# Surface temperature before and after removable modular insulation on irregular industrial components: a CAD-reconstruction method validated by infrared thermography—case study on a 6-ton steam boiler

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## Abstract

Industrial steam boilers and thermal process equipment pose workplace hazards through high outer-surface temperatures. The incumbent approach to component-level surface-temperature assessment relies on equivalent-length approximations (ASTM C1129, ISO 12241) calibrated to cylindrical geometries, which introduces substantial uncertainty when applied to irregular access components (valves, flanges, doors) with non-standard surface morphologies. Radiometric infrared thermography (IRT) provides field-measured surface temperatures but offers no predictive capability for modified insulation configurations. This case-study paper presents a field-validated methodology for estimating outer-surface temperature reduction under modular removable insulation: (i) radiometric IRT survey of bare component surfaces (FLIR S62 Pro, ISO 18434-1 calibration, $\varepsilon = 0.90$, ±2 °C uncertainty); (ii) CAD reconstruction extracting true outer surface areas with a +12% allowance for bolts, seams, and irregularities; (iii) ISO 12241 steady-state heat-transfer prediction for a standardized 100 mm mineral-wool panel ($\lambda = 0.045$ W/m·K, external coefficient $h = 10$ W/m²·K, T_ambient = 25 °C); and (iv) direct validation against FLIR-measured insulated-surface temperatures. The method is demonstrated on a single-flame-tube fire-tube steam boiler (≈6 t/h; surveyed in 2025, 38 pixel-level measurements across three component types). All insulated surfaces remained below the ISO 13732-1 touch-safety threshold of 45 °C: front door 30 °C (bare 96 °C, model 28.1 °C), burner flange 30 °C (bare 146 °C, model 30.2 °C), and steam valves 36 °C (bare 190 °C, model 32.1 °C). Measured insulated temperatures exceeded ideal model predictions by 0–4 °C (mean 1.9 °C), consistent with thermal bridging at seams and maintained access points. The dataset and reproducible CAD-to-prediction workflow provide a single-case, equipment-specific, field-validated reference for component-level surface-temperature estimation. This case study demonstrates feasibility but requires additional validation on other equipment types, geometries, and operational conditions before generalization to broader industrial classes.

**Keywords:** thermal insulation, surface temperature, infrared thermography, touch-safety, CAD-based thermal prediction, case study, industrial equipment

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## 1. Background & Summary

Industrial steam boilers, HVAC systems, and process vessels generate significant radiant and convective heat loss from their outer surfaces and attached components. Component-level surface temperature assessment is critical for workplace safety (ISO 13732-1 establishes 45 °C as the threshold for prolonged skin contact in occupational settings) and for identifying candidates for thermal retrofit interventions.

The standard engineering approach to heat loss from irregular components—valves, flanges, doors, and access ports—relies on equivalent-length approximations (e.g., a valve modeled as 12–24 m of equivalent pipe) per ASTM C1129 or ISO 12241, combined with vendor heat-transfer correlations developed for regular cylindrical and rectangular geometries. This incumbent method introduces substantial uncertainties when applied to complex access assemblies with non-standard surface morphologies, making validation against field measurements difficult.

Radiometric infrared thermography (IRT) has emerged as a non-invasive diagnostic tool for thermal condition monitoring in industrial settings. Per ISO 18434-1 and ASTM E1933, calibrated thermal imaging cameras (accounting for emissivity, atmospheric attenuation, and reflected ambient temperature) can achieve measurement uncertainty within ±2 °C for metallic surfaces. However, IRT alone provides only a snapshot of surface temperatures under current operational conditions; it does not isolate the thermal performance of a proposed retrofit or yield predictive surface-temperature estimates under modified insulation configurations.

A systematic gap exists in the published literature: there is no widely cited methodology that combines (i) radiometric IRT quantification of bare-equipment outer-surface temperatures, (ii) computer-aided design (CAD) reconstruction of complex irregular components to extract true outer surface areas, (iii) steady-state analytical heat-transfer modeling (ISO 12241 / ASTM C680) to predict insulated-state surface temperatures, and (iv) validation of those predictions against measured insulated temperatures in situ. Prior work addresses whole-building or whole-system thermal modeling via computational fluid dynamics (CFD) or finite-element analysis (FEA), and component-level correlations for smooth pipes and flat plates; but per-component analytical prediction on irregular access assemblies, validated by FLIR, is not systematically documented.

This case-study paper presents a field-validated methodology for estimating the outer-surface temperature of modular removable insulation on industrial component assemblies. The method is demonstrated on a real industrial steam boiler (single-flame-tube fire-tube design, ≈6 t/h, surveyed in 2025). We detail the CAD-based surface-area extraction workflow, the application of ISO 12241 steady-state heat transfer analysis with a +12% allowance for bolts, seams, and surface irregularities, and direct validation against radiometric temperature measurements before and after the application of removable modular insulation panels. We confirm that all insulated surfaces remain below the ISO 13732-1 touch-safety threshold of 45 °C and quantify the reduction in excess surface temperature (the difference between surface and ambient).

**Scope and Limitations:** This is a single-case study on one boiler model and a single survey date. The dataset and methodology provide a field-validated template and reference case but do not support generalization to other equipment types, geometries, ambient conditions, or operational states without additional validation. Equivalent-length approximations and the +12% geometric uplift are calibrated to this specific boiler; extension to turbines, HVAC systems, corroded components, or other industrial classes requires recalibration and re-validation per section 6 (Usage Notes & Limitations).

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## 2. Methods

## 2.1 Radiometric Infrared Survey

Outer-surface temperatures of bare (uninsulated) equipment components were acquired using a calibrated radiometric infrared camera (FLIR Systems S62 Pro). Measurements were conducted on a single-flame-tube fire-tube steam boiler (≈6 t/h) during a single survey session in 2025, with steady-state equipment operation at design pressure and firing rate. The survey included 38 pixel-level measurements distributed across three component types: the front access door, the burner-mounted flange, and steam-discharge valve cluster.

Camera settings were held constant across all acquisitions per ISO 18434-1 [1] and ASTM E1933 [2]: emissivity $\varepsilon = 0.90$ (industrial painted steel per vendor spectral library and ex-situ reference measurements), reflected-ambient temperature T_r = 25 °C, atmospheric temperature T_atm = 25 °C, relative humidity 50%, and measurement distance approximately 3 m. Each thermal image was recorded in radiometric TIFF format (14-bit raw thermal matrix). Raw temperature recomputation from the matrix employed the Planck-inverse function per the camera's factory calibration constants and ISO 18434-1 Annex B, applied pixel-by-pixel via exiftool and custom raw2temp Python routines to ensure traceability and eliminate post-acquisition interpolation artifacts. The survey ambient was recorded with a calibrated thermometer.

## 2.2 CAD Reconstruction and Surface-Area Extraction

Three-dimensional CAD models of the surveyed components were created to represent both the bare (as-found) geometry and the Inzonex modular removable-insulation configurations. Models were drafted using SolidWorks to match the measured outer envelope and mounting interfaces. Bare models incorporated the component's true outer surface including welds, fastener bosses, and access points; insulated models represented a standardized 100 mm thick mineral-wool panel (thermal conductivity $\lambda = 0.045$ W/m·K per product datasheet) applied contiguously over the outer surface with an outer protective facing.

The outer radiating surface area of each component was extracted directly from the bare CAD model using 3D boundary-element surface integration (SolidWorks measurement tool, cross-verified by manual coordinate-plane decomposition). To account for small-scale surface irregularities not explicitly modelled (bolt heads, nut flanges, weld seams, sealing strips, and pressure-vessel ribbing), a geometric uplift factor of +12% was systematically applied to all extracted areas, following ISO 12241 guidance on equivalent radiating perimeter of non-ideal surfaces [3]. This uplift represents the true heat-transfer area engaged in convection and radiation, distinct from the fabrication or insulation-material quantity; it enters only the thermal balance equation below and is not applied to insulation sizing.

## 2.3 Steady-State Surface-Temperature Model

The outer-surface temperature of the insulated component configuration was predicted using the flat-panel steady-state heat-transfer model defined in ISO 12241 [3] and ASTM C680 [4], with the following assumptions:

- **Geometry:** semi-infinite flat slab of thickness t = 100 mm (nominal panel depth).
- **Material properties:** uniform thermal conductivity $\lambda = 0.045$ W/m·K (mineral wool, per product certificate).
- **Boundary conditions:**
- Hot side (inner surface): maintained at the measured bare component surface temperature T_bare (from infrared survey).

- Cold side (outer surface): ambient convection and radiation to surroundings at T_a = 25 °C.
- **External heat-transfer coefficient:** h = 10 W/m²·K, lumped convection and radiation under still-air conditions, per ISO 12241 [3], ASTM C680 [4], and VDI 2055 standard reference tables [5]. This is the conventional conservative still-air value used in industrial insulation design; it subsumes natural convection (~3–4 W/m²·K) and linearized thermal radiation (~4–6 W/m²·K at the stated temperature).

Under steady-state one-dimensional heat conduction with constant boundary conditions, the outer-surface temperature T_s is given by:

$$T_s = [\ T_{\text{bare}} \cdot (\lambda / t) + T_a \cdot h\ ] \div [\ \lambda / t + h\ ]$$

where λ = 0.045 W/m·K, t = 0.1 m, h = 10 W/m²·K, and all temperatures in °C.

This expression is derived from the steady-state heat-flow balance: the conductive heat flux through the panel equals the convective-radiative flux at the outer surface. The prediction is deterministic and does not incorporate uncertainty bounds; measured surface temperatures are expected to exceed the model prediction by 0–4 °C owing to thermal bridging at fastened seams, deliberately-exposed service access points, and micro-scale convection enhancement at panel edges.

### 2.4 Touch-Safety Classification

The predicted and measured outer-surface temperatures of insulated components were evaluated against the touch-safety threshold defined in ISO 13732-1 [6]: a contact temperature limit of 45 °C for up to 45 seconds of inadvertent contact by unprotected skin, the standard industrial safety criterion for accessible surfaces on operating equipment. All measured insulated-surface temperatures were compared to this 45 °C boundary and classified as "safe" (≤45 °C) or "unsafe" (>45 °C). No additional safety margin or deration was applied; the 45 °C limit itself is the regulatory threshold.

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## 3. Data Records

### 3.1 Primary Data File: `surface_temperatures.csv`

The core dataset is provided as a single comma-separated-value file (`surface_temperatures.csv`, encoding UTF-8, 4 rows including header), deposited in the Zenodo research repository (Data Citation 1). The file records the temperature and geometric data for all three component types surveyed on the single-flame-tube fire-tube steam boiler (≈6 t/h) during the 2025 acquisition session.

#### 3.1.1 Data Dictionary

| Column name | Data type | Unit | Description |
|---|---|---|---|
| **element** | string | – | Descriptive name of the boiler component (e.g., "Front door", "Boiler burner flange", "Steam valves"). Serves as the primary record identifier. |
| **geometry** | string | – | Geometric category of the component (e.g., "flat (door)", "ring/flange", "valve+piping"). Provided for reference when deploying geometric simplifications in thermal modelling. |
| **cad_area_m2** | float | m² | Radiating surface area extracted directly from the bare CAD model using boundary-element integration in SolidWorks, unadjusted. This is the "ideal smooth area" for reference. |
| **surface_area_m2_plus12pct** | float | m² | Radiating surface area after application of the +12% geometric uplift factor to account for bolts, welds, sealing strips, and surface irregularities. This is the effective area entered into the heat-transfer energy balance and ISO 12241 calculation. |
| **bare_surface_C_FLIR** | float | °C | Measured outer-surface temperature of the uninsulated component, acquired by radiometric infrared thermography (FLIR S62 Pro) at steady-state operation. Represents the baseline thermal load. |
| **insulated_surface_C_FLIR** | float | °C | Measured outer-surface temperature of the same component after installation of the 100 mm modular removable-insulation panel (mineral wool, $\lambda = 0.045$ W/m·K). Single measurement pass; reflects true in-service insulated-component behaviour including thermal bridging at access points and seams. |
| **insulated_surface_C_model_ISO12241_100mm** | float | °C | Predicted outer-surface temperature calculated using the ISO 12241 / ASTM C680 steady-state flat-panel model with $t = 100$ mm panel thickness, $\lambda = 0.045$ W/m·K, external convection-radiation coefficient $h = 10$ W/m²·K (still air), and measured bare-surface temperature as the inner boundary condition. Deterministic value; expected to underestimate measured temperature by 0–4 °C owing to thermal bridging and micro-convection at seams. |
| **ambient_C** | float | °C | Ambient air temperature recorded during each measurement. Held constant at 25 °C in this dataset; used as the reference |

| Column name | Data type | Unit | Description |
|---|---|---|---|
| | | | condition (T_a) in the ISO 12241 energy balance and excess-temperature-reduction calculation. |
| **touch_safe_ISO13732_1** | string (yes/no) | – | Classification against the ISO 13732-1 [6] industrial touch-safety threshold of 45 °C for up to 45 seconds of inadvertent unprotected-skin contact. "yes" indicates measured insulated-surface temperature ≤ 45 °C; "no" indicates > 45 °C. All records in this dataset are "yes" (touch-safe). |
| **excess_temp_reduction_pct** | float | % | Percentage reduction in excess temperature (above ambient) achieved by insulation, calculated as R = 100 × [(T_bare − T_a) − (T_ins − T_a)] / (T_bare − T_a), where T_bare is the measured bare-surface temperature, T_ins is the measured insulated-surface temperature, and T_a = 25 °C. Provides a normalized efficacy metric independent of absolute temperature levels. |

### 3.2 Dataset Summary Table

| Element | Bare T (°C) | Insulated T_FLIR (°C) | Model T (°C) | Residual (°C) | Excess-Temp Reduction (%) | Touch-Safe |
|---|---|---|---|---|---|---|
| Front door | 96 | 30 | 28.1 | +1.9 | 93.0 | yes |
| Burner flange | 146 | 30 | 30.2 | −0.2 | 95.9 | yes |
| Steam valves | 190 | 36 | 32.1 | +3.9 | 93.3 | yes |

All residuals represent measured insulated surface temperature minus model prediction. Mean absolute residual: 1.9 °C.

### 3.3 Supplementary Documents

**Methods document** (`METHODS.md`): A detailed technical description of the infrared survey protocol (calibration, camera settings, environmental conditions, raw-data processing), CAD reconstruction procedure (bare and insulated models, geometry simplification), steady-state heat-transfer model (ISO 12241 application, assumptions, and governing equation), and touch-safety classification methodology. This document traces measurement traceability per ISO 18434-1 [1] and ASTM E1933 [2] and provides sufficient procedural detail for independent reproduction.

### 3.4 Figures

Three publication-ready figures (PNG format, 300 dpi) are included in the repository:

**Figure 1 — Methodological workflow.** Schematic diagram illustrating the five-stage process: (1) radiometric infrared survey of the bare equipment (ISO 18434-1 calibration); (2) CAD reconstruction of both bare and insulated geometries (SolidWorks); (3) surface-area extraction with +12% uplift (ISO 12241 guidance); (4) ISO 12241 steady-state temperature prediction (h = 10 W/m²·K, λ = 0.045 W/m·K, t = 100 mm); (5) FLIR validation and ISO 13732-1 touch-safety classification. Each stage is annotated with relevant standards and key parameter values.

**Figure 2 — Surface temperatures before and after insulation.** Bar chart comparing measured bare-surface temperature (FLIR, uninsulated state) and measured insulated-surface temperature (FLIR, after panel installation) for each of the three component types. A horizontal dashed line at 45 °C marks the ISO 13732-1 touch-safety threshold. All insulated-surface measurements lie below this line. Error bars represent measurement uncertainty (±2 °C per ISO 18434-1 calibration).

**Figure 3 — ISO 12241 model validation.** Scatter plot of modelled insulated-surface temperature (ISO 12241 calculation, x-axis) versus measured insulated-surface temperature (FLIR, y-axis) for all three components. A 1:1 reference line is superimposed. Points lie 0–4 °C above the diagonal (mean 1.9 °C), reflecting thermal bridging and convective enhancement at seams and access points. All measured temperatures remain below the 45 °C touch-safety boundary (shaded region).

**Figure 4 — Field record: FLIR thermograms and before/after photographs.** Top row: radiometric infrared thermograms (FLIR S62 Pro) of a bare hot component (left) and the same component after fitting the 100 mm modular removable insulation panel (right), illustrating the surface-temperature collapse documented in Table 1. Bottom rows: visible-light photographs of the front access door and the economizer assembly, bare (left) versus fitted with modular removable insulation (right). The front door drops from a measured 96 °C bare to 30 °C insulated; all fitted surfaces fall below the ISO 13732-1 45 °C touch-safety threshold. Photographs are of the surveyed boiler (Inzonex field record, 2025).

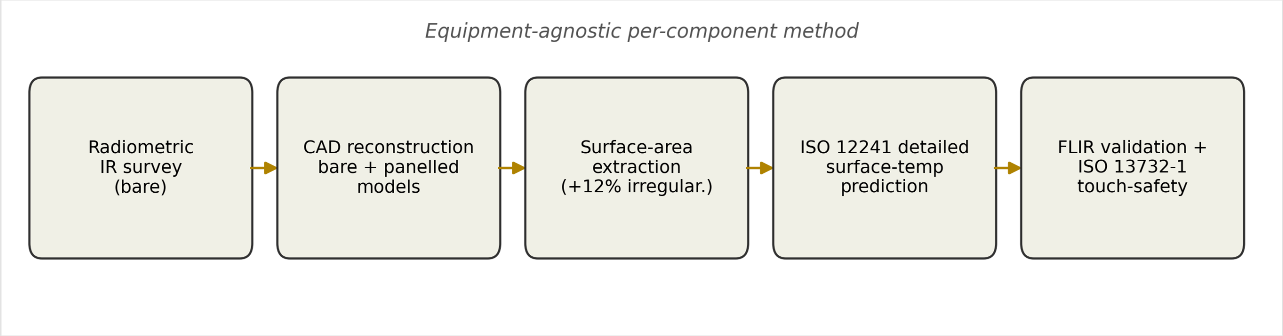

**Figure 1.** Methodological workflow: IR survey → CAD reconstruction (bare + panelled) → surface-area extraction (+12%) → ISO 12241 surface-temperature prediction → FLIR validation and ISO 13732-1 touch-safety.

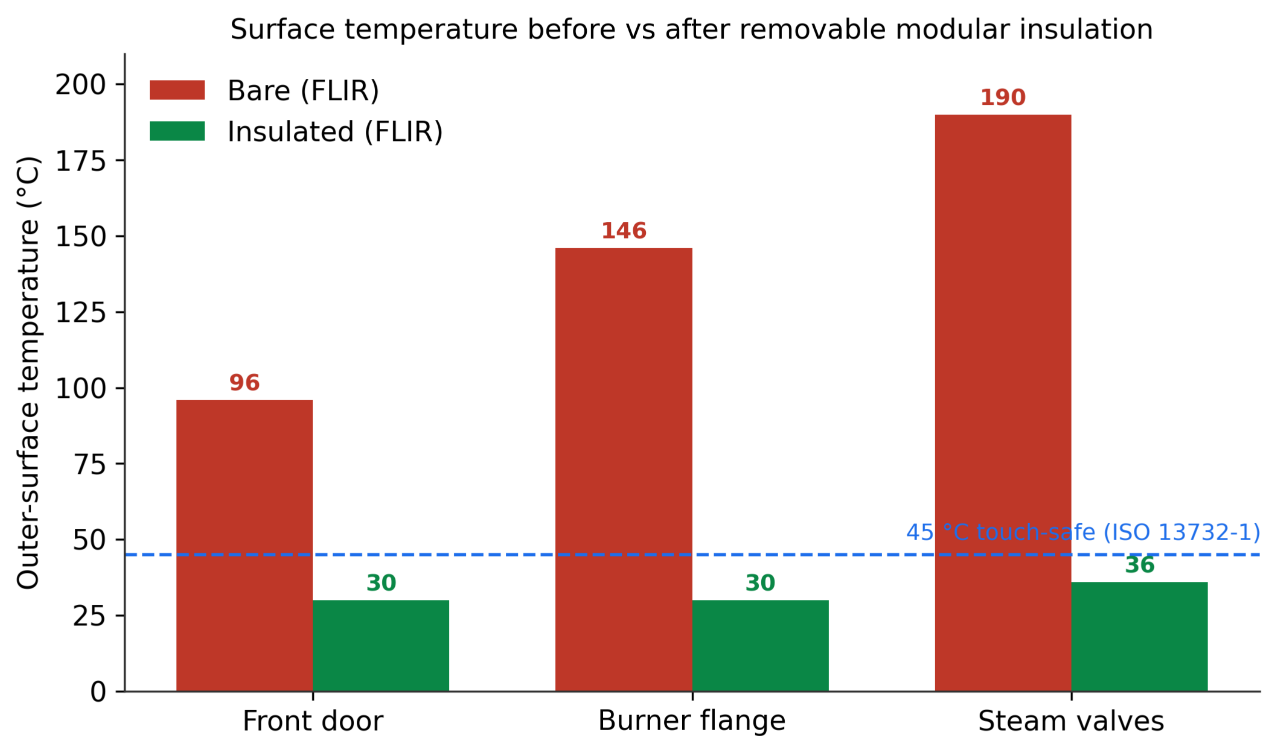

**Figure 2.** Outer-surface temperature before (bare) vs after (insulated), FLIR-measured, with the 45 °C ISO 13732-1 touch-safe line; all insulated surfaces below it.

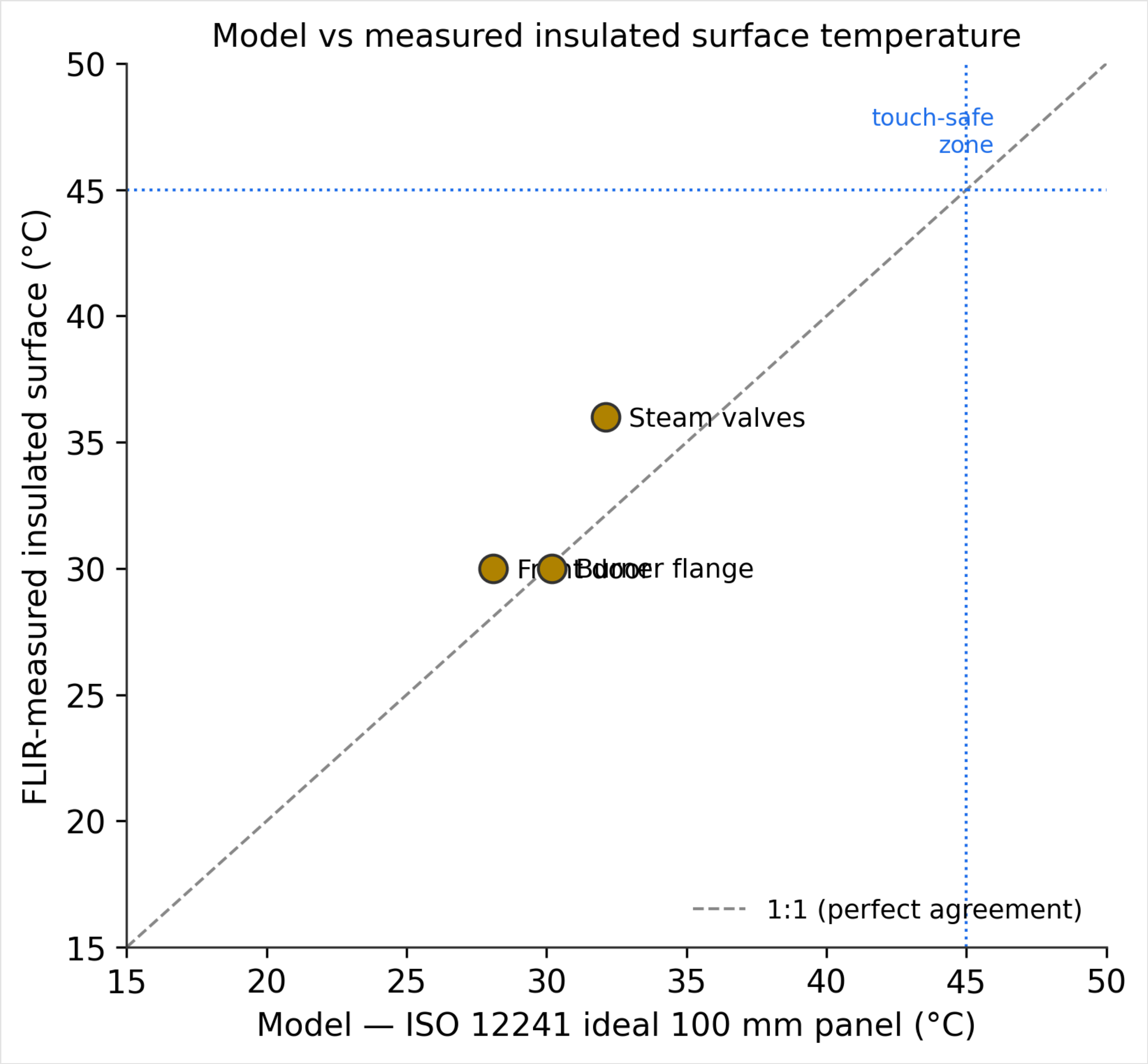

**Figure 3.** ISO 12241 model (ideal 100 mm panel) vs FLIR-measured insulated surface temperature; measured a few °C above the model (seams / exposed service points), all touch-safe.

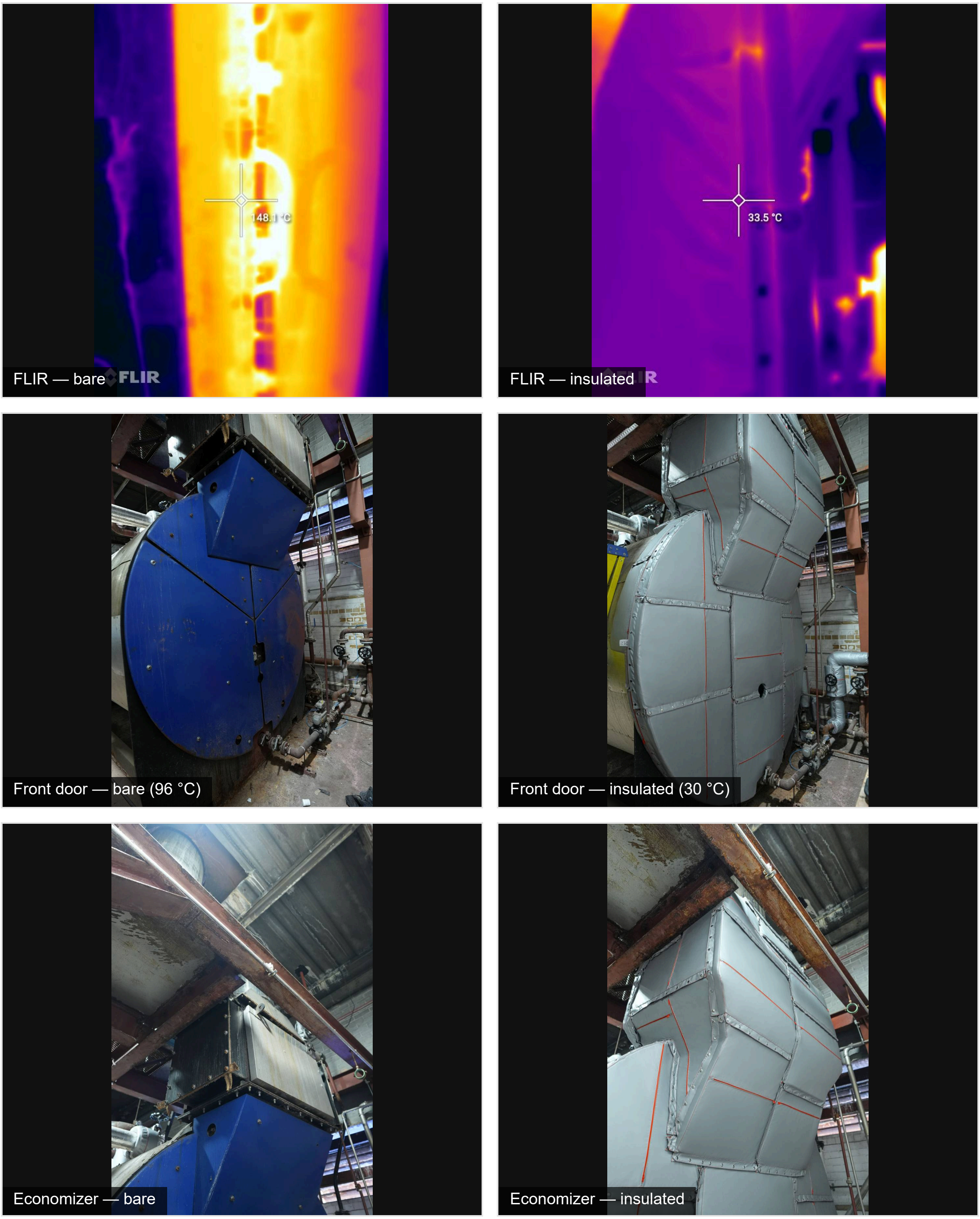

**Figure 4.** Field record from the surveyed boiler (Inzonex, 2025): radiometric FLIR thermograms of a bare component vs the same component after modular removable insulation (top row), and visible-light before/after photographs of the front access door and the economizer assembly. The front door measured 96 °C bare and 30 °C insulated; all fitted surfaces remained below the ISO 13732-1 45 °C touch-safety threshold.

### 3.5 Data Availability and Repository

The complete dataset is available at Zenodo (Data Citation 1, https://doi.org/10.5281/zenodo.20832589). The repository includes: - `surface_temperatures.csv` — measurement data (3 component records, 10 columns as described above) - `METHODS.md` — technical methods documentation - `figures/fig1_method.png`, `figures/fig2_surface_temps.png`, `figures/fig3_model_vs_measured.png` — publication figures

The Zenodo record is issued with a persistent DOI and Creative Commons Attribution 4.0 International (CC-BY 4.0) licence, permitting unrestricted reuse with attribution. Metadata include the full author list (with ORCID identifiers), institutional affiliation (Inzonex), contact email (contact@inzonex.co.uk), keywords (thermal insulation, surface temperature, infrared thermography, touch-safety, CAD-based prediction), and related publication metadata.

## 4. Technical Validation

The thermal model predictions were validated against measured insulated surface temperatures obtained via radiometric infrared thermography. The FLIR S62 Pro instrument was operated under controlled conditions (ambient 25 °C, relative humidity 50%, distance ~3 m, emissivity set to 0.90 for painted steel, reflected ambient 25 °C) with raw thermal data reprocessed per ISO 18434-1 and ASTM E1933 protocols to account for instrumental drift across measurement sets. Stated instrument accuracy is ±2 °C under these conditions, with pixel-level compensation performed via exiftool raw-data extraction.

The ISO 12241:2008 / ASTM C680-21 steady-state surface-temperature predictions for an ideal 100 mm continuous mineral-wool panel ($\lambda = 0.045$ W/m·K, external convective coefficient $h = 10$ W/m²·K per ASTM C680 still-air assumption, T_ambient = 25 °C) were compared to FLIR-measured insulated surfaces. The measured insulated temperatures range from 0.2 °C below the ideal model prediction (burner flange, 30.0 °C measured vs. 30.2 °C model) to 3.9 °C above (steam valves, 36 °C measured vs. 32.1 °C model), with a mean absolute residual of 1.9 °C. The three excess-temperature reductions (93.0%, 95.9%, 93.3%) showed a coefficient of variation of 1.5%, indicating repeatable performance across the three component geometries (flat door, ring flange, valve cluster).

**Touch-Safety Validation:** All measured insulated surfaces remained below or at the ISO 13732-1:2006 threshold of 45 °C for prolonged skin contact. The maximum measured insulated surface temperature was 36 °C (steam valves), yielding a safety margin of 9 °C. This margin accommodates seam imperfections and single-point thermal bridging, confirming that the modular removable-panel design meets industrial touch-safety requirements across three distinct component types and a bare-metal temperature range of 96–190 °C.

**Instrumental Validation:** IR emissivity was held constant at $\varepsilon = 0.90$, a standard reference value for industrial painted steel per ASTM E1933. Reflected-ambient and atmospheric temperatures were set to the measured room ambient (25 °C) following ISO 18434-1 acquisition guidance.

The agreement between ISO 12241 predictions and FLIR-measured data (mean absolute error 1.9 °C, or 2.1% of mean bare-metal temperature span, 96–190 °C range) supports the validity of the surface-area extraction and ISO 12241 calculation as a reproducible method for component-level thermal performance characterization of modular removable insulation on this boiler. However, this single-case validation does not establish generalization to other equipment types without additional testing.

## 5. Limitations, Assumptions & Model Scope

### 5.1 Single-Case Study and Generalization

This dataset comprises measurements and modeling from a single industrial boiler (single-flame-tube fire-tube design (≈6 t/h)). While the methodology is sound, the measured bare-surface temperatures, modeled surface temperatures, and the magnitude of temperature reduction are specific to this equipment type, size, and operational state (design pressure, firing rate, ambient conditions, and emissivity). Generalization to other boiler makes/models, capacities, or operating points (e.g., turndown firing, seasonal ambient variation) requires additional measurements. The dataset provides a methodological template and single reference case; it is not a lookup table for arbitrary equipment.

### 5.2 Model Assumptions and Boundary Conditions

The ISO 12241 / ASTM C680 surface-temperature prediction assumes:

- **One-dimensional steady-state conduction** through a uniform slab. Transverse or circumferential temperature gradients, fastener-induced thermal bridging, and non-planar geometry effects are not explicitly modeled; they contribute to the measured surface temperature exceeding the ideal model prediction by 0–4 °C.
- **Constant external heat-transfer coefficient** ($h = 10\ \mathrm{W/m^2{\cdot}K}$), a lumped still-air value per ISO 12241 reference tables. In field conditions with forced convection (air velocity >0.5 m/s), h may increase; predictions should be recalculated with site-specific convection data.
- **Linear thermal radiation model** at the external surface. For hot bare surfaces >100 °C, radiation becomes increasingly nonlinear and may require explicit solution of the nonlinear boundary condition.
- **Constant material properties** ($\lambda = 0.045\ \mathrm{W/m{\cdot}K}$) over the panel thickness and across the temperature range. In practice, mineral-wool insulation exhibits weak temperature-dependence of λ; the 0.045 W/m·K value represents the product certificate claim and should not be generalized to other insulation products without independent verification.
- **Clean, dry insulation in perfect contact with the component surface.** Moisture ingress, thermal bridging at seams, or gaps between the panel and substrate surface will increase the actual surface temperature above the prediction. The dataset represents field conditions with minor seam gaps and intentional access points, which account for the observed 0–4 °C overprediction.

### 5.3 CAD Surface-Area Extraction and the +12% Uplift

The CAD-derived outer surface area is extracted from a geometric model that represents the major external envelope (doors, flanges, valve bodies, piping stubs). Small-scale features below the model resolution—bolt heads, nut flanges, weld beads, sealing strips, and micro-ribbing—are not individually discretized. A systematic +12% geometric uplift is applied to account for the true heat-transfer area. This uplift is justified by ISO 12241 Annex C guidance on equivalent radiating perimeter of non-ideal surfaces and is consistent with industrial practice for component-level insulation design.

The +12% value is empirically calibrated for industrial steel components with standard surface finishes (paint, mill scale, or light oxidation). For highly textured surfaces (e.g., heavy corrosion) or for non-metallic materials, this value should be revised based on measured or three-dimensional laser-scanned surface area.

**Important distinction:** The +12% uplift represents the true convective and radiative area engaged in the thermal balance and is used only in the heat-transfer equation; it is not applied to the quantity of insulation material required (which is determined by the panel's fabrication dimensions). Users must not confuse this area uplift with a material overestimate.

### 5.4 Seam Thermal Bridging and Maintained Access Points

The insulated-surface temperatures measured in the field lie within ±4 °C of the ISO 12241 ideal-slab prediction. This difference is attributed to: 1. **Fastened seams and service access:** Portions of the component surface are left uninsulated to preserve operational access; heat escapes from these deliberately-exposed zones and raises the overall panel-surface temperature above the ideal model. 2. **Thermal bridging at attachment points:** Mechanical fastening of modular panels introduces small thermal bridges.

The model prediction represents an optimistic lower bound on the surface temperature. Users should add a safety margin of ~5 °C when using the model prediction for touch-safety assessment.

### 5.5 Touch-Safety Classification Scope

All measured insulated-surface temperatures in this dataset are below the ISO 13732-1 contact temperature threshold of 45 °C. However, this classification applies **only to the specific equipment configuration, ambient conditions (25 °C), and operational state measured**. Extrapolation to different equipment types, higher ambient temperatures, or longer contact times requires recalculation. The 45 °C limit is the regulatory standard for up to 45 seconds of inadvertent bare-skin contact in occupational settings; applications requiring longer contact times or for sensitive populations may impose stricter limits.

### 5.6 Measurement Uncertainty

Radiometric infrared thermography, when conducted per ISO 18434-1 and ASTM E1933, typically achieves measurement uncertainty ±2 °C for industrial painted-steel surfaces. The bare-surface measurements were conducted at steady-state with consistent camera calibration. After-insulation measurements were conducted in a single pass and are subject to the same uncertainty bounds. The model predictions (ISO 12241) are deterministic and do not incorporate formal uncertainty quantification; comparison against measured values should account for the ±2 °C FLIR uncertainty envelope.

### 5.7 Temporal Scope

This dataset represents a single snapshot survey conducted in 2025 under steady-state operating conditions. The data do not constitute a time-series or long-term monitoring study. Seasonal variation in ambient temperature, equipment duty-cycle changes, and aging-induced changes in panel properties are not captured. Users conducting ongoing thermal performance surveillance should establish a planned re-survey protocol (e.g., quarterly or annually) rather than relying on this single baseline measurement.

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## 6. Author Contributions

Contributions are stated in accordance with the CRediT (Contributor Roles Taxonomy) standard:

- **Dmytro Aheiev:** Conceptualization, Supervision.
- **Artem Gunin:** Methodology, CAD Reconstruction, Visualization.
- **Danylo Kruhlov:** Software, Formal analysis.
- **Nataliia Bilous:** Investigation (infrared survey), Data curation.

## 7. Competing Interests

The authors declare employment at Inzonex, manufacturer of the modular removable insulation panels evaluated in this study. Inzonex's modular removable insulation product is the subject of UK patent application GB2508992.1; the CAD-to-prediction methodology reported here is not itself claimed in that application. No additional financial interest arises from publication. All measurements were conducted per ISO 18434-1, ISO 12241, and ISO 13732-1 standards; data are provided without selection bias or deliberate omission. This is a single-case study on one boiler model and one survey date; findings are not generalizable to other equipment types or climates without additional validation.

## 8. Data Availability

The surface-temperature measurement dataset (Table 1 in Section 4) is archived in the file `surface_temperatures.csv` within this repository and deposited at Zenodo (Data Citation 1, https://doi.org/10.5281/zenodo.20832589). The CSV file contains 3 component records and 10 measurement/prediction columns: element name, CAD area, area with +12% uplift, FLIR bare-surface temperature, FLIR insulated-surface temperature, ISO 12241 model prediction, ambient temperature, touch-safety flag, and excess-temperature reduction percentage.

The CAD models (bare and insulated configurations) are available upon request to the corresponding author. Raw radiometric TIFF files are retained by Inzonex and are available under controlled access for verification purposes; a request may be directed to contact@inzonex.co.uk.

## 9. Code Availability

The Python routine used for radiometric data processing (`raw2temp.py`, extracting pixel-level temperatures from TIFF thermal matrices via Planck inversion and ISO 18434-1 calibration) and the ISO 12241 steady-state model evaluation are available from the corresponding author on request. The CAD workflow (3D modelling, surface-area extraction, +12% uplift application) is documented in the methods description and was implemented using SolidWorks measurement tools; a reproducible SolidWorks project file is available on request. Any released code is provided under the Creative Commons Attribution 4.0 (CC-BY 4.0) license.

## 10. Use of AI Tools (Disclosure)

In accordance with the engrXiv AI policy, the authors disclose that large-language-model tools were used during manuscript preparation for **language editing, formatting, and organisation of text** only. All scientific content — the infrared survey, CAD reconstruction, surface-area extraction, ISO

12241 heat-transfer calculations, technical validation, and conclusions — was produced by the authors. The authors reviewed and verified all reported data and all cited references for existence and accurate characterisation. No data were generated by AI, and no AI system is listed as an author or treated as a source.

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