Hybrid Temperature Compensation System Using Active Voltage Control and Deep Learning for Scintillation Detectors

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1. Introduction

Robust gamma-ray spectroscopy is essential for radioisotope identification in severe nuclear accident environments. Within containment buildings, detectors are exposed to cumulative radiation doses of several hundred kGy and temperatures exceeding 185°C over a 3-day period. These extreme conditions cause severe fluctuations in the overall detector gain; in particular, high temperatures significantly degrade the gain of the photomultiplier tube (PMT) in scintillation detectors.

Existing approaches to compensate for this gain loss face critical limitations at extreme temperatures. Hardware-based methods restore gain by increasing the applied high voltage (HV) [1]. However, above 150°C, the required compensation voltage exceeds the physical operating limits of the PMT. Software-based deep learning (DL) approaches can quantify radioisotopes without hardware compensation [2], but their maximum operating temperature is generally limited to 150°C. Beyond this threshold, essential spectral features—such as photopeaks and Compton continua—are severely degraded due to severe output degradation, rendering pure DL methods ineffective.

To overcome these limitations, this study proposes a hybrid temperature compensation system integrating active HV control with a Bidirectional Long Short-Term Memory (BiLSTM) model. The hardware architecture mitigates initial gain loss to preserve essential spectral features, while the BiLSTM model interprets residual spectral distortions. This synergistic approach enables accurate multi-isotope spectral analysis even at the extreme temperature of 185°C.

2. Methods and Results

2.1. System configuration

The hardware architecture consists of a Ce:GPS scintillator ($3 \times 3 \times 5$ mm^3, OXIDE Corporation) optically coupled to a photomultiplier tube (R3991AH-07, Hamamatsu). Thermal data acquisition is performed using a surface-mounted K-type thermocouple (SA3-K-120, Omega) and a precision thermocouple digitizer (MAX31856, Analog Devices Inc.). An FPGA-based ADC-SoC platform serves as the central data acquisition and control unit. It processes the PMT pulse signals, monitors the thermal data, and executes the active compensation logic by interfacing with a digital-to-analog converter (AD7801, Analog Devices Inc.) to dynamically regulate the high-voltage power supply module (C9619-50, Hamamatsu).

2.2. Active Voltage Control (Hardware)

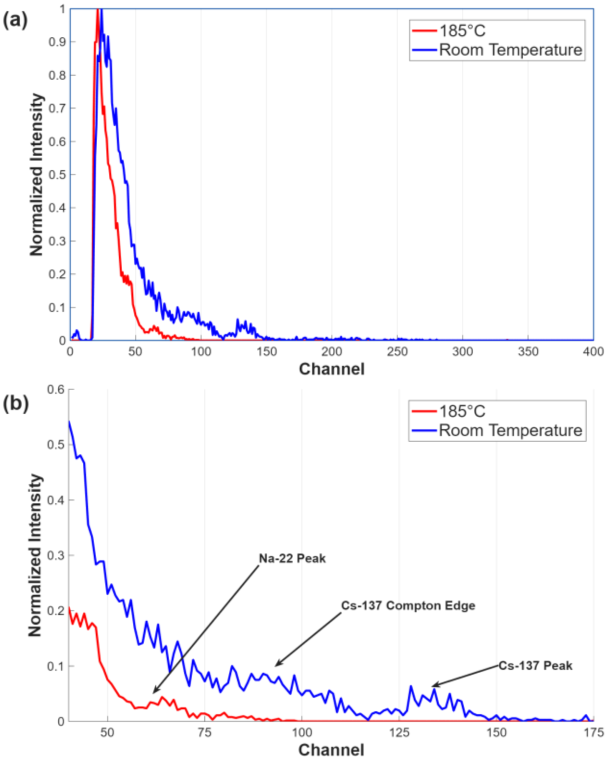

Fig. 1 (a) Full pulse-height spectra illustrating thermal degradation. The room temperature baseline is obtained with a single Cs-137 source, while the 185°C uncompensated spectrum incorporates both Cs-137 and Na-22. (b) Zoomed-in spectra demonstrating the loss of photopeaks for Na-22 (channel 62) and Cs-137 (channel 133), along with the Cs-137 Compton edge (channel 89).

At 185°C without voltage compensation, essential spectral features such as photopeaks were severely degraded (Fig. 1). To address this, an active temperature-voltage control relationship was derived experimentally. A baseline Cs-137 (82.7 µCi) spectrum was acquired at 23°C with a 1600V PMT bias, establishing the reference position of the 662 keV photopeak. The detector assembly was heated sequentially to 50°C, 75°C, 100°C, 125°C, and 150°C using a hot plate. A thermistor (TT2-10KC3-10, TEWA Sensors LLC) was mounted directly on the PMT window to monitor the PMT temperature precisely. At each thermal step, the HV was manually adjusted to realign the 662 keV photopeak with its reference position.

Data acquisition ceased at 150°C because the requisite compensation voltage reached the maximum applicable voltage limit of the PMT. Polynomial regression was applied to the acquired dataset to obtain the temperature-dependent voltage compensation function (Eq. (1)).

$$(1)\ V(T) = 0.01192T^2 - 0.4832T + 1604.12$$

This algorithm was embedded into the control logic. Applied voltage was strictly constrained between 1600V and 1780V to prevent hardware failure. When evaluated at 185°C, the required compensation voltage exceeded the 1780V hardware limit. Consequently, the maximum applied bias was insufficient to fully restore the gain, resulting in partial gain restoration that yielded a shifted spectral profile structurally equivalent to an uncompensated detector operating at 75°C (Fig. 2).

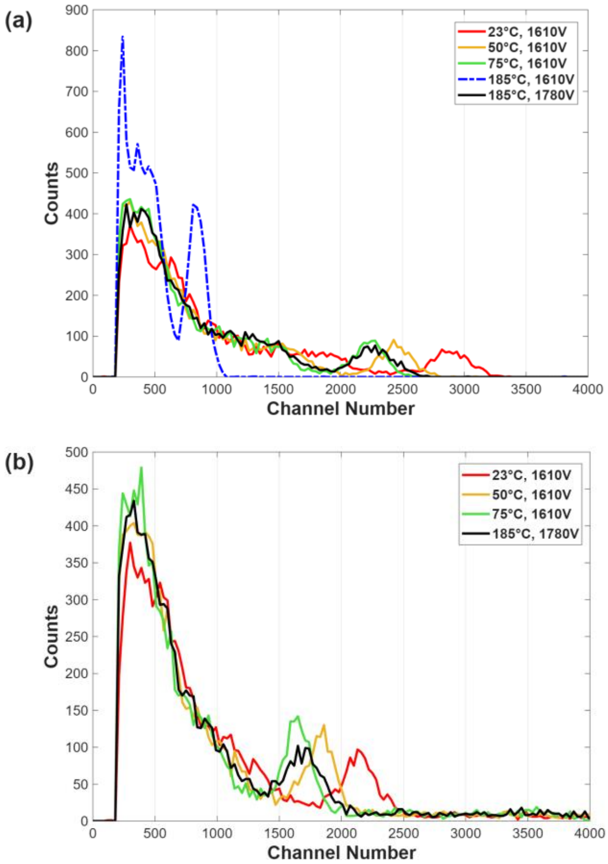

Fig. 2 Energy spectra of uncompensated and hardware-compensated (a) Cs-137 and (b) Na-22 under different temperatures. The gain is not fully restored at 185°C, yielding a shifted spectral profile.

2.3. BiLSTM-based Compensation (Software)

The spectral features of gamma-ray interactions—photopeaks, Compton edges, and continua—are physically correlated across energy channels; for instance, a photopeak at a given energy necessarily produces a Compton continuum extending to lower channels. This long-range inter-channel dependency makes the spectrum analogous to sequential data. A BiLSTM architecture was therefore adopted for its bidirectional processing capability. Compared to an initially tested 1D ResNet (~3.5M parameters), the BiLSTM (~570K parameters) achieved superior accuracy with significantly fewer parameters. Regarding computational efficiency and real-time applicability, the hardware actively updates the temperature every 143.8 ms. Furthermore, a single inference of the trained BiLSTM model requires only about 50 ms on a standard GPU. Because actual gamma-ray spectrum acquisition generally takes more than several seconds, this model inference time is negligible compared to the measurement cycle, confirming the proposed system's suitability for real-time radionuclide analysis.

Since the required voltage at 185°C exceeded the hardware limit (1780V), the hardware compensation alone was insufficient, necessitating BiLSTM post-processing. Instead of explicitly correcting physical anomalies such as photopeak shifts, broadened full widths at half maximum (FWHM), and reduced signal-to-noise ratios (SNR), the BiLSTM network was utilized to implicitly interpret the residual distortions.

The model was trained to recognize temperature-degraded spectral patterns directly from the dataset. By analyzing the synthesized composite datasets generated via Python, the network infers the quantitative ratios of five target isotopes (Cs-137, Ba-133, Co-60, Na-22, and Eu-152) directly from the distorted spectra.

2.4. Results and Discussion

The hardware pre-processing constrained the initial spectral variance allowing the BiLSTM model to generalize to 185°C utilizing training data from only three temperatures (23°C, 50°C, and 75°C). The hybrid system successfully quantified isotope ratios at 185°C, achieving an overall Mean Absolute Error (MAE) of 2.62% for Cs-137 and 3.45% for Na-22 (Fig. 3). Precision optimized further to an MAE of 2.36% within the critical 40-60% target ratio interval.

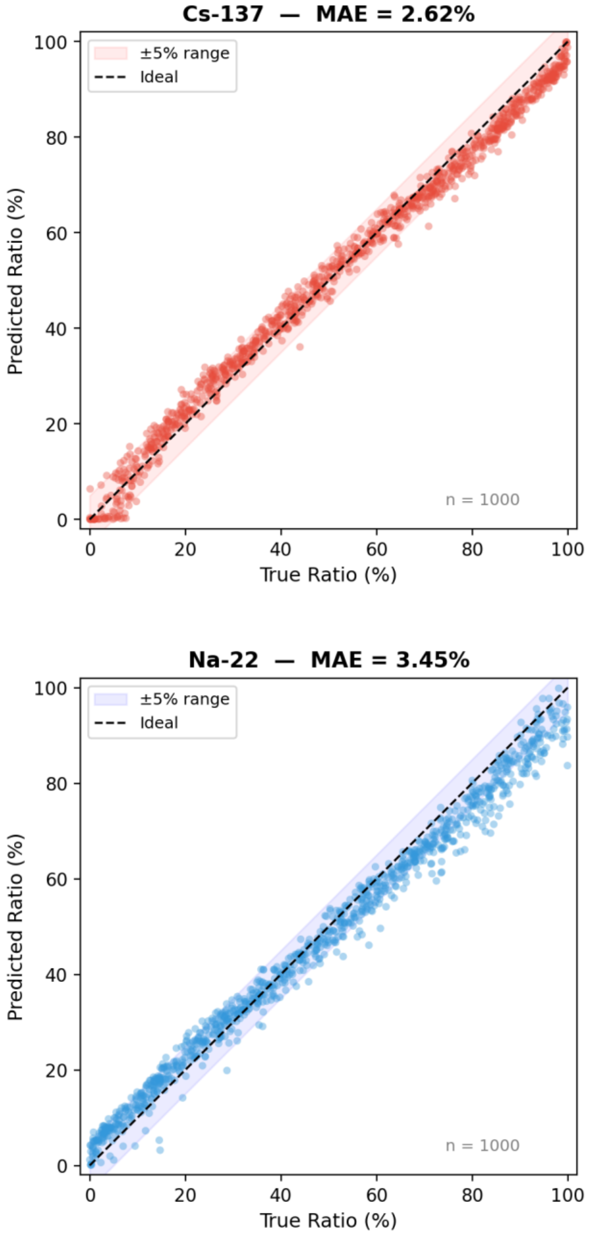

Fig. 3 Correlation between true and predicted nuclide ratios (Cs-137 and Na-22) using the hybrid compensation system. Predictions were performed on 1,000 test spectra synthesized from 50,000 empirical peaks acquired at 185°C under 1780V hardware compensation.

3. Conclusions

A hybrid temperature compensation system was developed for PMT-based scintillation detectors, enabling continuous and uninterrupted monitoring across the entire temperature range from room temperature up to 185°C in severe accident environments. The integration of algorithmic HV control and a BiLSTM network bypasses physical hardware voltage limits and minimizes deep learning training data requirements. This architecture ensures reliable radionuclide identification under extreme thermal stress.

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