

A Conjugate Heat Transfer Model for Autoclave Process Simulation

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OVERVIEW

Manufacturer-recommended cure cycles carry conservative margins that limit autoclave throughput. This work adds resin cure kinetics to a thermocouple-validated conjugate heat transfer (CHT) model of a full-scale autoclave in ConvergeCFD, so that temperature, Degree of Cure (DoC), and exothermic heat release are resolved together. The kinetics integration is verified against three independent solutions and then applied to an IM7-8552 laminate on an L-shaped aluminum mold.

MOTIVATION

- Autoclave part quality is governed by the coupled thermal, chemical, and mechanical history during cure, which airflow, part placement, and tooling thermal mass make non-uniform [1, 2].
- Most thermal FEA imposes a constant or spatially averaged Heat Transfer Coefficient and neglects turbulence, recirculation, and flow shadowing [3–5].
- Two prior efforts by the authors remained disconnected: a validated CHT model with no internal heat generation [12], and cure-coupled FEA with prescribed convection [13].
- Objective:** a single physics-based model that resolves the turbulent thermal environment and the in-situ cure response.

RESEARCH ROAD MAP

- ASC 2025 [13]** FEA cure-cycle optimization framework (CHILE constitutive model, multi-reaction cure kinetics).
- ASME SSDM 2026 [12]** Full-scale CHT CFD model verified against thermocouples; heating-rate and air-velocity parametric study.
- ASC 2026**, Cure kinetics coupled into the CHT model: temperature, DoC, and exotherm resolved together.
- Next** Experimental DSC validation, kinetic-parameter refinement, improved closed-loop cycle optimization upon [13].

AUTOCLAVE AND CURE CYCLE

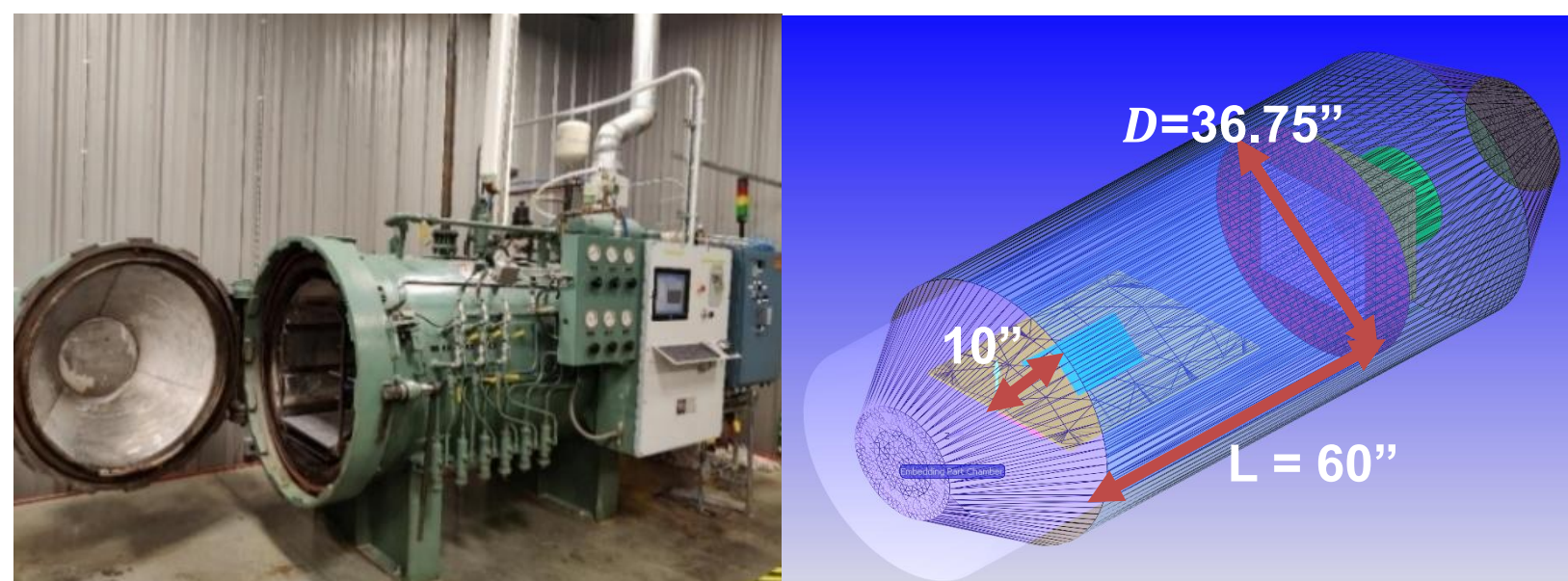


Fig. 1. BAC 35 Autoclave At Purdue University

- Equipment:** Baron Blakeslee BAC 35 at Purdue CMSC: forced convection, PID control, rated 600 °F and 120 psi; chamber 36.75 in diameter × 60 in in length.
- Part Specification:** 10 in × 10 in IM7-8552, [−45/0/45/90]_{3s}, 24 plies, 35% resin by mass, 4 mm cured, on an L-shaped Al 6061-T6 mold placed 10 in from the inlet plane.
- Modified Cure Cycle:** 5 °F/min to 380 K, 60 min hold, 5 °F/min to 450 K, 120 min hold. Pressure 30 psi, then 100 psi; vacuum relaxed after the first hold.

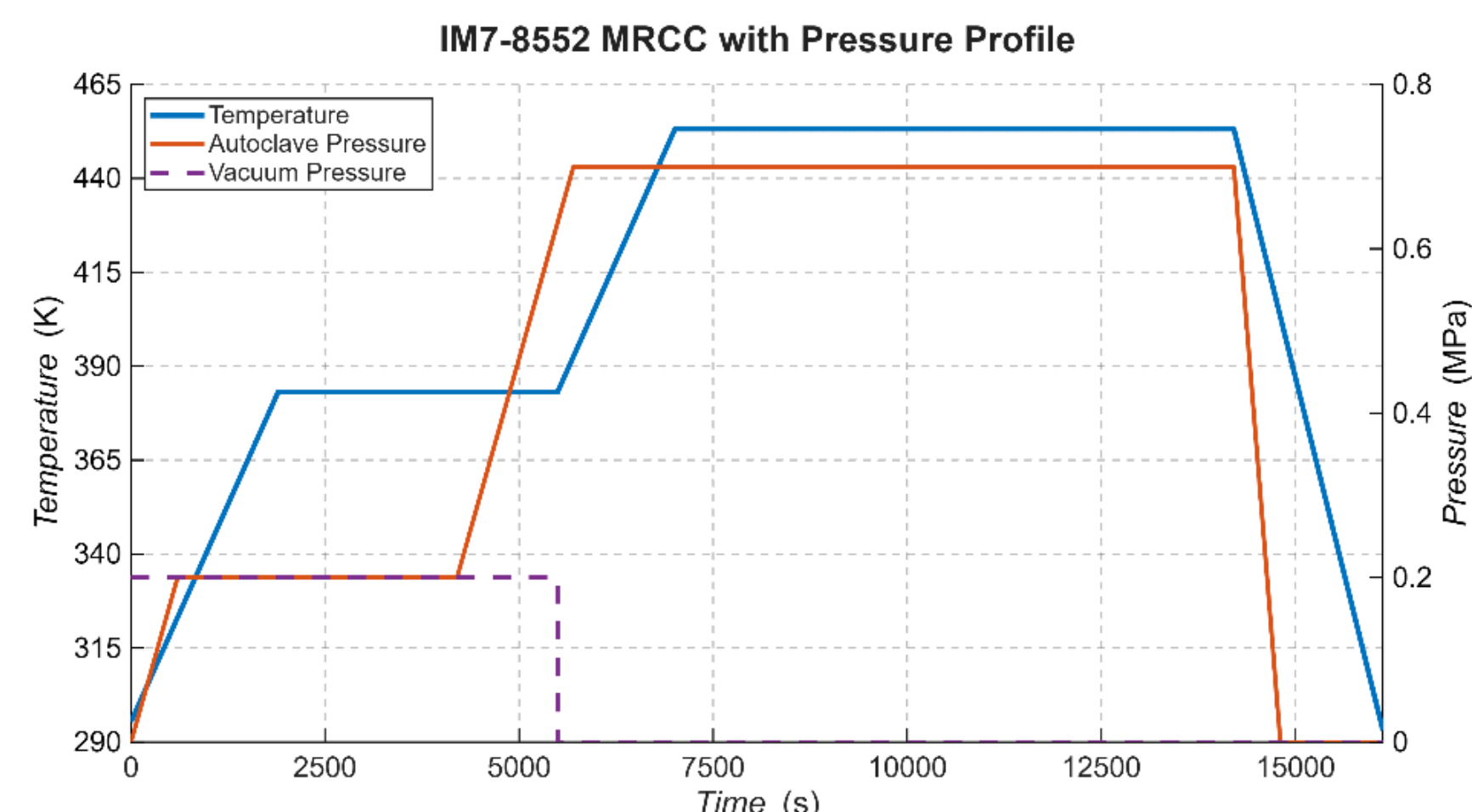


Fig. 2. Modified IM7-8552 Cure Cycle: Temperature, Autoclave Pressure, And Vacuum.

COUPLED CHT AND CURE KINETICS MODEL

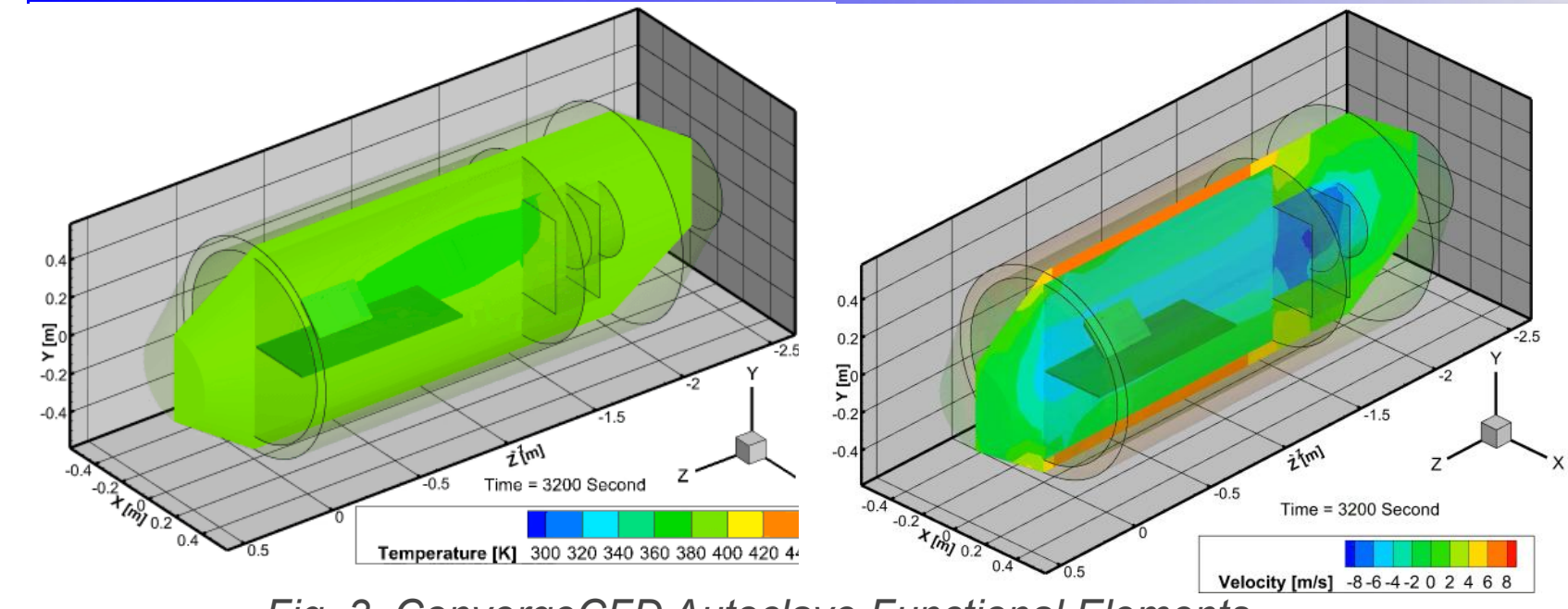
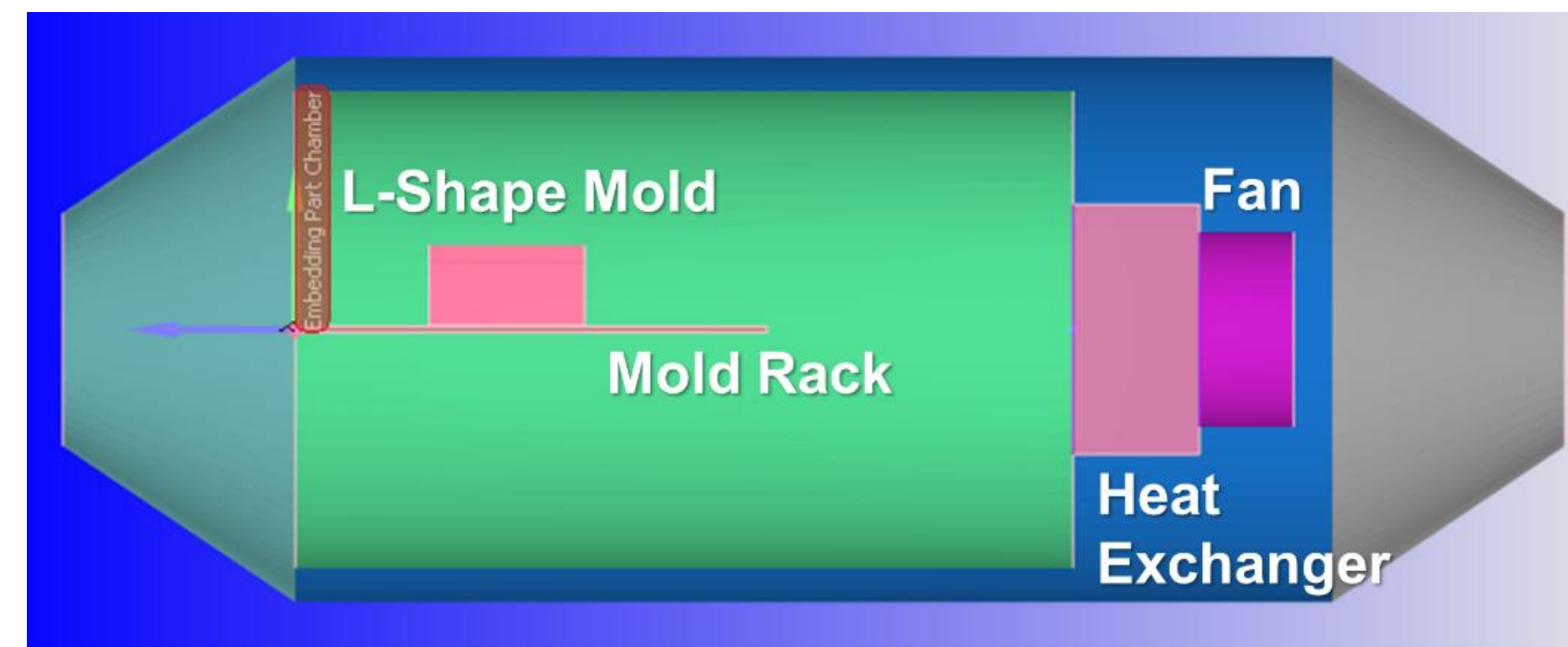


Fig. 3. ConvergeCFD Autoclave Functional Elements, Velocity and Temperature Contour (t=3200s)

Material	Density (kg/m ³)	Heat capacity (J/(kg·K))	Conductivity (W/(m·K))
IM7/8552 composite	1577	827	0.43
Aluminum 6061-T6	2700	896	167

Table 1. Simulation Implemented Material Properties.

RESULTS: FULL AUTOCLAVE, IM7-8552 LAMINATE

33 K / 37 K

Max Temperature Lag Of Part / Mold Vs Circulating Air

+1.2 K

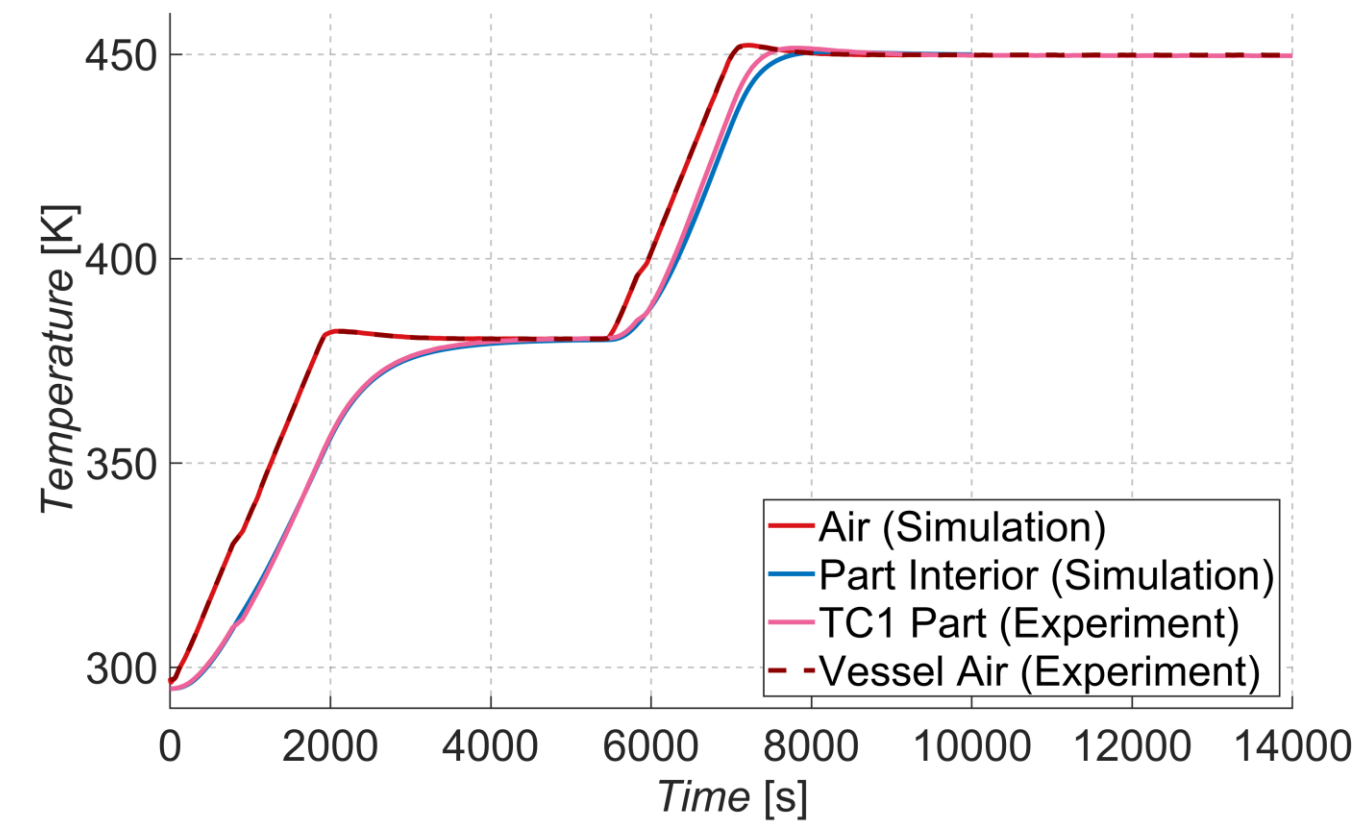
Temperature Of Part Over Air From Curing Exotherm

7.5 K

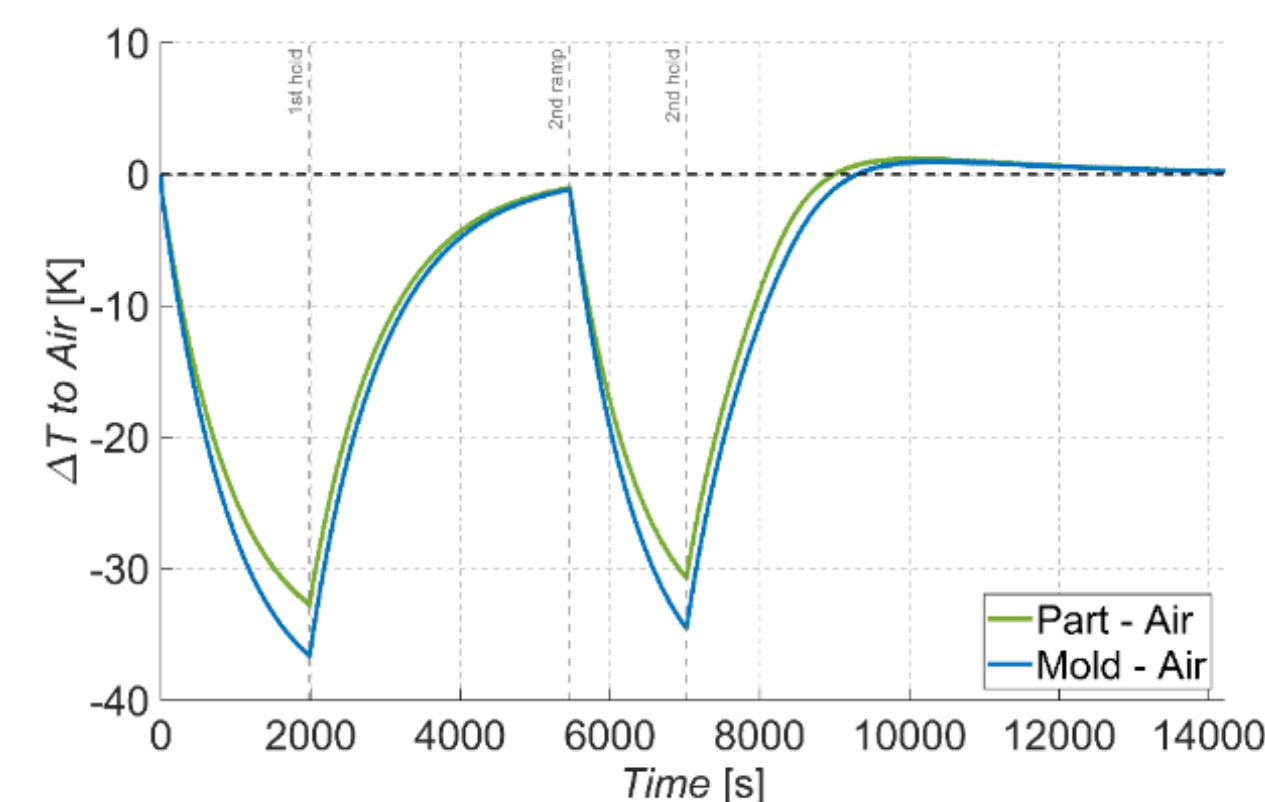
Peak Part-Mold Stack Through Thickness Temperature Difference

85% / 92.2%

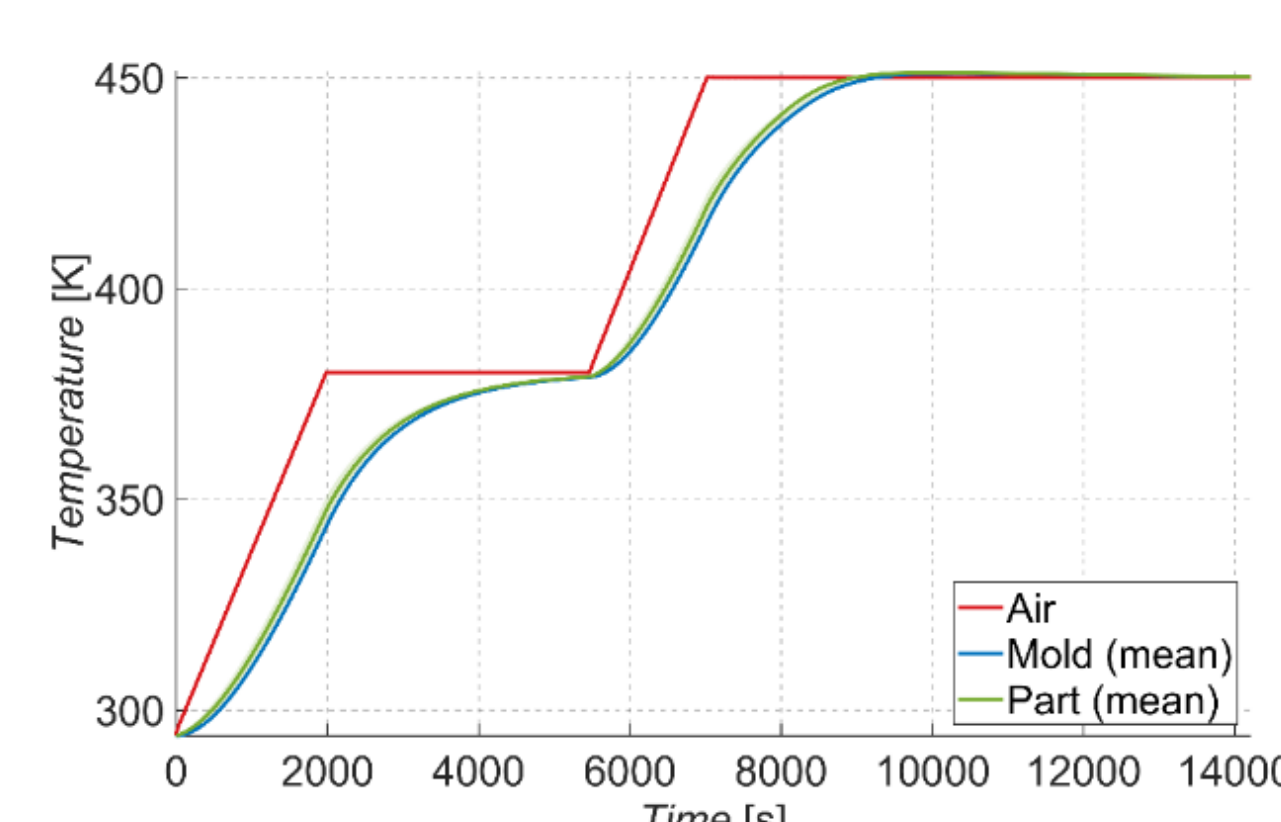
Predicted / Experimental Final Degree Of Cure



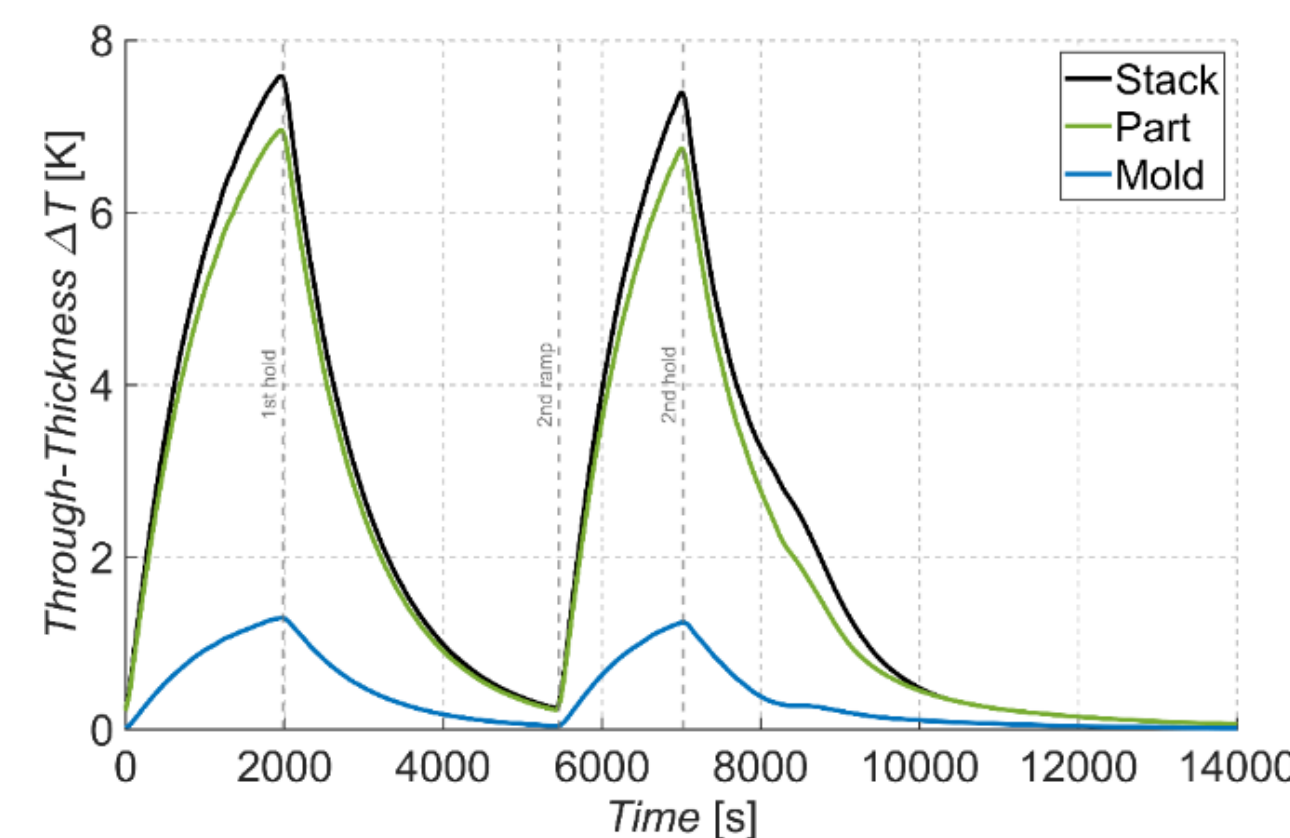
CFD Model Calibration. Experimentally calibrated CFD parameters comparing with thermocouple reading from Modified Cure Cycle.



Exotherm Crossover. Lag reaches 33 K (part) and 37 K (mold). Near 9000 s the sign reverses: the exotherm, not the controller, sets the peak part temperature (Fig. 6).



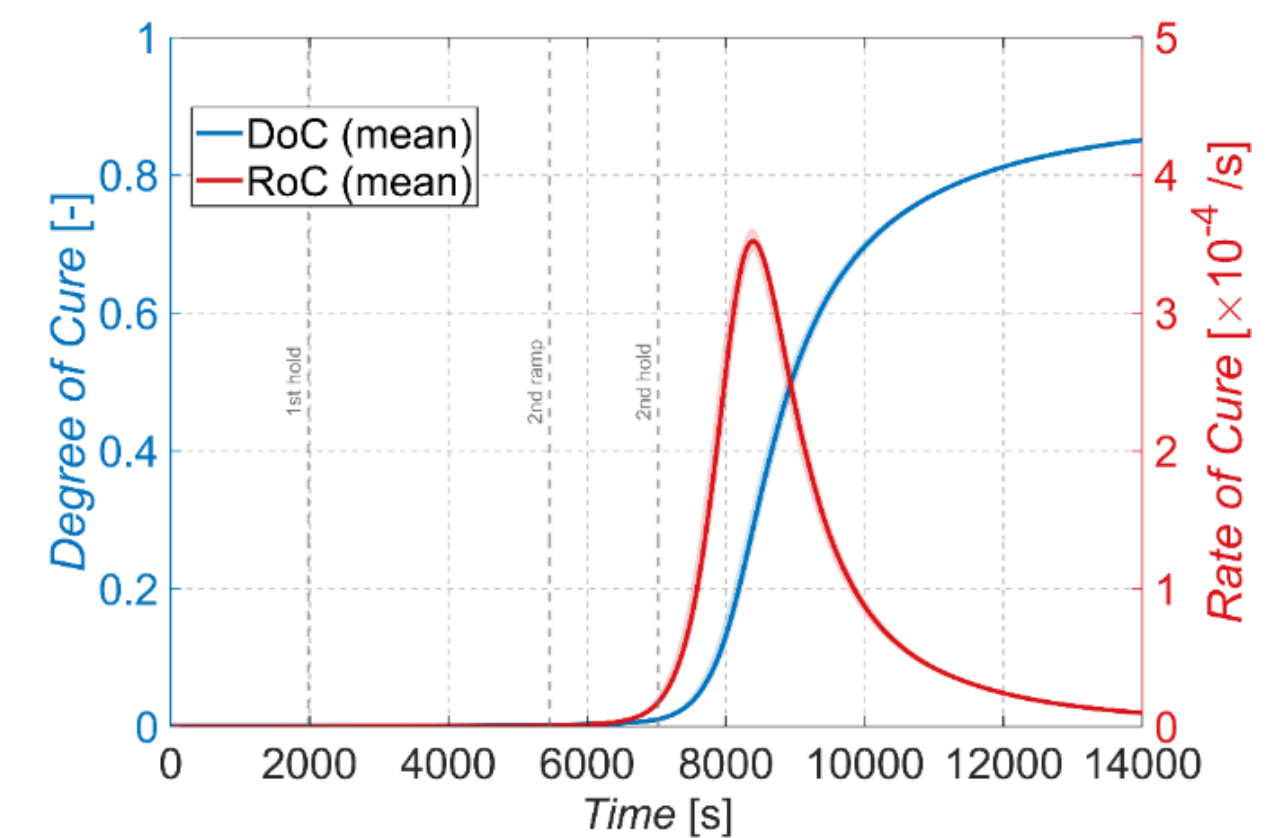
Thermal Lag. Mold and part lag the air during both ramps and converge to it at both holds (Fig. 5).



Through-Thickness Difference. The stack difference peaks near 7.5 K at the start of each hold and decays to zero: a convective transient, not a reaction effect (Fig. 8).



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Degree Of Cure. DoC levels off near 85%; the rate of cure peaks near 8400 s. The band across the 4 mm laminate is narrow (Fig. 7).

NUMERICAL METHOD VERIFICATION

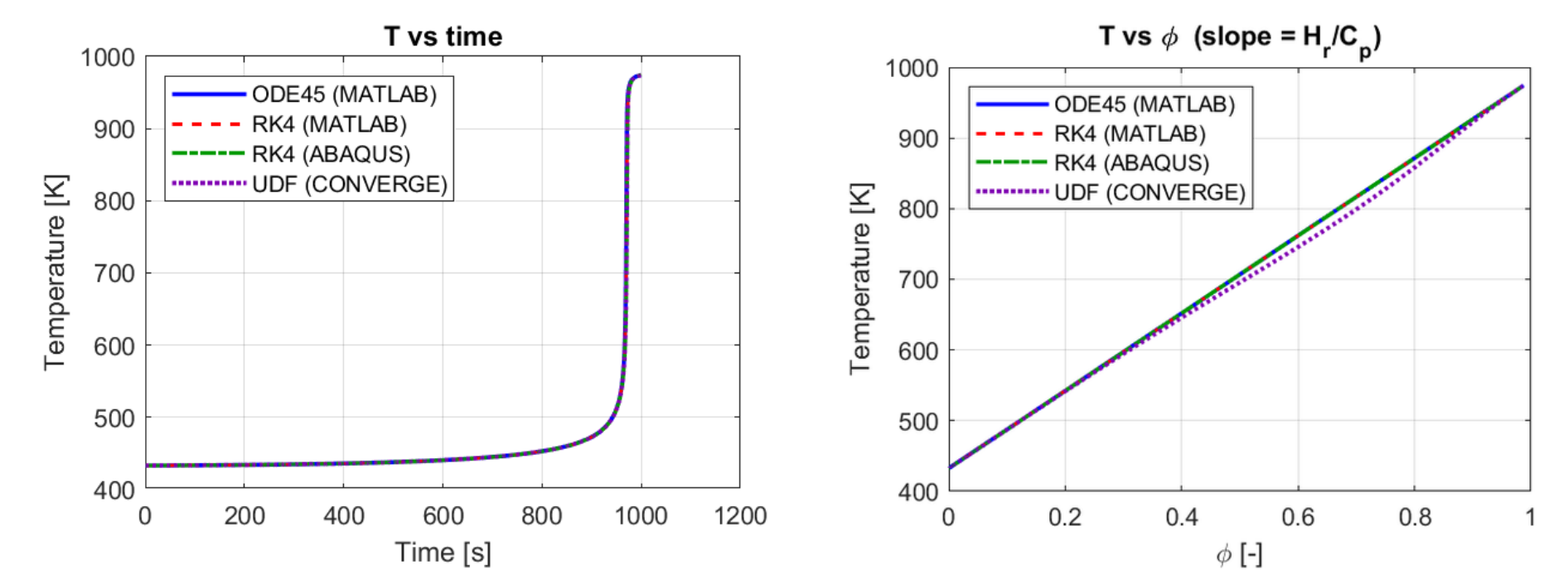


Fig. 4. Adiabatic Benchmark, $\Delta t = 0.15$ s: ODE45, MATLAB RK4, ABAQUS UMATHT, And ConvergeCFD UDF.

- Adiabatic single solid element: 1 mm³ neat 8552 resin, $T_0 = 433$ K, $\phi_0 = 0.001$, fixed-step RK4.
- The same RK4 runs in ConvergeCFD (UDF), ABAQUS (UMATHT), and MATLAB, benchmarking against MATLAB ODE45.
- T versus ϕ is linear with slope H_r/C_p : energy is conserved.
- Deviation is confined to the runaway near 970 s and decays within seconds; it comes from fixed sampling instants against a near-vertical Arrhenius rise, not from accumulated error.

$$\rho c \frac{dT}{dt} = \rho_r H_r \dot{\phi} \quad \Delta T = \frac{H_r}{C_p} = 548.7 \text{ K}$$

-9% / -13%

Max Transient Temperature Deviation: MATLAB RK4 Vs ConvergeCFD / ABAQUS

6 sig. figs.

Agreement Of All Solutions At The Asymptote

CONCLUSIONS

- Cure kinetics now run inside the validated CHT model** as a volumetric source, advanced cell by cell with RK4 and verified across MATLAB, ABAQUS, and ConvergeCFD.
- In the final hold the exotherm raises the part about **1.2 K above the circulating air**, a response a convective-only model cannot capture.
- The largest **through-thickness difference**, about 7.5 K, is a convective transient governed by the thermal mass of the aluminum mold.
- The predicted final DoC of about 85%, which is short from 92.2% in experimental DSC.
- Next:** DSC and coupon testing to validate the predicted cure, then cure-cycle refinement toward closed-loop optimization.

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