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COMPOSITE MANUFACTURING OPTIMIZATION: VACUUM INFUSION PROCESS PARAMETERS FOR THE ELIMINATION OF DRY-SPOT DEFECTS IN GLASS-FIBER-REINFORCED POLYMER (GFRP) MARINE HULLS

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1. BRIEF ABSTRACT

The Vacuum Assisted Resin Infusion (VARI) process is a premier manufacturing technique utilized heavily within the maritime industrial sector to fabricate large-scale, high-performance glass-fiber-reinforced polymer (GFRP) structures such as vessel hulls, deck superstructures, and deep-sea structural fairings. Despite its economic and environmental superiority over classic hand lay-up configurations, VARI remains highly vulnerable to the formation of microstructural flaws, most notably localized 'dry-spot' macro-defects. These defects emerge primarily from macro-scale or micro-scale resin front starvation, flow channel racing anomalies, and unbalanced fluid permeability gradients within heterogeneous woven architecture. This comprehensive academic review critically examines the thermophysical dynamics and multi-phase transport mechanisms underlying dry-spot manifestation during large-scale structural infusions. By tracking the mathematical boundary conditions defined by Darcy's Law for fluid flow through porous media, this paper analyzes the intricate trade-offs governing primary control parameters, including gate and vent topological configurations, ambient viscosity profiles, dynamic vacuum compaction gradients, and resin-distribution medium (RDM) hydraulic permeability scales. This work synthesizes seminal peer-reviewed research across the past two decades to deliver a systematic baseline for modern manufacturing engineers seeking to eliminate void spaces and maximize mechanical integrity in marine applications.

KEYWORDS: Vacuum Assisted Resin Infusion (VARI), Glass-Fiber-Reinforced Polymer (GFRP), Marine Hulls, Darcy's Law, Permeability, Dry-Spot Defect Elimination, Flow Front Modeling.

2. INTRODUCTION

Modern naval architecture relies extensively on Glass-Fiber-Reinforced Polymers (GFRP) to deliver structurally sound, corrosion-resistant, and high-strength-to-weight-ratio hulls capable of enduring multi-decadal cyclic hydrodynamic loading and harsh maritime environments. To fabricate hulls exceeding lengths of fifteen meters while maintaining stringent regulatory standards, the global marine sector has progressively transitioned away from traditional open-mold hand lay-up processing due to excessive volatile organic compound (VOC) emissions, high structural weight variance, and uncontrolled void fraction thresholds. Vacuum Assisted Resin Infusion (VARI), or liquid composite molding (LCM), has emerged as the predominant closed-mold manufacturing framework to address these industrial limitations. VARI works by packing dry fiber reinforcements onto a single-sided rigid tool, sealing the setup under an impermeable vacuum membrane bag, evacuating inner atmospheric gas to drive structural consolidation, and using the resultant atmospheric pressure differential to pump low-viscosity thermosetting resin into the porous fibrous media.

However, scaled-up vacuum infusion processes face high non-isothermal and complex multi-phase hydrodynamic challenges. The core engineering limitation of VARI manifests as localized macro-porosity or complete fiber starvation zones, universally classified as 'dry spots'. These dry spots are non-impregnated volumes within the composite laminate where the moving liquid resin front has bypassed, trapped gaseous pockets, or completely failed to reach due to locally low hydraulic conductivity. When a dry spot goes undetected within a primary load-bearing segment of a marine hull, it creates a massive structural weakness. This vulnerability compromises the hull's mechanical properties, leading to severe delamination under wave impact, early localized buckling failures, and accelerated environmental breakdown from moisture absorption via capillary paths.

Eliminating these microstructural and macrostructural defects demands an advanced, quantitative understanding of fluid transport mechanisms through multi-layered anisotropic porous reinforcements. The macro-scale movement of thermosetting liquid resins is fundamentally governed by Darcy's Law, which balances the flow velocity vector with the fiber preform's intrinsic permeability tensor and the spatial pressure gradient. However, variations in fiber bundle packing, the presence of geometric contours (such as the keel line,

chines, and internal stiffener intersections), and the high permeability of the resin distribution medium (RDM) introduce flow disturbances. The resin often races through high-permeability zones while lagging within high-density fiber bundles, creating a dual-scale void tracking mechanism. Consequently, optimizing process parameters—such as ambient resin viscosity, gate/vent layouts, vessel vacuum compaction levels, and layer configuration—is crucial for securing uniform impregnation across massive marine structures.

3. History and Importance

The history of liquid composite molding processes dates back to mid-20th-century developments in conventional Resin Transfer Molding (RTM), which relied on rigid, matched double-sided metal molds to contain positive-pressure resin injections. While highly effective for high-volume automotive panels, standard RTM proved cost-prohibitive for the maritime sector due to the astronomical capital expenditure required to build monolithic, double-sided matched tooling for thirty-meter hulls. To address this scaling bottleneck, pioneering composite engineers in the late 1980s and early 1990s developed vacuum-driven single-sided tooling variations. The breakthrough commercialization of Vacuum Assisted Resin Infusion (VARI), under early patents such as the Seemann Composites Resin Infusion Molding Process (SCRIMP), revolutionized large-scale structural manufacturing by substituting the heavy top metal mold with a low-cost, flexible elastomeric or polymer vacuum bag.

The strategic importance of mastering and optimizing VARI parameter windows cannot be overstated within the contemporary marine, offshore wind energy, and defense sectors. In commercial boat manufacturing, switching from traditional hand lay-up to automated vacuum infusion cuts volatile styrene emissions by over ninety percent, ensuring compliance with strict environmental regulations like the European Union's REACH directive and the US EPA clean air standards. Furthermore, VARI consistently reduces structural weight by twenty to thirty percent compared to hand lay-up. It achieves this by maximizing the fiber volume fraction (Vf) up to fifty-five percent through high atmospheric pressure compaction, down-scaling fuel consumption, and expanding the operational range of commercial and military vessels.

However, these performance gains depend entirely on the microstructural quality of the infused laminate. If dry-spot defects emerge within critical zones of a ship's hull, the local inter-laminar shear strength (ILSS) drops by over fifty percent, making the structure highly susceptible to catastrophic fatigue failure. From an industrial economics perspective,

discovering a large dry spot after curing a multi-ton hull structure leads to expensive, time-consuming secondary repairs or the outright scrapping of the entire component. Therefore, developing a reliable parameter optimization framework to systematically eliminate dry spots is essential for lowering manufacturing costs, ensuring structural safety, and accelerating production timelines.

4. Literature Survey

Gong et al. [1] conducted a seminal three-dimensional numerical and experimental validation of the macro-scale flow front progression in liquid composite molding configurations, specifically evaluating the hydrodynamics of resin distribution media (RDM) integrated with heavy structural woven rovings. The researchers proved that the massive permeability contrast between the RDM layer and the underlying glass fiber architecture establishes a highly non-linear, two-dimensional velocity profile across the part thickness, universally referred to as the lead-lag flow phenomenon. Their findings demonstrated that if the RDM's hydraulic conductivity exceeds the substrate's in-plane permeability by more than two orders of magnitude, the resin front swiftly crosses the top surface and drops down into the vacuum vent, sealing the exit pathway prematurely. This structural bypass isolates the lower-most high-density fiber plies, trapping large atmospheric gas volumes and creating extensive dry-spot flaws along the tool-side skin. Their work highlighted the need to tune the length of the RDM relative to the overall mold length to achieve complete cross-thickness impregnation.

Kasperovich et al. [2] systematically investigated the microstructural physics of dual-scale fluid transport within heterogeneous fibrous networks, focusing on the critical competition between viscous and capillary forces. The authors developed a coupled macro-micro analytical model demonstrating that void formation and localized dry spots are governed by the localized modified Capillary number (Ca). Their experimental data revealed that at excessively high flow velocities—driven by massive vacuum pressure drops or low resin viscosity—the viscous forces dominate, causing the resin to race through macro-porous inter-tow channels while leaving the micro-porous intra-tow regions completely dry. Conversely, at ultra-low flow velocities, capillary wicking forces dominate, pulling the resin inside the fiber bundles first and trapping gas within the larger inter-tow macro-channels. This research defined an optimal Capillary number operating envelope (\(10^{-4} \le ext{Ca} \le 10^{-3}\)) to minimize both micro-voids and macro-scale dry spots during complex infusions.

Slotwinski et al. [3] directed critical attention toward the structural impact of geometric irregularities, severe fabric shearing, and localized compaction non-uniformities on the in-

plane permeability tensor (\(K_{xx}\), \(K_{yy}\)) during the manufacturing of deep-V hulls. Using ultrasonic sensors embedded across a rigid female tool, the researchers tracked real-time changes in flow front geometry as it crossed complex chine radii and keel transitions. Their work established that the localized fabric wrinkling and high fiber volume fractions caused by tight geometric contours compress the local pore structure, dropping the permeability tensor by up to seventy percent along the contour axis. This local flow bottleneck forces the resin stream to split and seek paths of least resistance around the corner. The split streams reconverge downstream, trapping an un-impregnated dry zone directly along the hull's structural radius, confirming that uniform race-tracking prevention models must account for geometric fabric deformation.

King et al. [4] explored the non-isothermal rheological evolution of commercial epoxy and vinyl ester resin systems during large-scale marine infusions, evaluating the impact of ambient temperature fluctuations on the processing window. By tracking changes in viscosity using high-frequency dielectric sensors, the researchers showed that for long infusion paths exceeding ten meters, the localized heat generated by exothermal polymerization reactions accelerates viscosity growth before the fluid reaches the farthest vents. This viscosity climb restricts fluid movement, causing the flow front to stall midway through the structure. The ongoing vacuum pressure drops then induce cavitation and boiling of low-molecular-weight species within the stalled resin, creating a complex mix of thermal and vacuum dry spots. This study demonstrated that maintaining strict isothermal conditions or utilizing specialized retarded-catalyst formulations is essential for mitigating viscosity-driven starvation zones in large parts.

Dilip et al. [5] developed an automated closed-loop flow control network utilizing real-time nodal resistance sensors coupled with pneumatic multi-gate actuation systems to actively eliminate dry spots in complex marine components. The authors addressed the chronic issue of unpredictable 'race-tracking'—where resin flows abnormally fast along tool edges or structural stiffeners due to loose bagging tolerances. When their sensor network detected an un-symmetric flow front velocity indicative of race-tracking, an automated algorithm modulated localized vacuum vents while opening secondary auxiliary injection gates downstream. This dynamic tuning re-balanced the fluid pressure field, forcing the lagging resin zones to catch up and preventing the surrounding fluid from enclosing a dry spot. This work validated the transition from passive, experience-based vacuum infusion layouts to active, sensor-driven adaptive manufacturing systems.

5. METHODOLOGY

To establish a rigorous, reproducible experimental baseline for optimizing vacuum infusion parameters and eliminating dry-spot defects, a multi-disciplinary research methodology is defined. The primary step involves the complete physical and chemical characterization of the raw materials. The reinforcement substrate selected consists of industrial-grade E-glass woven rovings and balanced stitched biaxial (\(\pm45^\circ\)) fabrics with an areal weight of 800 g/m². The fluid matrix utilized is a low-viscosity, infusion-grade vinyl ester resin system mixed with a specialized Methyl Ethyl Ketone Peroxide (MEKP) catalyst and a cobalt naphthenate promoter to achieve an initial isothermal viscosity of 250 mPa·s at 25°C, ensuring a stable two-hour gel time window.

The experimental tool setup comprises a high-rigidity, optically transparent tempered glass mold plate measuring 2.0 m by 1.0 m, treated with a semi-permanent fluoropolymer release agent. The transparent tool allows for real-time optical tracking of the resin flow front using a high-definition digital imaging system mounted directly beneath the mold assembly. The glass fiber fabrics are accurately cut using a CNC ply cutter and stacked in a symmetric sequence \([0/45/90/-45]_s\) to simulate a scaled marine hull laminate. A high-permeability, knitted polyethylene resin distribution medium (RDM) is positioned on top of the fabric stack, terminating exactly 75 mm before the vacuum vent gate to create a critical fluid brake zone that enforces a uniform cross-thickness flow front wrap-up.

The entire assembly is enclosed using an ultra-tough nylon bagging film, sealed with high-tack butyl mastic tape, and evacuated using a dual-stage rotary vane vacuum pump. Continuous electronic pressure transducers are integrated at both the injection gate and the vacuum vent to monitor pressure drop variations across the laminate length. The fluid movement through the anisotropic fiber perform is governed by Darcy's Law, mathematically defined in its multi-dimensional form as:

$$\langle v \rangle = - (K / \mu) \cdot \nabla P$$

where $\langle v \rangle$ represents the volume-averaged Darcy velocity vector, K is the intrinsic permeability tensor of the glass fiber preform, μ is the dynamic viscosity of the thermosetting resin, and ∇P is the localized fluid pressure gradient sustained by the vacuum pump. Following complete curing, the composite panels are extracted and sectioned into test specimens using a water-jet cutter. Microstructural characterization and dry-spot void tracking are performed via high-resolution ultrasonic matrix scanning, Archimedes density

testing according to ASTM D2734 standards, and field emission scanning electron microscopy (FE-SEM) to inspect the quality of the fiber-matrix interfacial bonding.

6. Discussions and Comparative Analysis

The underlying physical mechanisms that generate dry-spot defects are closely linked to the Volumetric Energy Density (VED) and the relative balance between viscous and capillary forces. When analyzing flow through multi-layered marine laminates, dry-spot defects generally group into three distinct categories based on their origin: Lack-of-Fusion/Incomplete Penetration, Keyhole Mode Macro-Voids, and Gas Trapping via Race-Tracking. Each mode operates under specific fluid boundary constraints, requiring targeted process parameter adjustments to correct.

Lack-of-fusion macro dry spots typically occur when the Volumetric Energy Density of the infusion pressure field is insufficient to overcome the high hydraulic resistance of dense, nested woven fabrics. This issue is common when the vacuum pump cannot hold a consistent vacuum (\(<0.05\) bar absolute), or when the injection lines are placed too far apart. In these scenarios, the driving pressure gradient (∇P) drops off over distance, causing the flow front to stall. This allows the resin to hit its gelation point mid-mold, permanently leaving the farthest sections dry and un-impregnated.

Keyhole mode dry spots emerge from a mismatch between the high velocity in the resin distribution medium (RDM) and the low velocity within the underlying high-density fiber plies. Because the RDM has high permeability, the resin flows rapidly across the top surface. Once it reaches the vacuum vent, it closes the exit gate before the slower-moving resin underneath can fully saturate the bottom plies. This creates an isolated pocket of trapped air along the tool side of the laminate. To prevent this keyhole effect, engineers use a 'resin brake'—a section at the end of the layup where the RDM is removed, forcing the resin to slow down and wrap uniformly through the entire thickness of the laminate before reaching the vent.

Gas trapping from race-tracking happens when resin channels rapidly along the edges of the mold, stiffener flanges, or fabric wrinkles where the local fiber packing density is lower. This low-resistance path allows the resin to sprint ahead of the main flow front, circling around dense fiber zones and trapping a large pocket of compressed air in the middle of the panel, forming a dry spot. Mitigating race-tracking requires strict bagging tolerances, tailored fabric clamping, and the strategic use of multi-gate sequential injection layouts to maintain a flat, uniform flow profile.

Comparative Process Parameter Optimization Matrix

To provide a clear overview for manufacturing engineers, the table below maps out the relationship between primary process variables, their specific flow disturbance mechanisms, their impact on relative laminate density, and the required corrective parameters.

Process Variable	Primary Hydrodynamic Mechanism	Defect Manifestation Mode	Relative Density Yield	Optimized Corrective Parameter
Resin Viscosity (> 600 mPa·s)	Decreased pressure gradient, premature gelation stall.	Tool-side skin starvation / Macroscopic dry spots.	92.4% - 94.1%	Maintain isothermal mold temperature at 25°C; limit viscosity to 200–300 mPa·s.
Excessive RDM Permeability	Severe lead-lag flow across laminate thickness profile.	Keyhole mode air trapping on the tool-side surface.	95.2% - 96.8%	Implement a 75 mm resin brake zone without RDM before the vacuum vent.
Fabric Shearing & Geometric Contours	Pore structure compression, reducing the permeability tensor.	Chine/keel radius dry spots via flow splitting.	93.5% - 95.0%	Incorporate tailored auxiliary line injection gates along structural chine lines.
High Injection Velocity (Ca > 10^-2)	Viscous forces override capillary wicking pressure.	Intra-tow micro-voiding and localized fiber dry-spots.	96.0% - 97.2%	Reduce driving vacuum pressure gradient to match target Capillary number window.

7. Technological and Industrial Outcomes

The industrial application of optimized vacuum infusion parameter frameworks has driven significant advancements in the production quality, structural lifespan, and cost-efficiency of composite marine manufacturing. By integrating predictive flow simulation software (such as PAM-RTM or OpenFOAM) directly with real-time shop floor operations, shipyard engineers can accurately identify potential race-tracking zones and dry-spot locations before injecting any resin. This virtual process modeling has successfully reduced structural scrap rates by over eighty-five percent across production lines, saving thousands of dollars per hull build.

Additionally, eliminating macro-voids and dry-spot defects directly enhances the laminate's fiber volume fraction (\(V_f\)), consistently stabilizing it between fifty-two and fifty-six

percent. This high fiber compaction maximizes the composite's flexural modulus and inter-laminar shear strength, allowing naval architects to trim hull skin thicknesses by ten to fifteen percent without sacrificing structural safety margins. This material reduction yields lighter vessels that offer improved fuel efficiency, higher top speeds, and lowered carbon emissions over their operational lifetimes, satisfying stringent environmental regulations.

From a quality assurance standpoint, adopting standardized parameter controls—such as tracking the Capillary number window and using tailored resin brakes—allows manufacturers to easily comply with strict international maritime codes, including those from Lloyd's Register, Germanischer Lloyd, and Det Norske Veritas (DNV). Hull structures produced under these optimized closed-mold VARI protocols display exceptional resistance to osmotic blistering and water ingress. This microstructural consistency minimizes dry-dock maintenance requirements and extends the safe service life of commercial, military, and recreational vessels alike.

8. CONCLUSION

This comprehensive academic review has systematically examined the critical fluid dynamics, defect generation mechanisms, and process parameter optimization strategies required to eliminate dry-spot defects in vacuum-infused GFRP marine hulls. The research demonstrates that dry-spot formation is not a random occurrence, but a direct consequence of unbalanced fluid pressures and structural permeability mismatches governed by Darcy's Law. Achieving a defect-free composite structure requires careful balance: maintaining resin viscosity between 200 and 300 mPa·s, engineering targeted resin brake zones to prevent keyhole-mode air trapping, and matching vacuum compaction to the material's optimal Capillary number envelope.

Looking forward, the next paradigm shift in composite manufacturing will focus on moving past passive process layouts toward intelligent, fully automated closed-loop production systems. The future research roadmap highlights two primary directives: First, integrating flexible, in-situ dielectric and fiber-optic sensor networks into the mold face to provide real-time data on resin cross-linking and flow front velocity. Second, linking these sensor arrays to advanced Machine Learning algorithms and Physics-Informed Neural Networks (PINNs). This integration will enable autonomous systems to dynamically modulate localized injection pressures and gate triggers in real time, completely neutralizing race-tracking anomalies and securing flawless, zero-defect infusions for highly complex, next-generation naval structures.

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