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HPDC-Twin: Thermal Simulation for Engineering Decisions

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Document type: Technical overview and computational demonstration report.
Evidence basis: Reproducible software tests and a synthetic multi-cycle demonstration; customer process measurements are introduced within a separately scoped engagement.
Application: High-pressure aluminum die casting, die-temperature histories, solidification, cooling scenarios, and engineering decision support.

1 Executive summary

High-pressure die casting is governed by repeated heat exchange among the molten alloy, casting, die, and cooling system. Engineering teams therefore need to interpret temperature histories in relation to process timing, material properties, geometry, and thermal boundary conditions. HPDC-Twin provides a computational workflow for examining these relationships through a C++17 finite-volume thermal/solidification solver and a Python/Jupyter workbench. The workflow supports structured configuration, multi-cycle scenario execution, spatial and summary outputs, sensitivity analysis, numerical diagnostics, and run provenance. It provides a starting point for paid data-readiness assessments, customer-specific feasibility studies, and measurement-led calibration and evaluation.

HPDC thermal analysis: from process information to engineering decisions



2 The HPDC thermal problem

A typical HPDC cycle brings the die into contact with molten alloy, transfers heat through the casting–die interface, advances solidification, and then moves through ejection, die preparation, and cooling before the next shot. The temperature field in the tool evolves across these phases and across successive cycles. Initial die temperature, alloy and tool properties, local geometry, contact conditions, cycle timing, and cooling configuration all influence the transient response.

A useful thermal study links three layers: (i) the physical process and its operating sequence; (ii) the measurements and assumptions used to represent that process; and (iii) the engineering decision that the analysis is intended to inform. Published instrumented-die studies demonstrate the value of thermocouple histories and inverse heat-transfer analysis for understanding the metal–die interface and cooling boundaries [1–4].

> Engineering proposition. Turn process records and thermal measurements into a structured model, compare selected operating scenarios, and produce a documented basis for the next engineering decision.

3 Computational architecture

HPDC-Twin separates numerical computation from experiment configuration and result inspection. The compiled C++17 component performs the thermal/solidification calculation. Python orchestrates the executable, supplies structured JSON configuration, reads outputs, and supports the Jupyter workbench used for visualization and diagnostics.

Layer	Current role	Representative outputs
C++17 solver	Two-dimensional finite-volume heat conduction and enthalpy-based phase-change treatment across the casting/die domain.	Temperature and phase-fraction fields; thermal summaries.
Configuration	Structured JSON inputs for material, geometry abstraction, process sequence, initial conditions, and effective thermal boundaries.	Versioned configuration and reproducible run setup.
Python orchestration	Launches the compiled solver, organizes run directories, reads exported fields and summaries, and records provenance.	Run manifests; summary tables; optional spatial-field CSV files.
Jupyter workbench	Configures and runs studies, inspects temperature/phase-fraction fields, and visualizes diagnostics and scenario comparisons.	Plots, comparison views, sensitivity summaries, and review-ready outputs.

4 Inputs, outputs, and data structure

Information group	Examples to organize	Engineering purpose
Geometry	Die/cavity section, insert dimensions, casting thickness, sensor coordinates and depths.	Defines the modeled domain and locations where simulated histories can be compared.
Materials	Alloy and die grades; density, heat capacity, conductivity, latent heat, solidus/liquidus range.	Defines heat storage, conduction, and phase-change behavior.
Process sequence	Cycle identifiers, injection/contact timing, solidification, ejection, spray/cooling phases, initial temperatures.	Defines transient conditions and repeated-cycle structure.
Measurements	Thermocouple histories, sensor type, calibration, coordinates, sampling interval, units, uncertainty.	Supports traceable comparison at actual observation locations.
Cooling context	Available inlet/outlet temperatures, flow or pressure records, channel/insert description.	Informs the effective cooling-boundary representation and possible refinements.
Outputs	Temperature histories and fields, phase fraction, cycle summaries, residual diagnostics, sensitivity results, run manifest.	Connects model behavior to the intended engineering question and review process.

The original explanatory schematic below summarizes the process-input, casting–die, and computational layers. It is conceptual and not to scale.

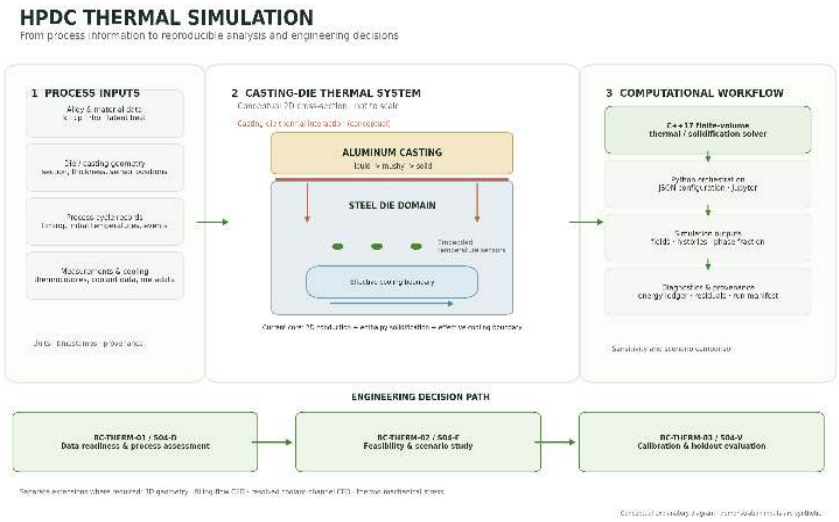


Figure 1. HPDC-Twin process-to-decision workflow. The current computational core represents a two-dimensional thermal/solidification domain with an effective cooling boundary; the diagram is an explanatory architecture view.

5 B1 computational demonstration

The B1 demonstration exercised the end-to-end workflow with a three-cycle synthetic telemetry scenario. It produced thermal summaries, cell-centered temperature and phase-fraction fields, solver diagnostics, and run metadata. The demonstration is useful for reviewing reproducibility, output structure, and numerical behavior under a documented configuration.

Measure	Recorded value	Interpretation
Cycle observations	3 cycles; 21 observations.	Synthetic multi-cycle demonstration input.
Spatial discretization	12 × 12 grid.	Two-dimensional computational demonstration.
Field output	3,024 cell-field records.	Exported spatial temperature/phase-fraction records.
Maximum absolute global energy-ledger residual	8.73×10^{-9} J.	Numerical diagnostic for the B1 configuration.
Maximum scaled nonlinear residual	1.38×10^{-11}.	Numerical solver diagnostic for the B1 configuration.

Software verification snapshots

Snapshot	CTest	Python tests	Notebook smoke
B1 demonstration snapshot	25/25	23/23	Not reported in this snapshot
Later v4.3/v4.3.1 staging audit	25/25	24/24	8/8 code cells

These are separate versioned records and are intentionally reported separately. The 1×10^{-5} J energy threshold is a software regression threshold, not a physical process acceptance tolerance. The synthetic telemetry and illustrative physical parameters are not industrial measurements. The exploratory sensitivity exercise comprised 576 evaluations across four illustrative U(0.8, 1.2) factors, with N=32 per horizon and one seed per horizon; its rankings are exploratory rather than empirical parameter-importance estimates.

6 Customer-specific study design

A customer engagement begins by defining the engineering question and intended use, then organizing the available process evidence. A bounded study maps customer geometry and measurements to the model, agrees the operating conditions to examine, and defines how results will be interpreted. Where measurement-based evaluation is required, calibration and holdout cycles are separated before parameter fitting.

Stage	Typical activities	Decision supported
BC-THERM-01 · Data readiness	Review the question, geometry, materials, cycle records, temperature histories, sensor metadata, and cooling information; identify priorities and model fit.	Is the available information suitable for a focused thermal study, and what should be collected next?
BC-THERM-02 · Feasibility	Configure a bounded model, compare a baseline with selected scenarios, map outputs to sensor locations, and examine sensitivity.	Which thermal scenarios are worth further engineering consideration?
BC-THERM-03 · Validation pilot	Calibrate selected parameters on designated cycles and evaluate the frozen model on independent holdout cycles or conditions.	What performance is supported within the agreed operating envelope?

7 Measurement and evaluation framework

A customer-specific evaluation should agree the measurement basis, operating envelope, metrics, and aggregation rules before calibration. Candidate measures include temperature-history MAE/RMSE, peak-temperature difference, time-to-peak, cooling-rate behavior, cycle-to-cycle drift, and residual patterns by sensor location or operating condition. Complete cycles or operating conditions are generally more meaningful holdout units than randomly selected adjacent time samples when temporal dependence is present.

8 Engagement pathway and deliverables

Service	Indicative effort	Core deliverables
BC-THERM-01 · Thermal Data-Readiness Gate (S04-D)	3–5 working days	Process/data inventory; question and assumption register; model-fit assessment; prioritized measurement plan; bounded study proposal.
BC-THERM-02 · Thermal Feasibility and Scenario Study (S04-F)	12–25 working days	Reproducible configuration; baseline and selected scenario runs; thermal fields/histories; sensitivity summary; engineering interpretation and holdout plan.
BC-THERM-03 · Calibration and Independent Validation Pilot (S04-V)	25–50 working days	Calibration record; frozen model configuration; independent holdout evaluation; sensor-level residuals; operating-envelope statement; engineering report.

Effort ranges are indicative planning ranges. The statement of work defines the actual geometry, data package, number of conditions, deliverables, review points, and acceptance measures.

9 Published engineering context

Study	Evidence reported	Relevance to an HPDC study
Dour et al. (2005) [1]	Instrumented production-die work covering 150 castings under varied process parameters; inverse analysis of temperature measurements.	Shows how piston velocity and initial die temperature can influence measured heat-transfer conditions.
Long et al. (2011) [2]	Thermocouple-instrumented production die and comparison of measured histories with simulation assumptions for AlSi9Cu3Fe.	Highlights the importance of metal–die interface assumptions and comparison against measured histories.
Teamah et al. (2025) [3]	A365/H13 experimental setup with nine embedded thermocouple channels at three depths; comparison with an industrial HPDC trial reported about 14% peak heat-flux deviation and less than 12% FWHM difference.	Illustrates measurement-led characterization of transient interface heat transfer; reported values belong to that specific experiment.
Bohacek et al. (2024) [4]	Inverse estimation of transient cooling-channel heat transfer from multiple temperature measurements.	Shows the value of representing cooling conditions in relation to spatial measurements.
Kunz et al. (2014) [5]	Dynamic modeling of fluid-cooled tools in periodic thermal processes, evaluated against experimental data.	Provides context for recurring thermal patterns across successive production cycles.

10 References

[1] Dour, G., Dargusch, M., Davidson, C., & Nef, A. (2005). Development of a non-intrusive heat transfer coefficient gauge and its application to high pressure die casting: Effect of the process parameters. Journal of Materials Processing Technology, 169(2), 223–233. doi:10.1016/j.jmatprotec.2005.03.026.

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