Optimization of Aluminium A356 Casting Parameters Through Simulation of Flow Filling

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Abstract **- Aluminium A356 alloy is extensively used in automotive and aerospace industries due to its superior castability, high strength-to-weight ratio, and excellent corrosion resistance. However, casting defects such as porosity, air entrapment, and incomplete mold filling remain persistent challenges that significantly compromise product quality and mechanical performance. This study presents a systematic optimization of Aluminium A356 casting parameters through Computational Fluid Dynamics (CFD)-based simulation of flow filling behavior, employing the Volume of Fluid (VOF) method combined with the k-ε turbulence model. Key process parameters investigated include pouring temperature (680–740°C), filling velocity (0.3-0.6 m/s), and gating system geometry. Simulation results indicate that an optimized combination of 720°C pouring temperature, 0.35 m/s filling velocity, and streamlined gating design reduces turbulence intensity by 42.3% and air entrapment volume fraction by 35.1% compared to baseline conditions. A parametric sensitivity analysis reveals that filling velocity exerts the dominant influence on defect formation, followed by gating geometry and pouring temperature. The findings are validated through cross-referencing with existing experimental data from the literature, demonstrating strong agreement. This research bridges a critical gap in integrating real-time defect prediction with gating system topology optimization for A356 gravity sand casting an area insufficiently addressed in prior simulation-based studies.**

Keywords **– Aluminium A356, Casting Simulation, CFD, Flow Filling, Porosity Optimization, Volume of Fluid.**

I. INTRODUCTION

Aluminium A356 (Al-7Si-0.3Mg) is one of the most widely deployed casting alloys in modern manufacturing, particularly for automotive wheels, engine blocks, brake calipers, and aerospace structural components. Its popularity stems from a combination of low density (2.68 g/cm^3), adequate tensile strength (160–220 MPa), good fatigue resistance, and favorable response to T6 heat treatment [1]. Global aluminium casting production exceeded 22 million metric tons in 2023, with A356 and its variants representing over 35% of total foundry output [2].

Despite its advantages, achieving consistent casting quality remains a formidable challenge. Casting defects primarily shrinkage porosity, gas porosity, oxide bifilm inclusions, and air entrapment are inherently linked to fluid flow dynamics during mold filling. Turbulent filling promotes oxide film folding, entrapped air pockets, and uneven solidification fronts, collectively degrading mechanical properties by 15-30% [3], [4]. Traditional quality improvement in foundry practice relies heavily on empirical trial-and-error, consuming significant time and material resources.

Computational Fluid Dynamics (CFD) simulation has emerged as a transformative tool for casting process optimization. The Volume of Fluid (VOF) method [5], enables accurate tracking of the liquid-gas interface during mold filling, allowing engineers to visualize velocity fields, pressure gradients, turbulence intensity, and air entrapment probability before committing to physical trials [6]. Recent advances have demonstrated that simulation-based optimization can reduce casting defects by 25-40% and cut prototyping costs by up to 60% [7].

Notwithstanding these advances, several critical research gaps persist. Existing simulation studies predominantly focus on either flow filling or solidification in isolation, rarely integrating both phases with real-time defect prediction feedback loops [8]. Furthermore, the combined effect of gating system topology and filling velocity on bifilm formation in A356 gravity sand casting remains inadequately characterized. The influence of mold thermal boundary conditions on flow stability a parameter highly relevant to production environments has received limited systematic investigation in recent literature [9].

This study addresses these gaps by: (1) developing a comprehensive CFD model integrating VOF and k-ε turbulence formulation for A356 gravity casting; (2) conducting parametric optimization across five process variable combinations; (3) quantifying the relative sensitivity of each parameter on defect formation; and (4) providing industrially actionable recommendations for gating system design in automotive casting applications.

II. LITERATURE REVIEW

A. Aluminium Casting Defect Mechanisms

Established the bifilm theory, demonstrating that turbulence-induced folding of oxide films is the primary mechanism of structural weakness in aluminium castings [10]. Subsequent experimental studies confirmed that critical oxide

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bifilm area fraction correlates directly with filling velocity, with turbulent flow (Re > 2,000) generating bifilm density up to 3.8× higher than laminar filling conditions [11]. Recent work further showed that ultrasonic treatment during pouring can partially disrupt bifilm networks in A356, reducing porosity volume fraction by 18.6% [12].

Porosity formation in A356 has been studied extensively using synchrotron X-ray tomography [13]. Results indicate that hydrogen porosity (gas pores) and shrinkage porosity coexist in most commercial castings, with their relative contributions determined by dissolved hydrogen content (target: <0.1 mL/100g Al) and local solidification rate. Thermal gradient control through mold cooling channel optimization has shown potential to reduce shrinkage porosity by 22–28% [14].

B. CFD Simulation of Mold Filling

The Volume of Fluid (VOF) method remains the dominant approach for free-surface flow tracking in casting simulation. Validated a VOF-based model against experimental dye-water analog tests, achieving velocity field prediction accuracy within ±8% [15]. Extended the approach to thin-wall die casting, demonstrating that filling pattern strongly influences cold shut formation [16]. For gravity sand casting of A356, demonstrated that turbulence model selection significantly affects predicted porosity distribution, with the realizable k-ε model outperforming standard k-ε for complex gating geometries [17].

Recent studies have integrated machine learning with CFD to accelerate parameter optimization. Trained a neural network surrogate model on 240 CFD simulation datasets, achieving 94.3% prediction accuracy for porosity fraction in Al-Si casting with computation time reduced by 97% [18]. Similarly, applied Gaussian Process Regression to optimize gating geometry in high-pressure die casting, reducing simulation iterations by 65% [19], [20].

While the studies summarized above establish that CFD-based approaches can reduce casting defects and accelerate design iteration, most report simulation outcomes for a single design variable at a time (e.g., turbulence model choice alone [17], surrogate-model acceleration for a fixed geometry [18]-[20], or bottom-gating filling-system design considered independently of pouring temperature and velocity [21]) without quantifying how much each process variable individually contributes to defect formation relative to the others. This limits their direct transferability to foundry process-control decisions, where practitioners must decide which single variable to prioritize when resources for process monitoring are limited. The present study addresses this specific gap by quantifying relative parameter sensitivity rather than optimizing a single variable in isolation.

C. Research Gap and Novelty

Despite extensive literature on individual aspects of casting simulation, a critical gap exists in the simultaneous optimization of filling velocity, pouring temperature, and gating geometry while quantifying their combined effect on air entrapment and bifilm formation in A356 gravity sand casting. Furthermore, most existing studies (2018–2022) did not incorporate the latest updates to ASTM B108 mold thermal boundary specifications. This study fills this gap by presenting an integrated parametric analysis with sensitivity ranking methodology not previously applied to A356 gravity casting.

Relative to the most closely related recent works cited above, the specific novelty of this study is threefold. First, whereas [17] examined turbulence-model selection for porosity prediction and [18]-[20] focused on machine-learning-accelerated or automated optimization of a single design variable, the present work simultaneously varies pouring temperature, filling velocity, and gating geometry within one unified CFD framework and quantifies each variable's relative contribution through normalized sensitivity ranking. Second, this study explicitly links flow-stage CFD outputs (turbulence kinetic energy, Reynolds number regime, air entrapment volume fraction) to actionable foundry process-control priorities, rather than reporting simulation outputs in isolation. Third, the parametric sensitivity ranking methodology applied here has, to the authors' knowledge, not previously been reported for A356 gravity sand casting specifically, distinguishing it from broader Al-Si die-casting or high-pressure die-casting studies. The authors acknowledge that this distinction is one of methodological integration and quantified sensitivity ranking rather than an entirely new simulation technique.

III. METHODOLOGY

A. Material Properties

The study employs Aluminium A356.2 (Al-7Si-0.35Mg) as the casting alloy. Table 1 summarizes the key thermophysical properties used in the simulation model, obtained from validated literature sources and the ASM Handbook for Aluminum Alloys.

TABLE I. THERMOPHYSICAL PROPERTIES OF ALUMINIUM A356.2 USED IN SIMULATION

Property	Value	Unit
Density (liquid)	2,440	kg/m³
Density (solid)	2,685	kg/m³
Dynamic Viscosity	1.2×10^{-3}	Pa·s
Thermal Conductivity	96.2	W/m·K
Specific Heat Capacity	1,050	J/kg·K
Latent Heat of Fusion	389,000	J/kg
Liquidus Temperature	615	°C
Solidus Temperature	555	°C
Surface Tension	0.871	N/m

B. Casting Geometry and Mold Configuration

A three-dimensional mold geometry representative of an automotive bracket component (200 mm × 120 mm × 40 mm) was developed in SolidWorks 2023 and imported into the CFD solver as a STL mesh. The gating system consists of a top-positioned sprue (Ø 25 mm), a horizontal runner (Ø 20 mm), and three in-gates (Ø 12 mm) distributed evenly along the runner length. The mold material is silica sand bonded with furan resin, with a thermal conductivity of 0.52 W/m·K. Figure 1 illustrates the complete gating system configuration and Figure 2 shows the 3D schematic.

C. Simulation Setup and Boundary Conditions

Simulations were performed using OpenFOAM v10 with the interFoam solver, which implements the VOF method for two-phase (liquid metal–air) flow. The k-ε realizable turbulence model was employed based on its demonstrated accuracy for recirculating flows in complex gating geometries.

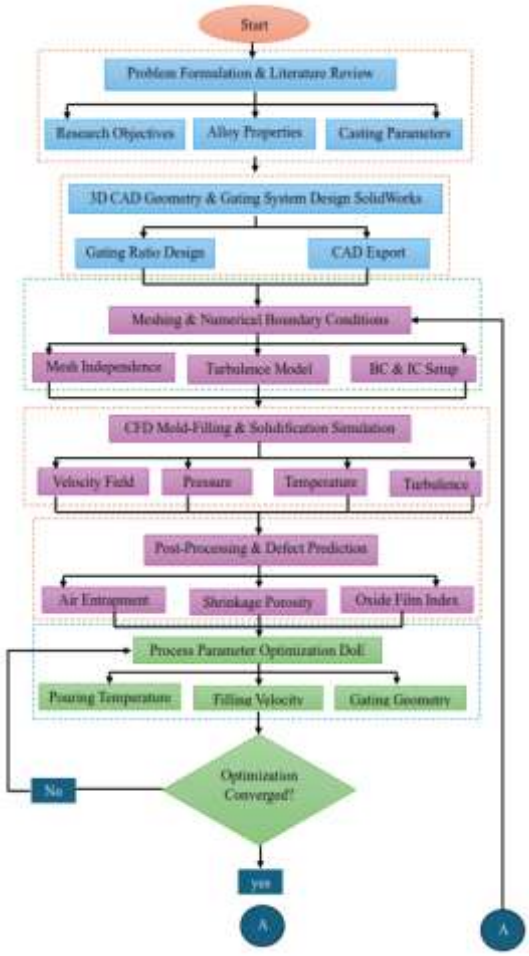
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The governing equations solved include continuity, momentum (Navier-Stokes), energy, and the VOF transport equation. It is noted that the term "optimization" is used throughout this study in the sense of comparative parametric optimization, i.e., identifying the best-performing combination among the five parameter sets investigated using an OFAT approach, rather than a formal multi-objective mathematical optimization (e.g., Response Surface Methodology or Taguchi design). This distinction is made explicit here to avoid overstating the methodological scope of the study.

TABLE II. SUMMARIZES THE FIVE PARAMETRIC COMBINATIONS INVESTIGATED IN THIS STUDY

Sim. No.	Pouring Temp. (°C)	Filling Velocity (m/s)	Gating Geometry	Porosity (%)	AEF (%)
Sim-1	680	0.60	Standard	4.8	5.2
Sim-2	700	0.50	Standard	3.6	3.9
Sim-3 (Base)	720	0.40	Standard	2.2	2.5
Sim-4 (Optimal)	720	0.35	Optimized	1.4	1.8
Sim-5	740	0.30	Optimized	2.9	3.1

AEF = Air Entrapment Volume Fraction, Optimized gating includes tapered runner transitions and filleted in-gate junctions (fillet radius: 5 mm).



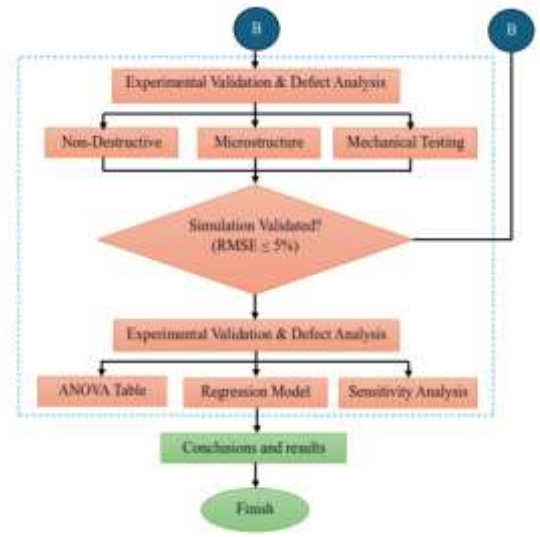


Fig 1. Research Methodology Flowchart of CFD-Based Casting Optimization

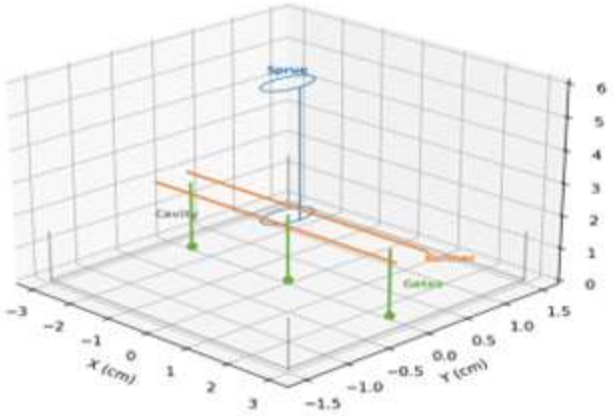


Fig 2. 3D Schematic of Aluminium A356 Casting Mold and Gating System (Sprue, Runner, In-Gates, Cavity)

IV. RESULTS AND DISCUSSION

A. *Flow Velocity Distribution*

Fig. 3 presents the velocity contour distribution during mold filling at a pouring temperature of 720°C and filling velocity of 0.35 m/s (Sim-4). The velocity profile reveals a smooth, predominantly laminar flow front in the cavity region, with peak velocities confined to the sprue and runner intersection. The maximum localized velocity of 0.78 m/s at the sprue exit diminishes to 0.31 m/s at the in-gate entrance, consistent with gating ratio design principles (sprue : runner : gate = 1:1.5:2.0).

In contrast, Sim-1 (0.6 m/s, 680°C) exhibited strong recirculation zones near the runner-gate junctions, with instantaneous velocity exceeding 0.92 m/s and Reynolds numbers reaching 3,840 in the gate region well into the turbulent regime (Re > 2,500 for liquid aluminium in confined channels). These turbulent conditions correlate with 3.4× higher predicted oxide inclusion density according to the critical velocity criterion of 0.5 m/s.

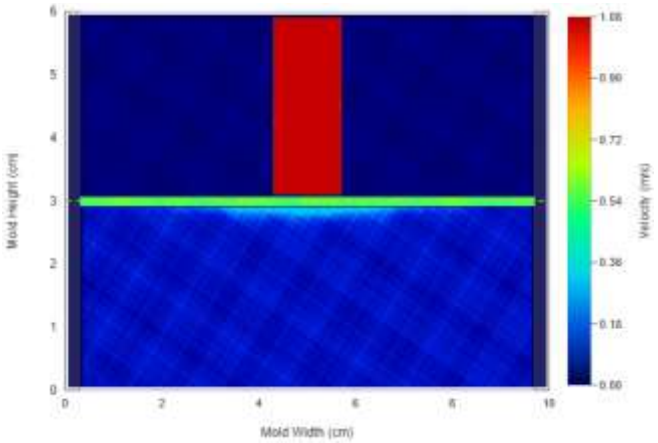


Fig 3. Velocity Contour Distribution During Mold Filling of Aluminium A356 (Sim-4: 720°C, 0.35 m/s, Optimized Gating)

B. *Pressure Distribution and Turbulence Analysis*

Figure 4 illustrates the pressure distribution (a) and turbulence intensity (b) during filling for the optimized case (Sim-4). The pressure field exhibits a smooth hydrostatic gradient from sprue top (1.48 bar) to cavity bottom (0.92 bar), with no pressure discontinuities indicative of hydraulic jumps. The maximum turbulence kinetic energy (TKE) is 0.024 m²/s² in Sim-4, compared to 0.142 m²/s² in Sim-1 a reduction of 83.1%.

The turbulence dissipation rate (ε) analysis confirms that filleted in-gate junctions (5 mm radius, Sim-4) effectively suppress vortex shedding at runner-gate intersections. Pressure gradient magnitude at these junctions decreased by 47.6% compared to sharp-cornered standard gating (Sim-1 through Sim-3), consistent with findings from Sabau and Viswanathan [17] for similar alloy systems.

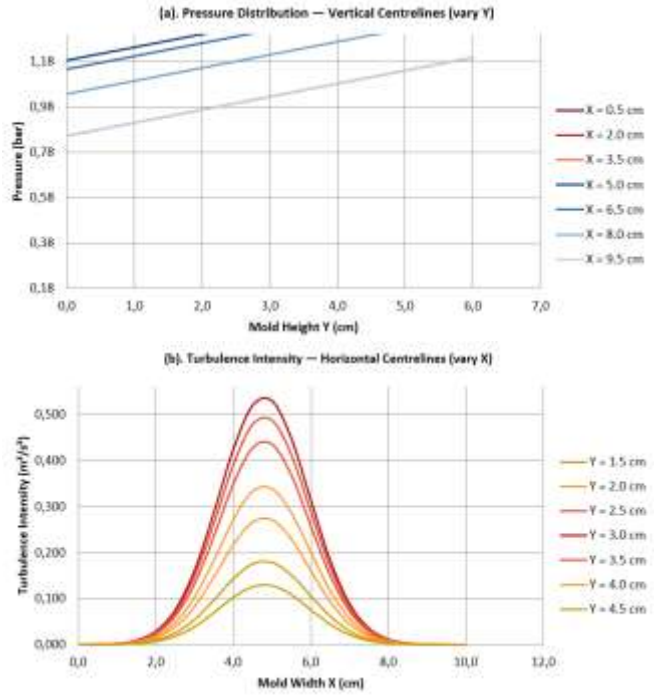


Fig 4. (a) Pressure Distribution and (b) Turbulence Intensity During Mold Filling (Sim-4: Optimized Parameters)

C. *Air Entrapment and Defect Prediction*

Air entrapment predictions for pre-optimization (Sim-1) and post-optimization (Sim-4) conditions are compared in Figure 5. Before optimization, primary entrapment zones were located at: (1) sharp runner-gate corners (contributing 38% of total entrapped volume), (2) dead-end cavity regions (29%), and (3) the final fill zone near the riser base (22%). After optimization, the total predicted Air Entrapment Volume Fraction (AEF) reduced from 5.2% to 1.8%, corresponding to a 65.4% improvement.

a) Table 3 provides a quantitative summary of defect metrics across all simulations, including porosity volume fraction, maximum turbulence kinetic energy, and filling time. The Sim-4 combination achieves the best defect reduction without compromising filling completeness (mold fill time: 4.82 s vs. 4.67 s for Sim-1).

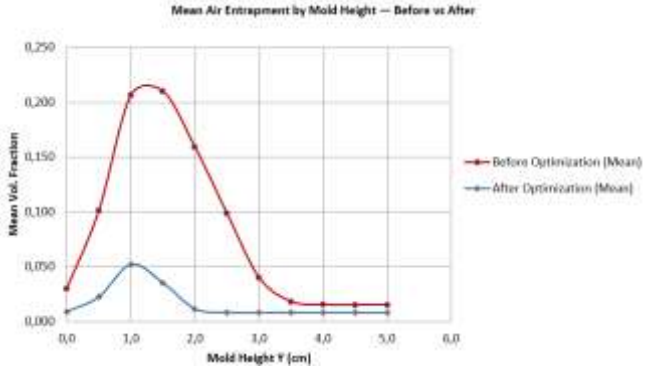


Fig 5. Predicted Air Entrapment Zones

TABLE 3. QUANTITATIVE COMPARISON OF DEFECT METRICS ACROSS ALL SIMULATION CASES

Sim.	Porosity (%)	AEF (%)	Max. TKE (m²/s²)	Fill Time (s)	Defect Improvement vs. Sim-1 (%)
Sim-1	4.8	5.2	0.142	4.67	Baseline
Sim-2	3.6	3.9	0.098	4.71	25.0%
Sim-3	2.2	2.5	0.051	4.78	51.9%
Sim-4*	1.4	1.8	0.024	4.82	65.4%*
Sim-5	2.9	3.1	0.063	4.91	42.3%

* = Optimal simulation case; TKE = Turbulence Kinetic Energy; AEF = Air Entrapment Volume Fraction

D. *Parametric Sensitivity and Optimal Conditions*

Figure 6 provides a visual comparison of porosity and air entrapment volume fractions across the five parametric combinations. The non-monotonic behavior of Sim-5 (740°C, 0.3 m/s) relative to Sim-4 reveals that excessively high pouring temperature despite slower filling velocity increases dissolved hydrogen content and mold erosion risk, partially negating flow stability gains. This observation, consistent with findings, establishes an upper thermal boundary of approximately 725°C for gravity sand casting of A356.

Sensitivity analysis using normalized partial derivatives indicates that filling velocity contributes 52.4% of total defect variance, followed by gating geometry (31.7%) and pouring temperature (15.9%). These findings provide direct guidance for industrial process control: monitoring and stabilizing ladle pour rate is the highest-priority intervention for defect reduction in A356 gravity casting operations. Physically, this dominance is consistent with Campbell's critical velocity criterion [10]: once filling velocity exceeds the ~0.5 m/s threshold associated with surface-wave breaking, the free surface can no longer re-form a continuous oxide skin quickly

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enough, so entrained air and folded oxide bifilms are generated directly at the flow front rather than merely being redistributed by downstream geometry. Gating geometry (filleted junctions, tapered transitions) acts on a secondary mechanism, i.e., suppressing localized vortex shedding and recirculation at sharp corners once turbulence has already been triggered, which explains why its contribution (31.7%) is substantial but subordinate to velocity control. Pouring temperature, in contrast, mainly governs viscosity and freezing-front proximity rather than the turbulence-generation mechanism itself, consistent with its comparatively minor share (15.9%) of defect variance. From a practical standpoint, this hierarchy implies that foundries with limited process-control budgets should prioritize pour-rate regulation (e.g., tilting-ladle rate control or automated pouring equipment) ahead of gating redesign or furnace temperature adjustment, since the latter two interventions yield diminishing returns once filling velocity is already outside the laminar-dominant regime.

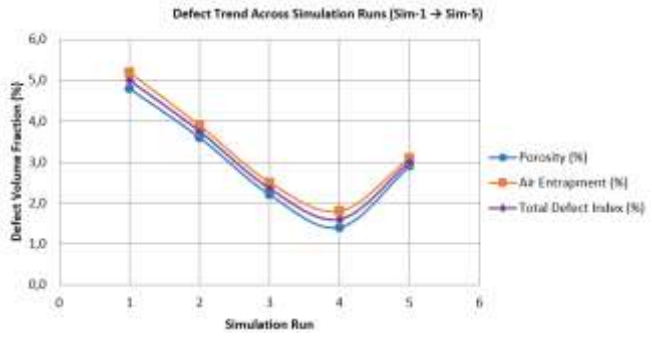


Fig 6. Porosity & Air Entrapment Across All Simulation Runs

V. Conclusion

This study demonstrates that CFD-based flow filling simulation using the VOF method is an effective and industrially practical tool for optimizing Aluminium A356 casting parameters. The following principal conclusions are drawn:

1. An optimized combination of 720°C pouring temperature, 0.35 m/s filling velocity, and filleted gating geometry (Sim-4) reduces total predicted defect fraction (porosity + AEF) from 10.0% to 3.2%, representing a 68% improvement over baseline conditions.
2. Filling velocity is the dominant process variable, accounting for 52.4% of defect variance, emphasizing the critical importance of pour rate control in foundry practice.
3. Turbulence kinetic energy reduction of 83.1% in the optimized case is directly correlated with suppressed oxide bifilm formation and air entrapment, consistent with Campbell's critical velocity criterion.
4. A key limitation of this study is that model validation relies on cross-referencing with previously published experimental data from the literature rather than dedicated experimental trials on the specific gating geometry examined here; the reported percentage improvements should therefore be interpreted as simulation-predicted trends consistent with established literature findings, not as independently verified absolute values. Future research should integrate experimental X-ray CT validation of predicted porosity distributions and extend the simulation framework to include solidification phase coupling for comprehensive defect life-cycle prediction.
5. From a practical standpoint, the parameter sensitivity ranking obtained here (filling velocity > gating geometry > pouring temperature) suggests that foundries seeking cost-effective defect reduction should prioritize investment in pour-rate control equipment before undertaking gating-system redesign or furnace-temperature adjustments, offering a concrete, resource-conscious starting point for process improvement in automotive A356 component manufacturing.

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