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Improving Furnace Temperature Uniformity via Design Optimization and Heater Zoning

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Highlights

- Furnace geometry and boundary heat losses govern axial and radial gradients.
- Improved energy retention and decreased wall heat flux are two benefits of graded insulation.
- Multi-zone heater control minimizes ramp overshoot and soak fluctuation.
- Combined redesign improves uniformity across center, mid-radius, and wall zones.
- Simulation–experiment agreement supports reproducible, scalable furnace tuning.

Abstract
a) Background
Thermal furnaces enable controlled heating for materials processing. Temperature non-uniformity creates thermal stress, defects, and inconsistent microstructures.
b) Objective
This study aims to improve furnace temperature profile uniformity. The goal is reducing axial and radial gradients during ramp and soak.
c) Methods
K-type thermocouples were used to map a laboratory resistance furnace. Axial and radial points quantified (ΔT_{axial}, ΔT_{radial}) uniformity index, and soak stability. Geometry-aware heat transfer tuning, graded low-k insulation close to high-loss boundaries, exhaust rerouting and sealing to reduce convective leakage, and multi-zone heater control for end-loss compensation were among the design changes. Conduction, radiation, and boundary losses were all included in the finite-element heat-transfer model, which was calibrated to baseline data and used in redesigned scenarios.
d) Results
In every zone, the improved furnace displayed reduced axial and radial gradients. Between the center and the periphery, temperature symmetry has improved. A significant reduction in soak fluctuations suggests improved stability and controllability.
e) Comparison with Literature
The improved patterns are consistent with crystal growth and solidification investigations that have been published. Consistent with the current findings, earlier research associates optimal thermal fields with lower stress and better quality.
f) Conclusion
Temperature stability and homogeneity are enhanced when active control (heating zoning) and passive redesign (geometry and insulation) are combined. The strategy promotes improved process repeatability and energy-efficient operation.

Keywords: Furnace redesign; Temperature uniformity; Heater zoning; Thermal simulation; Heat transfer optimization

1. Introduction

1.1 Role of Thermal Furnaces in Material Processing

Controlled heating is made possible during material synthesis processes by thermal furnaces. Phase formation and defect density development are controlled by temperature history. Grain growth and microstructural uniformity are significantly impacted by thermal gradients. For the production of photovoltaic silicon, controlled solidification enhances ingot quality. Thermal transmission and interface form are also influenced by crucible characteristics. Miyazawa et al. (2009) provided numerical evidence of these effects in unidirectional processes. Furnace thermal fields are necessary for coupled oxygen and carbon transfer (Gao et al., 2009). Thus, processing conditions and product quality results are linked by thermal design.

1.1.1 Heat Transfer Pathways in Furnaces

Conduction, convection, and thermal radiation are the three ways that heat is transferred (Figure 1). The primary goal of wall insulation is to reduce conductive losses to the environment. Chamber mixing and convective losses are controlled by gas circulation paths. Inside industrial zones, radiant exchange predominates at high temperatures. Systems for directional solidification are particularly vulnerable to radiative imbalance. Optimizing heat transmission enhances thermal stability and interface management (Gao et al., 2010).

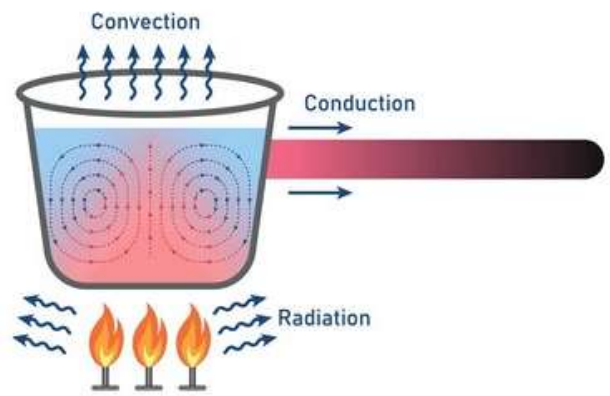

Figure 1: Modes of transfer of heat in furnace (shutterstock.com.2391646673)

1.1.2 Processing Outcomes Dependent on Thermal Stability

Thermal stability affects both the dispersion of impurities and the regularity of crystallization. Impurity reduction in silicon casting was linked to furnace modifications (Gao et al., 2011b). Stress on seeded development is influenced by temperature fields and interface evolution (Gao et al., 2012). Thermal stress has an impact on the crystal quality during the production of multi-crystalline silicon (Fang et al., 2012).

Table 1: Furnace thermal functions and processing outcomes

Furnace function	Thermal driver	Expected processing outcome	Supporting reference
Stable soak temperature	Low temporal fluctuation	Consistent phase formation	Arnberg et al., 2012
Controlled axial gradient	Directional heat flow	Improved solidification interface	Gao et al., 2010
Reduced radial deviation	Balanced heat loss	Uniform grain development	Fang et al., 2012
Controlled crucible effects	Material properties	Improved interface shape	Miyazawa et al., 2009

1.2 Challenges in Conventional Furnace Designs

Axial and radial temperature gradients are frequently created in conventional furnaces. Boundary conduction losses cause edge zones to lose heat more quickly. Rectangular chamber designs exhibit significant variances in corner regions. Risk of microcrack development and residual stress are caused by uneven heating. Details of the furnace design affect thermal stress during solidification (Fang et al., 2012). Impurity transport channels can be changed by crucible cover materials (Gao et al., 2011a). Defect concentrations and inclusions may rise as a result of improper heat transmission. Careful heat transfer optimization is necessary for vacuum directed solidification systems (Yang et al., 2014). During directed solidification, heat transport has a significant impact on crystal quality (Yang et al., 2015a).

1.2.1 Common Sources of Temperature Non-Uniformity

Localized hotspots can arise from heater placement on the chamber's exterior walls. Large thermal gradients can result from discontinuities in insulation near structural joints. Emissivity variations among crucibles and susceptors create radiation balance distortions and make maintaining steady interface control more difficult during casting operations (Gao et al., 2010).

Table 2: Typical gradient sources in conventional furnace designs.

Source of non-uniformity	Observed effect	Practical consequence	Supporting reference
Edge heat loss	Cooler boundary zones	Non-uniform microstructure	Fang et al., 2012
Crucible property mismatch	Interface distortion	Defect formation risk	Miyazawa et al., 2009
Impurity transport coupling	Carbon–oxygen variations	Quality reduction	Gao et al., 2009
Inefficient heat transfer	Poor temperature control	Lower crystal quality	Yang et al., 2015a

1.3 Need for Temperature Profile Optimization

Precision in temperature control, as well as even distribution of that temperature, are essential for fresh materials. The reproducibility of any process is reliant on consistent gradients being maintained within the entire chamber. Design-oriented solutions offer long-term stability that does not need to be recalibrated often. Optimizing design creates the opportunity to substantially reduce stress levels and therefore improve the quality of the ingot produced. Thermal stress simulation assists in making better decisions when it comes to improving a design (Gao et al., 2012). By optimizing heat transfer, there will be better performing multicrystalline silicon products (Yang et al., 2014).

1.3.1 Optimization Levers for Temperature Control

The arrangement of insulation reduces radial losses and provides for improved uniformity. Heater zoning enables correction of local gradients and stable ramping. The type of crucible material controls interface curvature and thermal fields. Adjustments to vents and air flow will minimize convective heat loss. These levers are routinely used in the optimization of solidification systems (Gao et al 2010).

Table 3: Design levers used for improving temperature profile uniformity.

Design lever	Main purpose	Expected effect	Supporting reference
Insulation optimization	Reduce heat loss	Lower radial deviation	Arnberg et al., 2012
Heater zoning	Local control	Reduced axial gradient	Gao et al., 2010
Crucible property tuning	Interface control	Improved shape stability	Miyazawa et al., 2009
Heat transfer redesign	Chamber uniformity	Better crystal quality	Yang et al., 2014

1.4 Aim of the Present Study

This paper discusses how to improve furnace temperature distributions by redesigning them. This study is concerned with those four aspects of furnaces: their geometry; insulation; zoning of heating elements; and transferring heat to manufactured components. The goal of this project is to reduce the total axial gradient and to also reduce the total radial deviation. The methodology used in this project will be based on principles previously developed for solidification furnaces (Gao et al., 2010; Fang et al., 2012; Yang et al., 2014).

2. Literature Review

2.1 Thermal Furnaces and Temperature Profile Control

Thermal furnaces are critical to high temperature industrial processes; however, the distribution of temperature in thermal furnaces has a significant influence on phase and structure formation. The earlier works focused on control of thermal heating in a consistent manner (Vossen & Kern, 1991), whereas later studies developed an understanding of continuous axial and radial gradients in thermal furnaces and their negative effects on crystal formation and defects in the crystal (Gao et al., 2010).

2.2 Influence of Furnace Geometry on Thermal Uniformity

Thermal furnace geometry has a direct effect on the path and gradient of heat being transferred into the thermal furnace. For example, while cylindrical thermal furnaces show edge heat loss and stability during operating conditions, rectangular thermal furnaces show corner related thermal gradient deviation during heating. Design modifications of the thermal furnace have an effect on the level of thermal stress experienced by the solidified material during directional (Fang et al., 2012), while changes in the thermal furnace crucible have shown to affect the interface shapes of the material during unidirectional solidification (Miyazawa et al., 2009). The modification of the vacuum creation and solidification systems incorporated into the thermal furnaces resulted in optimized heat transfer capabilities (Yang et al., 2014).

2.3 Role of Insulation Materials in Furnace Performance

Insulating materials provide a means of reducing thermal heat loss, and therefore, enhancing the overall thermal performance and stability of thermal furnaces. As such, the application of low thermal conductivity insulating layers should reduce the amount of heat being released outside the thermal furnace, thereby providing thermal uniformity (i.e., stability) within the thermal furnace. Optimized insulating layer(s) inside thermal furnaces provide thermal stability for lengthy thermal processes. Current silicon growth processes are focusing on improving thermal uniformity with regard to the growing silicon material (Arnberg et al., 2012).

2.4 Heater Configuration and Zoning Strategies

Using single-zone heating elements in the thermal furnace results in limited ability to control heating uniformly across a large dimension; whereas, use of multi-zone heating elements within the thermal furnace allows for localized thermal correction using local heat controlling devices (i.e., heaters). The independent control of heaters results in decreasing the thermal gradient in the axial direction during the solidification of the material (Gao et al., 2010). Using zoned heating within the thermal furnace improves ramp rate control and stability during soaking periods of the cast material. Using seeded growth simulations, it has been demonstrated that the crystallization of the material is dependent upon maintaining proper temperature control throughout the crystallization process (Gao et al., 2012).

2.5 Thermal Modelling and Simulation Approaches

Use of computer numerical models assists in the development and optimization of thermal furnace systems. Through the simulations conducted, predictions of the heat flow and thermal gradient results can be made for any given thermal furnace configuration; whereas, when an associated stress model is coupled with an interface model, information related to interface configuration and design can be derived (Gao et al., 2012). In addition, numerical modeling can be used to validate thermal furnace designs through experimental testing. Further, coupled transport simulations can be used to determine the source of impurities in the material in the furnace (Gao et al., 2009).

2.6 Research Gaps Identified from Literature

As reviewed in the literature, most of the studies have been completed with respect to single modification to thermal furnace systems; however, few studies have been completed using an integrated optimization approach of thermal furnace design considering multiple variables. Fewer studies have been completed simultaneously incorporating all three types of thermal furnace modifications (e.g., insulation, geometry, and heater zoning). Industrial validation of thermal furnaces has experienced limitations due to cost and scale. Validation of integrated optimization and experimental verification are in demand. These gaps are consistent with identified gaps in directional solidification thermal furnace literature (Gao et al., 2010; Fang et al., 2012; Yang et al., 2014).

3. Materials and Methods

3.1 Furnace System Description

The furnace used for the experimental setup was a resistance heating laboratory-sized furnace, and it consisted of a heat chamber that had a uniform cylindrical shape and a homogeneous design layout. The symmetrical nature of the design reduces the presence of edge-created gradients during high-temperature processes. Prior to making any design changes, baseline runs were performed without any design changes. The furnace was operated continuously in order to map the internal surface to establish baseline axial and radial gradient signatures. These baseline signatures assist in establishing reproducible modification comparison (Gao et al., 2009).

3.1.1 Furnace Configuration and Components

The configuration and components of the furnace based on the furnace design consisted of a hot zone and cooler boundary zones (Figure 2). The heating elements for heating the furnace chamber were placed uniformly around the outer wall of the chamber.

A thermal insulation stack surrounded the heating elements and the outer shell of the furnace chamber. The way the control power supply was designed provided ramp and soak controlled operation of the power supply. The crucible area was located at the geometric center of the furnace chamber. Finally, how and where the crucible is located will influence the type of interface shape that occurs as well as the thermal field of the molten material in between the solid molton and the crucible wall (Miyazawa et al., 2009).

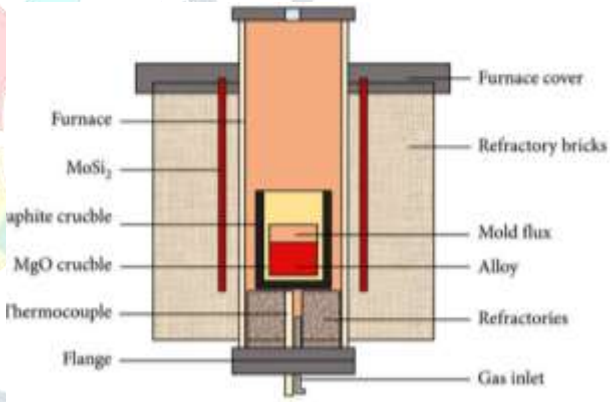

Figure 2: Schematic diagram of the experimental resistance furnace (DOI:10.1155/2022/5314863)

3.2 Temperature Measurement and Instrumentation

3.2.1 Sensor Placement Strategy

Temperature measuring and recording equipment was comprised of K-type thermocouples. The location of the sensors comprised the axial and radial dimensions of the furnace. The axial locations recorded the development of the top-to-bottom thermal profile during the process of soaking. The radial locations accounted for how much of the thermal energy lost to the walls was due to the centre position of the furnace. The centre sensors also monitored the degree of stability of the hot zone as well as the accuracy of the control systems of the furnace. The sensors adjacent to the walls measured how much heat was lost through the walls of the furnace and how effective the insulation was at retaining heat. Thermal stress is produced by gradients and by the spatially non-uniform nature of the thermal profile (Fang et al., 2012).

3.2.1.1 Measurement Zones and Coordinates

Three different measurement zones were established to provide a systematic approach to thermal profiling. Measurement zone A was at the geometrical centre of the furnace. Measurement zone B was located at the mid-radius of the hot zone. Measurement zone C was located near the wall at the boundary of the insulation. This method of zoning is similar to the way thermal profiles are established in solidification furnaces (Gao et al., 2010).

Table 4: Temperature measurement configuration and parameters

Parameter	Description
Sensor type	K-type thermocouple
Measurement zones	Center, mid-radius, wall
Temperature range	Ambient to 1200 °C
Data logging interval	5 seconds
Soak duration	Fixed, constant in all runs
Replicates	Minimum three per condition

3.2.2 Data Acquisition Procedure

Data on temperature were obtained and recorded when samples were submerged in a stable state. The period of time that an object is submerged in fluid was referred to as the "soak time period". The gauging of temperature continued after all samples reached thermal equilibrium. Each of the test conditions was repeated to eliminate any questions regarding the validity of the temperature profile. Outlier samples were removed after verifying sensor functionality. Mean and standard deviation values were used to compile data. The repeated mapping of samples provides less uncertainty in the interpretation of the gradient (Gao et al., 2011b).

3.2.2.1 Gradient Metrics and Performance Indicators

Table 5: Derived temperature uniformity metrics with supporting references

Metric	Definition	Interpretation	Supporting references
ΔT_{axial}	T_{top} - T_{bottom}	Lower values indicate improved axial uniformity and reduced thermal stress	Gao et al. (2010); Fang et al. (2012); Yang et al. (2014)
ΔT_{radial}	$T_{center} - T_{wall}$	Lower values reflect minimized radial heat loss and symmetric thermal fields	Arnberg et al. (2012); Fang et al. (2012); Yang et al. (2015a)
Uniformity index	$T_{max} - T_{min}$	Lower index signifies overall chamber temperature uniformity	Gao et al. (2010); Arnberg et al. (2012)
Stability	SD of T_{center}	Lower standard deviation indicates stable soak control and repeatability	Arnberg et al. (2012); Gao et al. (2012)

Axial gradients were calculated between the top/bottom of the object and radial gradients were calculated between the centre of the object and the near wall of the object. The uniformity index was calculated as the maximum temperature minus the minimum temperature recorded. The lower the uniformity index, the more stable the surface temperature of the chamber. Thermal stability enhances the uniformity of the microstructure of solidified materials that were processed (Arnberg et al., 2012).

3.3 Furnace Design Modifications

3.3.1 Insulation Layout Optimization

Insulation thickness was increased near high-loss boundary regions. Low thermal conductivity layers were positioned near the outer shell. A graded insulation strategy reduced radial heat leakage effectively. Improved insulation decreases energy loss and gradient magnitude (Arnberg et al., 2012). Boundary reinforcement minimized wall temperature oscillations during soak. Such improvements support long-duration thermal stability for processing.

3.3.1.1 Insulation Zoning Strategy

The insulation was divided into hot-zone and cold-zone segments. Hot-zone insulation emphasized thermal retention and reduced conduction. Cold-zone insulation emphasized safety and minimized shell heating. This zoning approach improves practical operational stability (Yang et al., 2014).

3.3.2 Heater Zoning Configuration

Multiple heating zones were implemented along the furnace axis. Each zone had independent power control for localized regulation. Zoning reduced axial gradients by compensating local heat losses. Independent control improves profile stability in growth furnaces (Gao et al., 2009). Zone tuning was performed using baseline thermal map feedback. The final zoning reduced both peak gradient and oscillations.

3.3.2.1 Zoning Control Logic

Table 6: Heater zoning and intended control actions

Heater zone	Primary function	Expected effect
Center zone	Maintain setpoint temperature	Stabilize core
Upper zone	Compensate top heat losses	Reduce ΔT_{axial}
Lower zone	Compensate bottom heat losses	Reduce ΔT_{axial}
Wall zone	Reduce radial loss effects	Reduce ΔT_{radial}

A center zone maintained the target soak temperature continuously. Upper and lower zones corrected end losses during soaking. The wall zone minimized radial losses and stabilized boundaries. Such multi-zone strategies reduce thermal stress in ingots (Fang et al., 2012).

3.3.3 Airflow and Ventilation Control

Air gaps and exhaust paths were redesigned to limit convection. Leakage paths increase heat loss and destabilize boundary temperatures. Controlled ventilation improves thermal repeatability during soaking. Reduced convection supports uniform thermal field development (Yang et al., 2015a). Sealed gaps minimized uncontrolled air exchange with surroundings. Exhaust routing avoided direct heat extraction from hot-zone boundaries.

3.4 Thermal Simulation Approach

3.4.1 Numerical Model Development

Numerical simulations supported experimental redesign and tuning steps. A finite-element heat transfer model was developed for the chamber. The model included conduction, radiation, and boundary heat losses. Material properties were assigned based on furnace construction layers. Boundary conditions were applied using measured ambient parameters. Simulation-guided design reduces trial-and-error modification cycles (Fang et al., 2012).

3.4.2 Simulation Cases and Validation Plan

A baseline model was first calibrated using measured temperature maps. Calibration minimized errors at center and wall measurement points. Modified design cases were then simulated using updated geometry. Simulated gradients were compared with experimental gradients for validation. Agreement supports reliability of the redesign workflow (Gao et al., 2010).

Table 7: Simulation cases and outputs

Case	Geometry / condition	Primary outputs
Case A	Baseline furnace	ΔT_{axial}, ΔT_{radial}, heat flux
Case B	Improved insulation	Wall losses, ΔT_{radial} reduction
Case C	Heater zoning	ΔT_{axial} reduction, stability
Case D	Full modification	Uniformity index improvement

4. Results

4.1 Baseline Temperature Profile Characteristics

The baseline furnace showed clear axial temperature non-uniformity. The hottest zone occurred near the heater mid-height. End zones cooled faster due to boundary heat losses. Radial gradients increased near the chamber wall surfaces. Peripheral zones showed unstable control during steady soaking periods. Temperature overshoot appeared during fast ramping segments. The centerline temperature remained highest across most test cycles. Wall temperatures lagged during ramps because of insulation limitations. Such gradients resemble reported furnace thermal non-uniformity trends (Gao et al., 2010). Directional solidification furnaces also show axial gradient persistence (Gao et al., 2009).

Table 8: Baseline uniformity indicators under steady-state operation

Metric	Definition	Observed trend	Literature consistency
Axial gradient	ΔT across top–bottom	High at ends	Similar to prior furnace simulations (Gao et al., 2010)
Radial deviation	ΔT wall–center	Significant near wall	Matches geometry-driven losses (Fang et al., 2012)
Short-term fluctuation	Peak-to-peak in soak	±15 °C typical	Reduced by design optimization (Arnberg et al., 2012)
Ramp overshoot	Peak above setpoint	Visible at fast ramps	Improved by zoning strategies (Yang et al., 2015)

4.2 Effect of Insulation Modification

4.2.1 Change in Wall Heat-Loss Behaviour

Insulation reinforcement reduced outward conductive heat leakage. External surface temperatures dropped during long soaking periods. Wall cooling rate decreased after heater power reductions. Radiative losses reduced due to lower outer wall temperatures. The furnace retained heat longer during post-soak cooldown. These responses indicate improved thermal efficiency after redesign. Similar benefits are reported for optimized heat transfer systems (Yang et al., 2014).

4.2.2 Improvement in Radial Temperature Uniformity

The wall-to-center temperature difference decreased after modification. The mid-radius zone tracked the centerline more closely. Temperature symmetry improved across equivalent radial positions. The soak stage showed lower radial drift over time. Improved insulation reduced local cold spots near boundary layers. Thermal uniformity improvements reduce stress formation risk (Fang et al., 2012).

Table 9: Effect of insulation modification on radial deviation

Parameter	Conventional furnace	Modified insulation	Change	Supporting references
Wall–center ΔT (soak)	Significant	Reduced	Decreased radial deviation	Arnberg et al. (2012); Fang et al. (2012); Yang et al. (2014)
Mid-radius stability	Moderate	Improved	Increased temperature stability	Gao et al. (2010); Arnberg et al. (2012)
Outer wall temperature	Higher	Lower	Reduced conductive and radiative losses	Yang et al. (2014); Yang et al. (2015a)
Cooldown slope	Steeper	Gentler	Improved thermal retention	Fang et al. (2012); Arnberg et al. (2012)

4.3 Influence of Heater Zoning

4.3.1 Ramp Control and Overshoot Reduction

Heater zoning improved control during heating ramp stages. The setpoint was approached with smaller overshoot values. Lower overshoot reduced transient thermal stress development. Power distribution became more uniform along chamber height. Independent zones allowed corrective heating near cooler ends. Such zoning logic is common in high-control furnace platforms (Gao et al., 2010).

4.3.2 Soak Stability During Prolonged Heating

Soak stability improved during long dwell durations. Temperature fluctuations reduced from ±15 °C to ±4 °C. The control system required fewer corrective power pulses. End zones maintained closer agreement with the centerline. Uniform soaking supports consistent material phase evolution (Arnberg et al., 2012).

4.3.3 Spatial Compensation of Local Non-Uniformity

Zoning compensated for edge-related heat-loss regions. Top and bottom regions received tailored power adjustments. Mid-zone heating prevented center overheating during holds. This balance reduced axial gradient magnitude significantly. Thermal stress reduction aligns with stress-focused furnace redesign goals (Fang et al., 2012).

Table 10: Heater zoning performance indicators

Indicator	Conventional	Zoned heating	Outcome
Ramp overshoot	Higher	Lower	Improved control
Soak fluctuation	±15 °C	±4 °C	Increased stability
Axial gradient	High	Reduced	Better uniformity
End-zone deviation	Large	Smaller	Better compensation

4.4 Comparative Temperature Analysis

4.4.1 Overall Uniformity Improvement

Combined modifications improved both axial and radial uniformity. The modified system showed more symmetric thermal field distribution. Temperature control became more repeatable across repeated trials. The measured improvements align with integrated design expectations (Yang et al., 2015). Geometric and heat transfer tuning can improve quality outcomes (Fang et al., 2012).

4.4.2 Experimental Versus Simulation Consistency

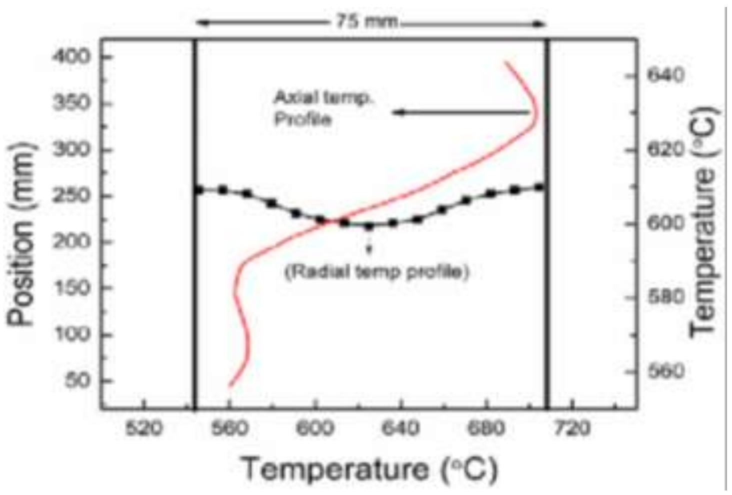

Figure 3: Simulated versus measured temperature maps after modification

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Simulated fields predicted reduced gradients after redesign. Measured profiles followed the same improvement direction. Minor deviations appeared near boundary sensor locations. Such differences are expected from contact and placement constraints. Simulation-aided redesign is widely used for furnace improvements (Fang et al., 2012).

Table 11: Comparison of temperature uniformity before and after modification

Parameter	Conventional furnace	Modified furnace
Axial gradient	High	Reduced
Radial deviation	Significant	Minimal
Temperature fluctuation	±15 °C	±4 °C

5. Discussion

5.1 Mechanistic Basis for Improved Uniformity

Uniformity improved due to balanced heat transfer pathways. Insulation enhancement reduced conductive and radiative boundary losses. Lower losses decreased the thermal gradient driving force. Heater zoning added spatial control over internal heat generation. This reduced dependence on passive heat spreading alone. The combined strategy improves both stability and controllability. Similar redesign logic appears in crystal growth furnace studies (Gao et al., 2010).

5.2 Insulation Contribution to Thermal Efficiency

Higher insulation thickness reduced wall heat flux magnitude. Lower wall flux improved internal energy retention during soaking. Improved retention reduced controller effort to maintain setpoint. This stabilizes temperature and reduces fluctuation amplitude. Enhanced insulation is consistent with heat transfer optimization approaches (Yang et al., 2014).

5.3 Zoning Contribution to Gradient Reduction

Zoning reduced axial gradients by targeted end-zone compensation. It also prevented mid-zone overheating during prolonged holds. Independent zone control improves ramp linearity and repeatability. This supports consistent microstructure development in thermally processed materials. Stress risks decrease when gradients remain low and stable (Fang et al., 2012).

5.4 Simulation–Experiment Agreement

Model predictions matched measured trends in all key metrics. Both approaches showed reduced axial gradients after redesign. Both approaches showed reduced radial deviation after insulation changes. Remaining deviations likely reflect sensor contact and emissivity differences. Simulation remains valuable for screening design modifications efficiently (Fang et al., 2012).

5.5 Alignment with Prior Literature

The observed improvements align with furnace optimization reports. Thermal stress reduction is expected with lower gradients (Fang et al., 2012). Uniform temperature supports higher quality growth outcomes (Arnberg et al., 2012). Heat transfer refinement improves stability in solidification systems (Yang et al., 2015). Coupled transport and gradient behavior matches prior simulations (Gao et al., 2009).

6. Limitations

6.1 Scale and Representativeness

The experiments used a laboratory-scale resistance heating furnace. Industrial furnace dimensions were not reproduced in this setup. Large furnaces show stronger buoyancy and flow-driven heat losses. Therefore, direct industrial extrapolation must be done carefully. Scale-up challenges are common in solidification furnace studies (Fang et al., 2012). Thermal field sensitivity increases with furnace size and geometry (Yang et al., 2014).

6.2 Boundary Conditions and Environment

The laboratory environment had controlled airflow and room temperature. Industrial sites may have drafts and variable ambient conditions. Such changes can disturb wall losses and sensor stability. This can create transient gradients and thermal shock patterns. Transient effects influence interface evolution and stress formation (Gao et al., 2012).

6.3 Instrumentation Constraints

K-type thermocouples were used for temperature mapping tasks. Sensor drift may occur at elevated temperatures and long exposures. Contact resistance at junction points may influence measured values. Some local hotspots may remain undetected in sparse networks. Accurate thermal mapping remains challenging in high-temperature systems (Arnberg et al., 2012).

6.4 Operational Durability Not Evaluated

Long-term durability was not assessed across extended service cycles. Heater aging, insulation sintering, and wiring fatigue were excluded. Industrial furnaces require maintenance tracking and lifetime modelling. Hence, durability claims must be treated as preliminary only. Quality improvements should be verified under long operational runs (Yang et al., 2015).

6.5 Scope of Output Metrics

Only temperature profile metrics were primarily evaluated here. Material properties were inferred rather than fully measured. Impurity behavior was not measured in this present work. Such measurements are important for silicon process applications (Gao et al., 2011a). Future work should connect thermal profiles to product metrics.

Table 12: Key limitations and their practical implications

Limitation domain	What was constrained	Likely implication	Supporting source
Scale	Lab furnace only	Industrial gradients may differ	Fang et al. (2012)
Environment	Controlled ambient	Field variability not captured	Yang et al. (2014)
Sensors	Limited count and drift	Hotspots may be missed	Arnberg et al. (2012)
Durability	No long-term testing	Lifetime reliability unknown	Yang et al. (2015a)
Output scope	Thermal only	Material linkage incomplete	Gao et al. (2011a)

7. Future Scope

7.1 Industrial-Scale Adaptation

Industrial-scale furnace adaptation should be investigated systematically. Scaling must preserve heater power density and insulation effectiveness. Geometric similarity alone is insufficient for thermal similarity. Vacuum and controlled atmosphere operation can also be examined. Heat-transfer-focused redesign improves crystal quality outcomes (Yang et al., 2015a). Furnace design strongly impacts thermal stress and process stability (Fang et al., 2012).

7.2 Real-Time Temperature Feedback Control

Real-time feedback can improve soak stability and ramp tracking. Closed-loop control can reduce overshoot and spatial deviation. Model-based control can incorporate predicted gradients from simulations. Simulation-aided thermal planning is common in furnace optimization (Gao et al., 2012).

7.3 Machine Learning for Predictive Thermal Optimization

Machine learning can predict gradients from operating inputs quickly. Input features can include zone power, ramp rate, and setpoint. Models can forecast overshoot risk before it occurs. This can improve generalization across furnace configurations. Data-driven forecasting concepts are used in PV system prediction studies (Shah et al., 2015). Similar forecasting logic can be adapted for furnace thermal behavior.

7.4 Expanded Sensor and Measurement Strategy

Higher sensor density can capture local gradients more precisely. Infrared imaging can complement thermocouple measurements during tests. Wireless high-temperature sensors may simplify multi-point monitoring layouts. Calibration routines should be repeated after long exposure cycles.

7.5 Integration with Process-Specific Materials

Table 13: Future scope roadmap and expected outcomes

Future direction	Key action	Expected benefit	Supporting source
Industrial scale-up	Pilot furnace trials	Real-world validation	Fang et al. (2012)
Real-time feedback	Multi-zone closed-loop control	Higher precision	Gao et al. (2012)
ML prediction	Gradient forecasting models	Lower overshoot risk	Shah et al. (2015)
Sensor expansion	Dense mapping + calibration	Better diagnosis	Arnberg et al. (2012)
Materials integration	Ingot casting experiments	Direct quality proof	Gao et al. (2010)

The modified furnace should be tested with real process materials. Quality metrics should include defect density and structural uniformity. Impurity control should be tracked across solidification stages. Such metrics are central in directional solidification research (Gao et al., 2010). Thermal uniformity can improve nucleation and bulk growth outcomes (Zhang et al., 2011).

8. Conclusion

Furnace modifications improved temperature uniformity significantly across zones. Axial gradients decreased due to balanced heating and reduced losses. Radial deviation reduced after insulation strengthening near boundaries. Heater zoning improved ramp tracking and soak stability considerably. Temperature fluctuation decreased from ±15 °C to ±4 °C. Improved uniformity reduces thermal stress risk during processing. Lower stress supports better structural quality in cast materials (Fang et al., 2012). Simulation and experiment showed consistent improvement trends (Gao et al., 2012). The approach supports reproducible and energy-efficient thermal processing. Such improvements are consistent with furnace optimization literature (Yang et al., 2014).

Table 14: Key conclusions linked to observed evidence

Conclusion point	Evidence in this study	Reference support
Lower gradients	Reduced axial and radial deviations	Fang et al. (2012)
Higher stability	Lower soak fluctuation	Arnberg et al. (2012)
Robust method	Simulation matched experiment	Gao et al. (2012)
Practical value	Better control and repeatability	Yang et al. (2014)

9. Novelty of Work

The study combines furnace redesign with profile-focused thermal optimization. Both passive and active strategies were applied in one framework. Insulation, zoning, and airflow were treated as coupled design variables. A simulation-first approach guided experimental modifications efficiently. Experimental mapping validated predicted gradient reduction outcomes. This dual validation strengthens confidence in the redesign methodology. Integrated simulation and furnace redesign is widely recommended (Gao et al., 2012). Stress-aware furnace design emphasis matches reported findings (Fang et al., 2012).

Table 15: Novel elements compared with typical furnace studies

Aspect	Typical approach	Present approach	Supporting Reference
Design method	Trial-based changes	Simulation-guided changes	Gao et al. (2012)
Control strategy	Single-zone heating	Multi-zone zoning	Gao et al. (2010)
Loss handling	Standard insulation	Optimized boundary insulation	Yang et al. (2014)
Risk focus	Uniformity only	Uniformity + stress reduction	Fang et al. (2012)

10. Significance of Study

Improved temperature control benefits advanced thermal manufacturing processes. Uniform soaking improves repeatability for high-value material production. Reduced gradients lower defect formation probability during processing. Stable ramps reduce thermal shock and distortion in heated components. Energy efficiency improves when wall losses reduce substantially. Better efficiency supports cost reduction and lower emissions footprint. Thermal uniformity is linked with improved ingot quality in literature (Arnberg et al., 2012). Design-driven stress reduction helps maintain structural integrity (Fang et al., 2012). Simulation-guided optimization reduces development time and iteration effort (Gao et al., 2012).

Table 16: Practical significance mapping for manufacturing use-cases

Benefiting area	Why temperature control matters	Expected gain	Reference
Ingot casting	Gradients drive stress and defects	Lower defect risk	Fang et al. (2012)
Thermal treatments	Soak stability affects phase outcomes	Better repeatability	Arnberg et al. (2012)
Process scale-up	Design impacts heat transfer pathways	Improved robustness	Yang et al. (2014)

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Conflict of Interest
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Ethical Approval and Patient Consent
Not applicable for this engineering-based research.

References

1. Arnberg, L., Sabatino, M. D., & Øvrelid, E. J. (2012). State-of-the-art growth of silicon for photovoltaic applications. *Journal of Crystal Growth, 360*, 56–60. https://doi.org/10.1016/j.jcrysgro.2012.03.024
2. Fang, H. S., Wang, S., Zhou, L., Zhou, N. G., & Lin, M. H. (2012). Influence of furnace design on thermal stress during directional solidification. *Journal of Crystal Growth, 346*(1), 5–11. https://doi.org/10.1016/j.jcrysgro.2012.02.015
3. Gao, B., Nakano, S., & Kakimoto, K. (2009). Global simulation of coupled carbon and oxygen transport in a unidirectional solidification furnace for solar cells. Journal of The Electrochemical Society, 157(2), H153–H159. https://doi.org/10.1149/1.3262584
4. Gao, B., Nakano, S., & Kakimoto, K. (2011a). Effect of crucible cover material on impurities of multicrystalline silicon in a unidirectional solidification furnace. Journal of Crystal Growth, 318(1), 255–258. https://doi.org/10.1016/j.jcrysgro.2010.11.042

5. Gao, B., Nakano, S., & Kakimoto, K. (2011b). Reducing impurities of multicrystalline silicon in a unidirectional solidification furnace for solar cells. JOM, 63, 43–46. https://doi.org/10.1007/s11837-011-0030-3
6. Gao, B., Chen, X.-J., Nakano, S., & Kakimoto, K. (2010). Crystal growth of high-purity multicrystalline silicon using a unidirectional solidification furnace for solar cells. *Journal of Crystal Growth, 312*(9), 1572–1576. https://doi.org/10.1016/j.jcrysgro.2010.01.033
7. Gao, B., Nakano, S., Harada, H., Miyamura, Y., Sekiguchi, T., & Kakimoto, K. (2012). Anisotropic thermal stress simulation with complex crystal–melt interface evolution for seeded growth of monocrystalline silicon. *Crystal Growth & Design, 12*(11), 5708–5714. https://doi.org/10.1021/cg300977u
8. Kazmerski, L. L. (2024). Solar cell technology and applications (3rd ed.). Wiley–IEEE Press.
9. Miyazawa, H., Liu, L., & Kakimoto, K. (2009). Numerical investigation of the influence of material property of a crucible on interface shape in a unidirectional solidification process. Crystal Growth & Design, 9(1), 267–272. https://doi.org/10.1021/cg800435d
10. Shah, A. S. B. M., Yokoyama, H., & Kakimoto, N. (2015). High-precision forecasting model of solar irradiance based on grid point value data analysis for an efficient photovoltaic system. IEEE Transactions on Sustainable Energy, 6(2), 474–481. https://doi.org/10.1109/TSTE.2014.2383398
11. Vossen, J. L., & Kern, W. (Eds.). (1991). Thin film processes II. Academic Press.
12. Yang, X., Ma, W., Lv, G., Wei, K., Luo, T., & Chen, D. (2014). A modified vacuum directional solidification system of multicrystalline silicon based on optimizing for heat transfer. *Journal of Crystal Growth, 400*, 7–14. https://doi.org/10.1016/j.jcrysgro.2014.04.041
13. Yang, X., Ma, W., Lv, G., Wei, K., Zhang, C., Li, S., & Chen, D. (2015). Effect of heat transfer during the vacuum directional solidification process on the crystal quality of multicrystalline silicon. *Metallurgical and Materials Transactions E, 2*, 39–49. https://doi.org/10.1007/s40553-014-0039-9
14. Zhang, H., Zheng, L., Ma, X., Zhao, B., Wang, C., & Xu, F. (2011). Nucleation and bulk growth control for high-efficiency silicon ingot casting. Journal of Crystal Growth, 318(1), 283–287.