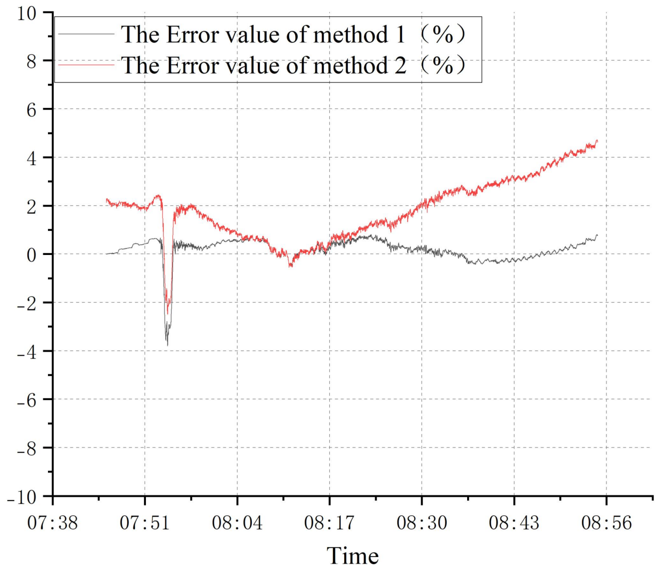

Figure 4 Comparison of Helium Volume Estimation Error Curves

Figure 3 and Figure 4 show that both methods capture the overall trend of helium volume change during ascent. However, estimation errors increase with altitude. Analysis suggests contributing factors include solar radiation heating the envelope interior and inaccuracies in atmospheric temperature data at different altitudes.

Furthermore,Figure 4 indicates Method 1 exhibits higher precision than Method 2 during ascent. Analysis of the atmospheric temperature comparison curve in Figure 5 reveals that Equation 2 predicts monotonically decreasing temperature with altitude. In reality, at a fixed location, ambient temperature increases diurnally while simultaneously decreasing with altitude gain during ascent. These opposing trends moderate actual envelope temperature changes. Method 1 uses measured ground temperature data, whose temporal trend aligns better with the actual conditions experienced during ascent, leading to smaller errors and higher precision.

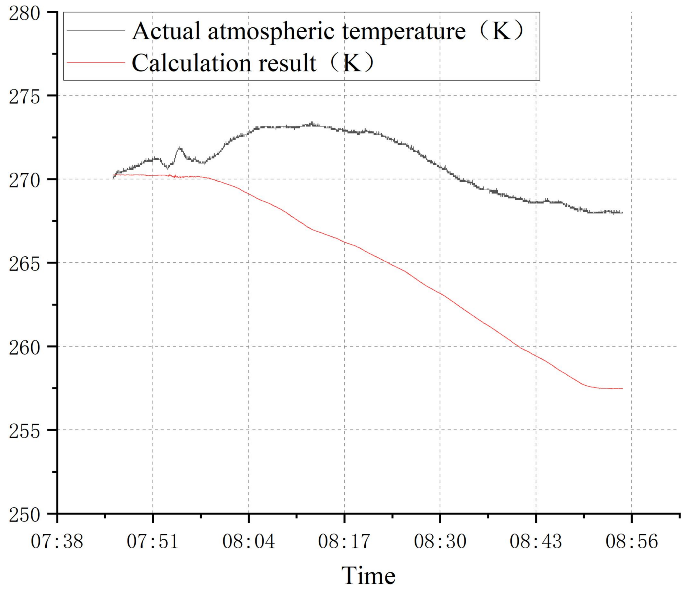

Figure 5 Comparison of Measured and Estimated Atmospheric Temperature Curves

The results and analysis above indicate that estimating helium volume during ascent requires considering both altitude-induced changes in atmospheric parameters and diurnal temperature variations. Estimating atmospheric state parameters under these multiple influences is challenging. Additionally, unknown helium leakage occurs during long-term station-keeping. Therefore, a helium volume estimation method based on multi-factor analysis is urgently needed.

3 HELIUM VOLUME ESTIMATION METHOD BASED ON MULTI-FACTOR ANALYSIS

3.1 Helium Volume Estimation Method Considering Multiple Factors

During station-keeping, environmental wind causes continuous changes in tether inclination angle, envelope pitch angle, and trajectory, resulting in a complex overall force model. Considering factors like tether angle, wind speed, pitch angle, and angle of attack, the force model is simplified.

The simplified force model is shown in Figure 6. In the tethered state, the envelope is in equilibrium under the action of: upward buoyant force from helium (F_b), aerodynamic lift from fins (F_L), structural weight (G_{struct}), and tension at the tether's upper end (T_1).

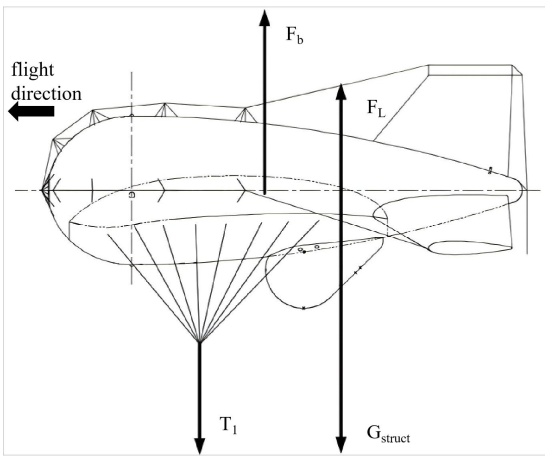

Figure 6 Simplified Force Model of Tethered Aerostat

Analyzing these forces: T_1 can be measured by onboard sensors; G_{struct} is known; the aerodynamic lift coefficient C_L is determined during design, enabling calculation of F_L. Therefore, the net buoyant force (F_{net}) generated primarily by the helium can be derived from the force balance Equation 5. As buoyancy is strongly related to helium volume, the volume during station-keeping can be solved.

The force balance equation is:

$$F_{\text{net}} = T_1 + G_{\text{struct}} - F_L \tag{5}$$

Where:

F_{net} represents the net buoyant force;

T_1 represents the tension at the upper end of the tether;

G_{struct} represents the structural weight;

F_L represents the aerodynamic lift force.

The net buoyant force F_net is derived through Equation 5 to Equation 9, resulting in Equation 10 and Equation 11:

$$F_{\text{net}} = F - G_{\text{air}} - G_{he} \tag{6}$$

$$F = \rho_{air} V_{\text{env}} \tag{7}$$

$$G_{\text{air}} = \rho_{air} V_{\text{he}} \tag{8}$$

$$G_{he} = \rho_{he} (V_{\text{气囊}} - V_{\text{side-env}}) \tag{9}$$

$$F_{\text{net}} = (\rho_{air} - \rho_{he})(V_{\text{env}} - V_{\text{side-env}}) \tag{10}$$

$$F_{\text{net}} = (\rho_{air} - \rho_{he}) V_{he} \tag{11}$$

T_1 is measurable. G_{struct} is known. F_L relates to wind speed (V_w) and the aerodynamic lift coefficient (C_L), expressed as:

$$F_L = \frac{1}{2} P v^2 \times V^{\frac{2}{3}} \times C_L \tag{12}$$

C_L depends on the angle of attack (α):

$$C_L = 0.029 \times (\alpha - 0.53) \tag{13}$$

Deriving from Equation 5 to Equation 13, the expression for helium volume V_{he} is:

$$\rho_{air}^{*} = 0.12492 \times \left(1 - 0.0000225577 \times H\right)^{4.25588} \times 9.80665 \tag{14}$$

$$\rho_{air} = \rho_{air}^{*} \times \frac{T^*}{T} \tag{15}$$

$$\rho_{he}^{*} = \frac{c}{n_{he}} \times 4 + \frac{(1-c)}{n_{air}} \times 29 \tag{16}$$

$$\rho_{he} = \rho_{he}^{*} \times \frac{T^*}{T} \tag{17}$$

$$V_{he} = \frac{T_1 + G_{\text{结构}} - \frac{1}{2} P v^2 \times V_{\text{env}}^{\frac{2}{3}} \times 0.029 \times (\alpha - 0.53)}{(\rho_{air}^{*} - \frac{c}{n_{he}} \times 4 + \frac{(1-c)}{n_{air}} \times 29) \times \frac{T^*}{T}} \tag{18}$$

Where:

V_{env} represents the envelope volume;

ρ_{air}^{*} represents the standard atmospheric density;

ρ_{air} represents the actual atmospheric density;

ρ_{he}^{*} represents the helium density at the ground-moored state;

ρ_{he} represents the helium density at the actual temperature;

T^* represents the ground temperature;

T represents the actual temperature;

c represents the measured helium purity on the ground;

n_{he}、n_{air} represent the molar masses of helium and air, respectively.

This estimation method depends on factors such as helium purity, wind speed, upper tether tension, and atmospheric pressure. During the aerial phase, upon measuring parameters like T_1, helium volume can be estimated using Equation 18.

3.2 Correction of the Estimation Method Based on Experimental Data

Figure 7 to Figure 11 show that during station-keeping, the maximum environmental wind speed reached 10.7 m/s. As per the derivation, wind speed affects aerodynamic lift (F_L), and the upper tether tension (T_1) fluctuates significantly with wind speed. In reality, the balloon and tether undergo coupled motion; the tether constrains the balloon, so T_1 increases with wind speed during gusts. Consequently, errors in T_1 measurement due to wind effects cause significant deviations in the estimated helium volume. Measuring tether state parameters during flight is difficult. Therefore, establishing a relationship between wind speed and T_1 is proposed to reduce errors induced by wind-affected tension measurements and improve estimation accuracy.

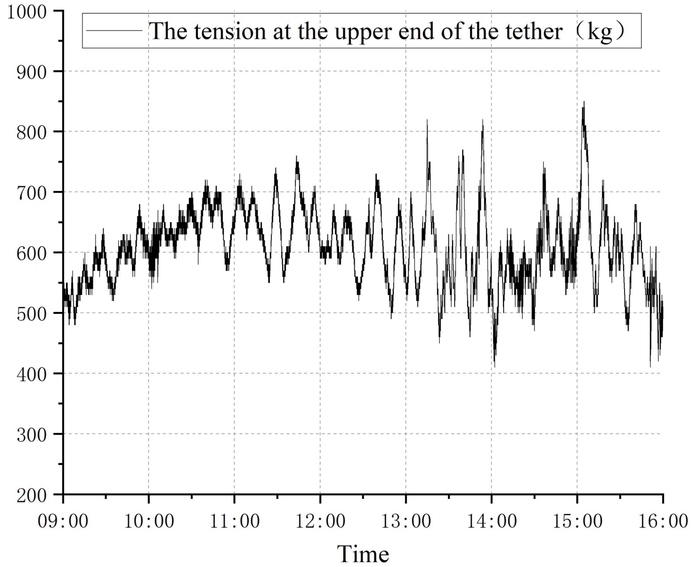

Figure 7 Measured Variation of Upper Tension during Station-Keeping

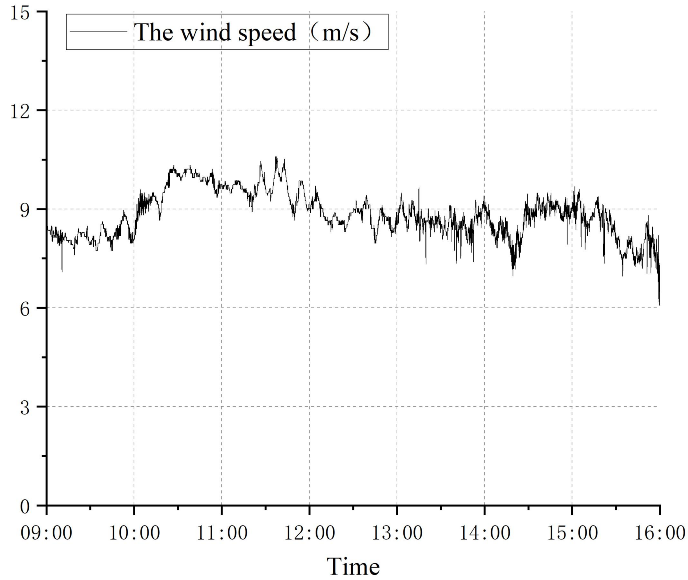

Figure 8 Measured Variation of Wind Speed during Station-Keeping

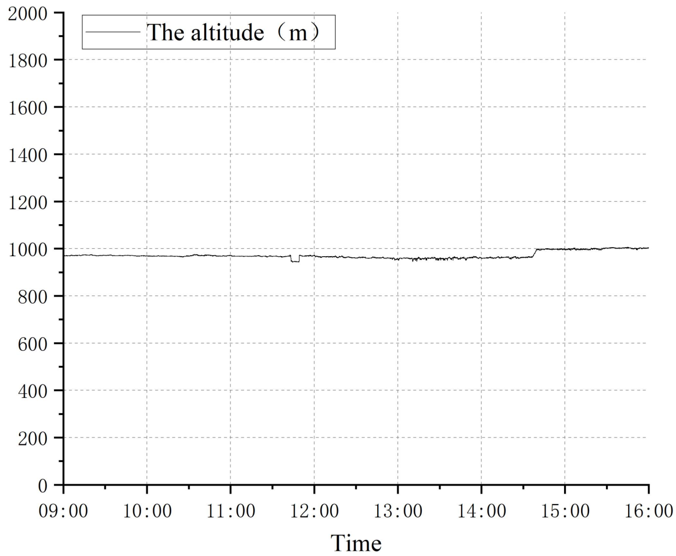

Figure 9 Measured Variation of Altitude during Station-Keeping

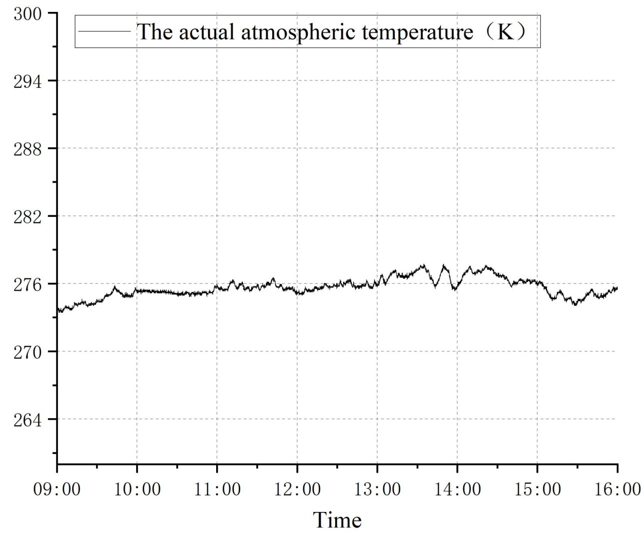

Figure 10 Measured Variation of Atmospheric Temperature during Station-Keeping

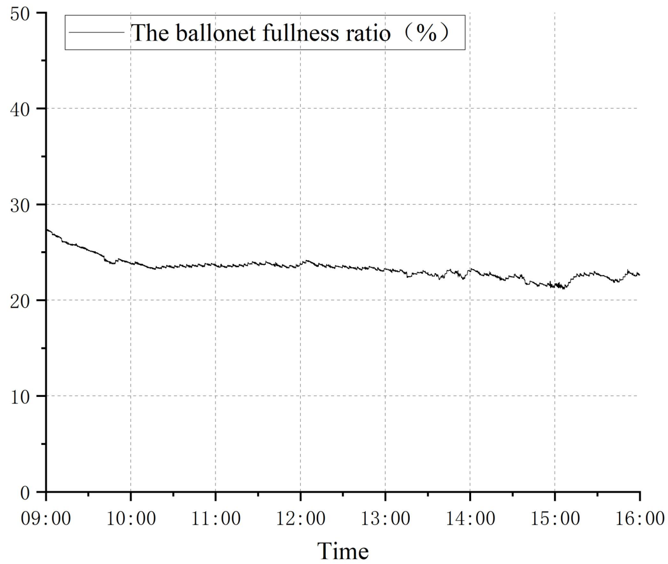

Figure 11 Measured Variation of Ballonet Fullness Ratio during Station-Keeping

A wind speed-upper tension relationship is proposed for rapid estimation:

$$T_1 = \eta v + T_1^* \tag{19}$$

Where:

η represents the rate of change of upper tension with wind speed;

T_1^* represents the upper tension under windless conditions.

Fitting the equation to measured data yielded:

η ≈ 8 (units: force/wind speed, e.g., N/(m/s)

T_1^* ≈ 2022.5 kg (force units implied)

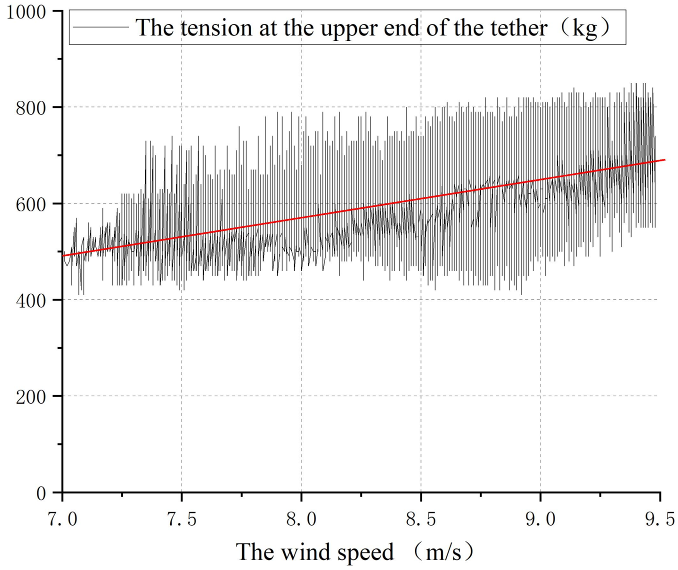

Figure 12 Wind Speed vs. Upper Tension Fitting Equation from Station-Keeping Data

Substituting Equation 19 into Equation 18 gives the corrected estimation formula:

$$V_{he} = \frac{(T_1 - \eta v) + G_{struct} - \frac{1}{2} P v^2 \times V_{env}^{\frac{2}{3}} \times 0.029 \times (\alpha - 0.53)}{(\rho_{air}^{\ *} - \frac{c}{n_{he}} \times 4 + \frac{(1-c)}{n_{air}} \times 29) \times \frac{T^*}{T}} \tag{20}$$

The estimated helium volumes using the corrected formula, compared against actual ascent test data, are shown in Figure 13 and Figure 14. The figures show that the estimated values fluctuate within the range of the measured helium volumes, consistent with test data variability. The estimation error remains within 5%, demonstrating that this multi-factor helium volume estimation method achieves high precision for tethered aerostats during station-keeping.

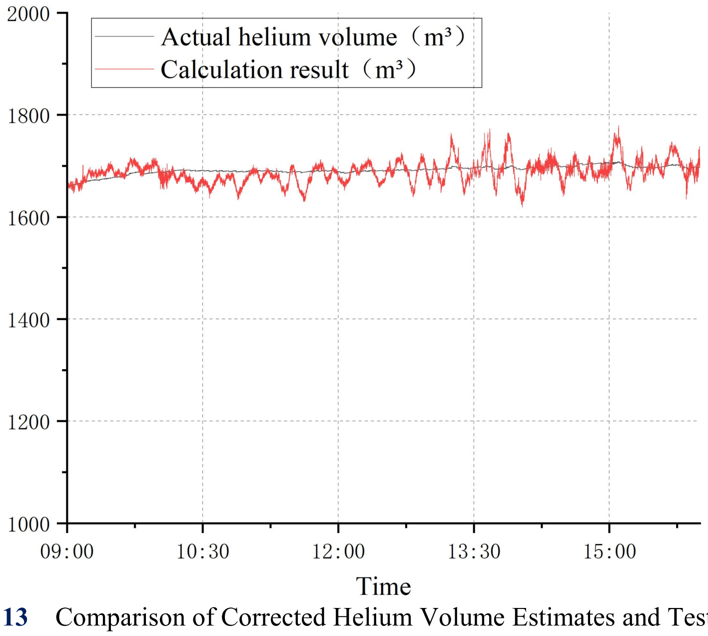

Figure 13 Comparison of Corrected Helium Volume Estimates and Test Values

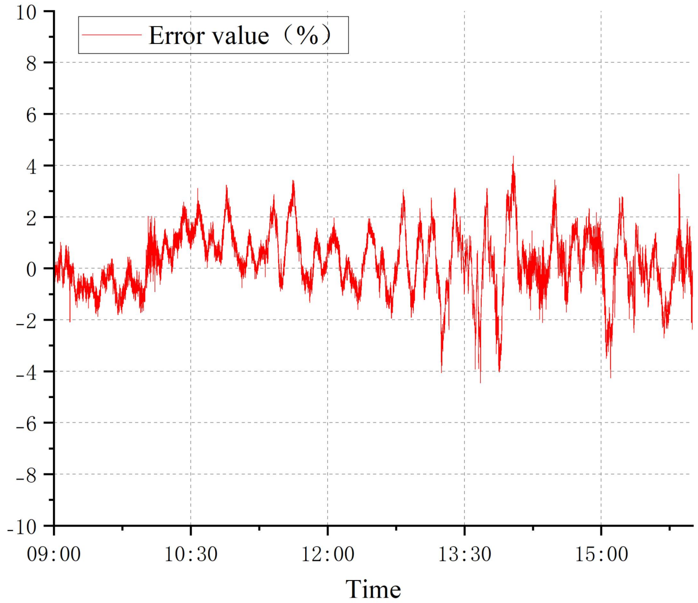

Figure 14 Magnitude of Error between Corrected Estimates and Test Values

4 CONCLUSION

This study systematically investigates engineering methods to meet the requirement for precise estimation of envelope helium volume in tethered aerostats during station-keeping. The main conclusions are as follows:

1.Single-factor methods (ground temperature and atmospheric parameters) were investigated. The ground-temperature-based method proved highly accurate under ground-moored conditions, suitable for predicting ballonet volume limits during cooling to inform helium replenishment. The atmospheric-parameter-based method reflected volume trends during ascent, but its error increased significantly with altitude, primarily limited by unaccounted factors like solar radiation heating and deviations in measured atmospheric parameters. Both methods exhibit limited applicability in the complex dynamic environment of aerial tethering.

2.A high-precision helium volume estimation method suitable for aerial tethering was proposed. This method correlates helium volume with real-time measurable key parameters (upper tether tension, wind speed, atmospheric temperature, etc.) by simplifying the aerostat's force model and establishing force balance equations. Specifically, a wind speed-tension fitting relationship was introduced to correct measurement errors in tension caused by wind disturbances. Model correction and validation using field test data demonstrated significantly improved accuracy. The corrected multi-factor coupling estimation method achieves errors within 5%, effectively overcoming the precision limitations of single-factor methods in complex environments.

3.The proposed high-precision, practical multi-factor coupling helium volume estimation method provides reliable technical support for real-time monitoring and management of envelope helium volume during long-term station-keeping missions of tethered aerostats. It significantly enhances estimation accuracy and engineering applicability in complex environments, holding substantial practical value. Future work could integrate intelligent sensor networks and adaptive algorithms to optimize robustness and real-time performance under extreme or transient meteorological conditions.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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