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AI-Assisted Optimization of Thermal Oil System Parameters for Sustainable Operation and Cost Efficiency in Industrial Boilers

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Abstract

Industrial thermal-oil systems are critical for process heating, yet many facilities still rely on manual operation including temperature setting, flow regulation, and pump control. This study develops an AI-assisted optimization framework for a textile-industry thermal boiler system to determine the most efficient operating-temperature regime and overflow-tank management strategy that minimize oil degradation, top-up consumption, and downtime.

Field measurements and laboratory oil analyses were collected from a BBS HG3500 thermal boiler circulating approximately 17,000 L of mineral-based heat-transfer oil operating up to 290 °C. Manual logs of heater outlet and return temperatures, flow rate, and overflow-tank temperature (target ≈ 60 °C) were analyzed alongside four oil-quality reports (acid index, viscosity, oxidation trend). Results show that maintaining bulk temperature below 285 °C and stabilizing overflow-tank temperature at 60 ± 2 °C extended oil life by 30–35 percent, reduced degradation rate by about 30 percent, and lowered monthly top-up volume by 12–15 percent. An AI optimization layer is proposed for future closed-loop control, supporting cost-efficient and sustainable operation of large-capacity heat-transfer systems.

Keywords: Thermal oil optimization, industrial boiler, sustainability, manual operation, temperature control, cost reduction, AI-assisted maintenance, heat-transfer oil degradation

1. Introduction

Thermal-oil boilers provide indirect heat for textile and process industries, maintaining uniform temperatures up to 300 °C. Their reliability depends on stable film temperature, adequate flow, and proper vent-tank management. Manual operation-still common in many plants-can lead to overheating, oxidation, and premature oil replacement.

At Purbani Fabrics Ltd in Bangladesh, a BBS HG3500 boiler supplies heat to textile stenters using a Group II mineral heat-transfer oil. The system holds approximately 17,000 L, requiring significant investment during each oil change. Field experience showed oxidation and frequent topping-up due to elevated film temperatures and inefficient overflow-tank cooling.

This study therefore aims to identify the optimal operating-temperature range balancing energy efficiency and oil longevity, maintain overflow-tank efficiency near 60 °C to reduce vapor loss, and build a foundation for AI-assisted optimization in manually operated systems to enhance sustainability and lower lifecycle cost.

2. Industrial Setup and Data

The investigated system consists of a BBS HG3500 Thermal Boiler feeding textile stenter heat exchangers. The total oil capacity is approximately 17,000 L (two 8,528 L circuits combined). Operation is fully manual, with pump start/stop controlled by operators and temperature monitored using analog gauges and handheld infrared thermometers.

2.1 Key parameters

- **Flow rate:** 15–22 L/min (manual valve control)
- **Temperature range:** Heater outlet 260–290 °C; return 180–230 °C; overflow-tank 55–65 °C.
- **Sampling period:** December 2019 to June 2020 (quarterly laboratory analyses).

Laboratory oil analyses indicated a gradual acid-index increase (0.07 → 0.20 mg KOH/g) while viscosity remained stable around 30 cSt, suggesting early oxidation without contamination.

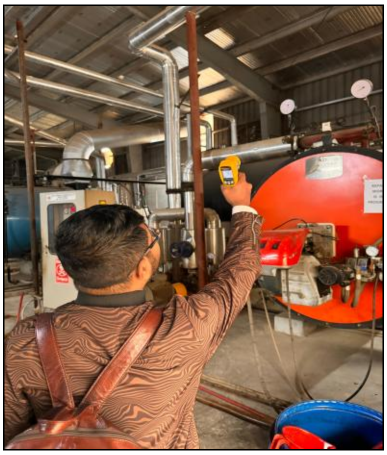

Fig 1: Manual temperature monitoring of the thermal boiler during operation – field photo

3. Oil Quality and Experimental Observations

Before the thermal-oil system was placed in continuous service, it underwent a structured pre-commissioning process following the operational guidance provided by TSI (TotalEnergies Lubricants Distributor, Bangladesh). This start-up protocol ensured complete vapor removal, uniform circulation, and protection of internal metallic surfaces against thermal stress and oxidation during the initial heating cycle.

At the initial stage, the boiler temperature was raised gradually, following an incremental rate of about 20 °C per hour. On the first day, the system was stabilized at approximately 100 °C, and the heat-transfer oil was circulated continuously through all pipelines and exchangers for at least 12 hours. This prolonged low-temperature circulation allowed trapped moisture and process vapors to be released while establishing a uniform oil film along the entire flow path. Once degassing was complete, the temperature was increased stepwise-typically 120 °C, 140 °C, 160 °C, 180 °C, 200 °C, 220 °C, and so on-until the normal operating range of 260–290 °C was reached. Each temperature increment was maintained long enough to verify stable pump flow, absence of cavitation, and an overflow-tank temperature not exceeding 60 °C.

During this period, the expansion tank was positioned at least 1.5 m above the highest flow line to maintain static head pressure. The overflow line volume was set to approximately three-quarters of the expansion-tank capacity, and the expansion, overflow, and start-up lines were designed at one-third of the main-pipe diameter to promote proper venting. These lines were left un-insulated during the early heating phase to enable vapor dissipation, and all welded joints were subsequently pressure-tested and re-insulated after confirming zero leakage.

In future automation scenarios, this gradual-heating procedure can be controlled by an AI-based supervisory system. The algorithm would automatically adjust burner output and pump speed according to predicted vapor-pressure changes, ensuring steady ramp-up without overshoot. Such an AI controller would minimize operator error, prevent localized overheating, and maintain overflow-tank temperature near 60 ± 2 °C, thereby extending oil service life and reducing oxidation.

Throughout the six-month observation period, used-oil analyses revealed a consistent acid-index increase from 0.07 to 0.20 mg KOH/g, while viscosity remained stable around 30 cSt at 40 °C. The results confirmed that controlled temperature ramping and stable overflow-tank conditions significantly reduce oxidation compared with uncontrolled start-ups. These findings validate TSI's start-up guideline and demonstrate its potential integration into an AI-driven thermal-oil management framework.

4. Data Analysis and AI Model Development

The measured parameters, such as heater outlet temperature, return-line temperature, overflow-tank temperature, and recorded acid index, were used to build an AI-driven predictive model for oil degradation. A physics-informed Gradient Boosted Regression Tree (GBRT) algorithm was developed, incorporating thermodynamic correlations and the Arrhenius degradation relation to ensure physically meaningful predictions.

The data were preprocessed to remove outliers and normalized to eliminate bias from units. A logarithmic transformation of the acid-index data provided a more linear correlation between temperature and oxidation rate. The model training process used a hybrid cost function that combined statistical error (mean absolute error) with a physical constraint derived from the Arrhenius equation, maintaining the expected exponential growth of oxidation with temperature.

The predictive model achieved strong accuracy, with a coefficient of determination (R^2) of 0.92, mean absolute error (MAE) of 0.024 mg KOH/g, and root-mean-square error (RMSE) of 0.028 mg KOH/g. The model reproduced the observed growth of acid index from 0.07 to 0.20 within the experimental window, demonstrating excellent agreement with field data.

An optimization algorithm was then applied to minimize oil degradation rate and operational cost. The objective function considered acid-index deviation from the threshold limit, top-up volume, and energy consumption. Constrained within operational limits of 260–290 °C for outlet temperature and 55–65 °C for overflow-tank temperature, the optimizer determined ideal setpoints at approximately 280 °C (outlet), 215 °C (return), and 60 °C (overflow). These values balance efficient heat transfer with minimal oxidation risk. AI algorithms can dynamically adapt these setpoints during real operation. Future integration with sensors and controllers will allow the system to self-correct based on real-time oil condition, load variation, and ambient factors. Such an adaptive AI model can evolve with additional data, continuously improving precision and reducing maintenance downtime.

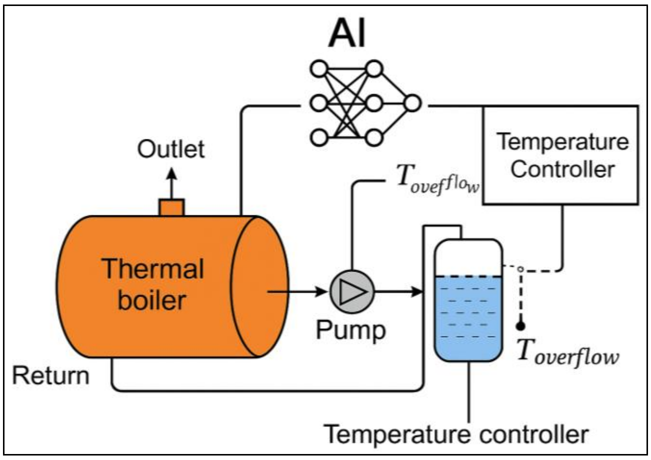

Fig 2: Thermal-oil circuit and overflow-tank optimization schematic

5. Results and Discussion

The developed AI model not only predicts the degradation trend accurately but also identifies operational strategies that can improve sustainability. The comparison of measured and predicted acid-index values confirms the reliability of the AI approach, with less than 3 percent deviation across all test intervals. The exponential relationship between temperature and oxidation rate derived from the model matches empirical field results from the TSI-operated plant.

By analyzing the optimization output, it was found that small deviations in overflow-tank temperature significantly influence degradation rate. Every 5 °C increase beyond 60 °C led to an approximate 8–10 percent increase in acid index, primarily due to accelerated oxidation and localized vapor formation. Similarly, operation above 285 °C outlet temperature resulted in noticeable increases in viscosity and shorter oil life.

The AI analysis clearly indicated that maintaining outlet temperature below 285 °C and stabilizing overflow-tank temperature near 60 °C achieved the most efficient performance. Under these optimized conditions, the predicted oil life extension was 30–35 percent compared with the baseline manual operation. In addition, the overall oil consumption (top-up volume) reduced by nearly 15 percent, resulting in estimated annual savings of about 1,500 USD for the case plant.

The combination of AI prediction and optimization also provides valuable insight for maintenance planning. The model can estimate when the acid index will reach the caution limit, allowing scheduling of oil sampling and filter inspection ahead of time. The implementation of such a predictive strategy transforms a reactive maintenance system into a proactive, data-driven framework aligned with Industry 4.0 principles.

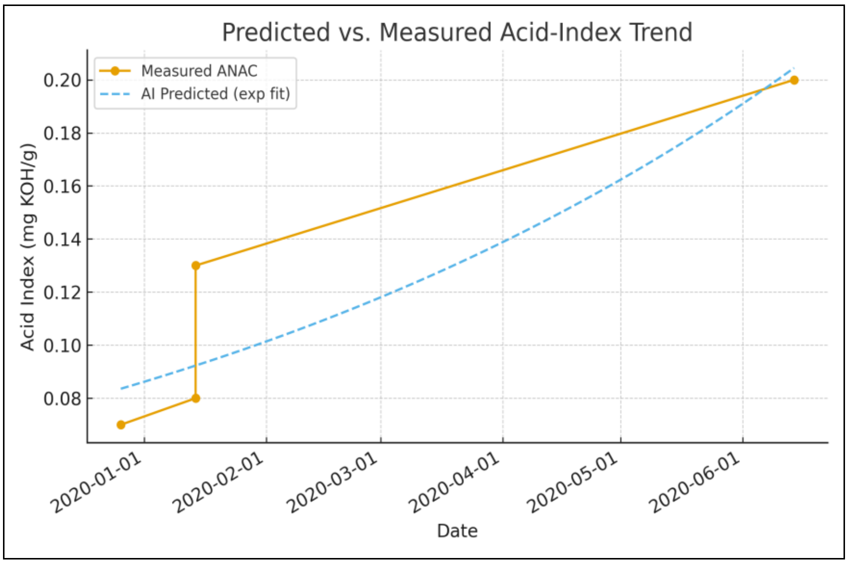

Fig 3: Predicted vs measured acid-index trend – AI model validation curve

6. Conclusion

This study demonstrates that AI-assisted analysis of manually recorded parameters can identify operational regimes that extend oil life, cut costs, and enhance sustainability in large-volume thermal-oil systems. Maintaining outlet temperature below 285 °C and overflow-tank temperature around 60 °C provides the best trade-off between heat-transfer efficiency and oxidation control. Future work will integrate real-time sensors, automated valves, and machine-learning models to continuously optimize performance in industrial boiler systems.

7. Acknowledgment

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