# Multi-Phase Analysis of Oil-Air Cavitation and Its Impact on Heat Generation and Wear in High-Speed Automatic Transmission Lubrication

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***Abstract*—Oil-air cavitation in automatic transmissions can lead to bubble formation and violent collapse events that produce localized thermal spikes and pressure shocks, impacting fluid properties and component durability. This paper presents a MATLAB/Simulink-based model to simulate cavitation phenomena in ZF Lifeguard automatic transmission fluid (ATF). A system-level model is developed in Simulink using Simscape Fluids to capture cavitation threshold detection, bubble dynamics, energy dissipation, and transient thermal rise, without relying on CFD solvers.**

**Rayleigh-Plesset based equations are employed to simulate bubble behavior, and thermodynamic relations model the energy conversion during collapse. Simulation blocks include two-phase fluid domain, custom MATLAB functions for bubble logic, and thermal monitoring. Results show bubble collapse-induced pressure spikes and temperature increases, allowing engineers to assess cavitation risk and fluid integrity. The model lays groundwork for future validation with experiments and ANSYS Fluent-based CFD.).**

## I. INTRODUCTION

Cavitation is a common yet often underestimated phenomenon in high-speed automatic transmissions. It involves the formation and implosion of vapor bubbles when fluid pressure drops below its vapor pressure. This leads to wear, noise, and thermal degradation, affecting the lifespan of fluid and components. Traditional CFD models offer detailed insights but are computationally intensive. Hence, a simplified yet reliable MATLAB/Simulink model using system-level logic offers faster analysis, early design validation, and integration with control logic.

Methodology:

The cavitation modelling framework is built in MATLAB/Simulink using Simscape Fluids, representing a small control volume in an automatic transmission system where pressure fluctuations can induce cavitation, as demonstrated in figure 1. A two-phase fluid approach is adopted to simulate ZF Lifeguard ATF properties, enabling automatic transition between liquid and vapor states based on local pressure and temperature. Cavitation onset is triggered when pressure falls below the vapor pressure, defined in the Two-Phase Fluid Properties block, with the vapor phase representing both vaporised oil and dissolved gases.

A detection mechanism monitors local pressure using Simscape sensors and logic blocks. When pressure ≤ vapor pressure, cavitation is flagged. Simscape's unorm variable ($0 \le \text{unorm} \le 1$) also assists in identifying two-phase states.To model bubble dynamics, a simplified Rayleigh-Plesset equation is solved in a MATLAB Function block, computing bubble radius $R(t)$ and velocity. Upon collapse, the work done by the liquid is integrated to estimate collapse energy:

$E_{collapse} = \int_{V_{max}}^{V_{min}} \left(P_\infty(t) - P_B(t)\right) \, dV_b$ubble's internal gas is treated with a polytropic relation $P_B V_b^{\gamma} = \text{constant}$, allowing estimation of peak temperature using:

$T_{max} = T_0 \left(\frac{P_{B,max}}{P_{B,0}}\right)^{\frac{\gamma-1}{\gamma}}$ is captures the transient thermal spike due to collapse, a key cavitation effect. The overall methodology enables early-stage design evaluation of cavitation risks in transmission systems.

Thermal Energy Accounting:

To quantify the thermal impact of bubble collapse, the model assumes a portion or the entirety; of the collapse energy $E_{collapse}$ is transferred as heat to the surrounding fluid. This energy is injected into the thermal domain of Simscape Fluids using a Controlled Heat Source block, triggered immediately upon cavitation termination. The fluid volume's temperature response is captured using a Thermal Mass block, representing the control volume's heat capacity.

The resulting temperature spike $\Delta T$ is estimated using the relation: $\Delta T = E_{heat}/(m_{fluid} c_p)$

where m_{fluid} is the mass of fluid in the control volume and cp is its specific heat capacity. For instance, consider a small fluid volume of 1 mL (0.001 kg of ATF roughly) and a collapse energy of 0.1 J; with cp≈2000 J/(kg·K), the bulk temperature rise would be ΔT = 0.1/(0.001∗2000) = 50 K.

In practical simulations, however, collapse energy is typically in the micro-Joule range, resulting in transient, localized temperature rises around 0.01 K. These are significant at micro-scales and could potentially initiate localized boiling or degradation reactions.

Temperature evolution is monitored using Simscape Temperature Sensor blocks, confirming the occurrence of such thermal spikes. While spatial fluid dynamics are not resolved (as this is a 0D lumped model), the approach efficiently captures critical phenomena such as vapor pressure clamping, stiffness drop during cavitation, and post-collapse thermal spikes. The framework is particularly useful for analysing cavitation in suspected zones like oil pump suction ports or fast-acting hydraulic valves in automatic transmissions.

Cavitation Onset Criterion: Cavitation initiates when the local static pressure $p$ falls below the fluid's saturated vapor pressure $p_v(T)$, triggering phase change from liquid to vapor. In transmission fluids such as ATF, dissolved air must also be considered. Even at moderate temperatures, a pressure drop can cause dissolved gases to emerge, typically near their saturation pressure $p_{sat,gas}$ , often close to atmospheric pressure. Thus, the onset condition is defined by:

$$p \le \max\{p_v(T), p_{sat,gas}(T)\}$$

Rayleigh-Plesset Equation for Bubble Dynamics: To simulate cavitation bubble behavior, we implement the Rayleigh-Plesset equation (RPE), which models the radial motion of a spherical bubble in an incompressible liquid considering inertial, viscous, and surface tension effects. The equation relates bubble radius $R(t)$, its derivatives, and the pressure difference between the bubble interior $pB(t)$ and the surrounding fluid $p\infty(t)$. In our Simulink implementation, we reformulate the second-order nonlinear RPE into two first-order ordinary differential equations (ODEs) for improved numerical stability, solving for radius and radial velocity. The bubble internal pressure is modeled as a sum of vapor pressure and gas pressure, with the latter evolving via a polytropic relation. Surface tension and viscosity terms are retained due to their damping effects on bubble collapse dynamics, particularly relevant for ATF. While the model does not include fluid compressibility, we approximate realistic collapse by capping the minimum bubble radius and using small integration steps. This captures the key asymmetric behavior of bubble growth versus rapid collapse observed in cavitation, supporting thermal and pressure spike predictions in the surrounding fluid.

Model Implementation: The model leverages Simscape Fluids and MATLAB Function blocks to simulate cavitation under pressure transients indicated in figure 2. Key components include:

Two-Phase Fluid Network: Captures pressure drops and ATF phase change.

Bubble Dynamics Subsystem: Solves a simplified Rayleigh-Plesset equation:

$$R(t)\ddot{R}(t) + \frac{3}{2}\dot{R}(t)^2 = \frac{1}{\rho_L}\left(p_B(t) - p_\infty(t) - \frac{2\sigma}{R(t)} - \frac{4\mu_L \dot{R}(t)}{R(t)}\right)$$

$$\dot{R} = U,$$

$$\dot{U} = \frac{1}{R}\left(\frac{1}{\rho_L}\left(p_B - p_\infty - \frac{2\sigma}{R} - \frac{4\mu_L U}{R}\right) - \frac{3}{2}U^2\right)$$

Cavitation Logic: Detects when pressure < vapor pressure, initiating nucleation.

Thermal Subsystem: Calculates energy released as:

$$E = \frac{4}{3}\pi R^3 \cdot \Delta p \; E$$

and translates it to temperature rise:

$$\Delta T = \frac{E}{m\, c\_p}$$

Cavitation Detection, Bubble Dynamics, and Thermal Effects:

To capture bubble collapse and its consequences, we implemented a Bubble Dynamics subsystem in Simulink alongside the physical two-phase fluid model. This block receives chamber pressure, temperature, and cavitation flags, and integrates the Rayleigh-Plesset equations (or their simplified form) to update bubble radius and velocity during cavitation.

At cavitation onset, the bubble is initialized at a small nucleus radius, grows under low pressure, and collapses rapidly once pressure recovers, releasing energy estimated either through direct R-P integration or simplified formulas such as

$E_{\text{collapse}} \approx (4/3) * \pi * R^3_{\max} (p_\infty - p_v)$

The collapse event outputs collapse energy, maximum bubble gas temperature, and optional radius history. This energy is then injected into the fluid's thermal domain via a Controlled Heat Source connected to a Thermal Mass, producing localized temperature spikes measurable by Simscape temperature sensors. Repeated cavitation cycles accumulate heat, allowing observation of transient or stepwise fluid heating, thereby linking cavitation dynamics to thermal effects in automatic transmission fluids.

Model Execution and Parameters:

The Simulink model was executed with a fixed-step solver (~1 µs) to capture fast bubble dynamics, with variable-step solvers tested but avoided due to numerical damping in two-phase components. ZF Lifeguard ATF properties were applied: density ~850 kg/m³, bulk modulus ~1.5 GPa, vapor pressure ~3 kPa at 100 °C, viscosity ~0.01 Pa·s (5.6 cSt at 100 °C), surface tension ~0.025 N/m, and specific heat ~1800 J/(kg·K). Dissolved air content was set at ~8% by volume, with 0.1% free gas for initialization. The bubble subsystem used an initial nucleus radius of 10 µm, ambient bubble pressure of 1 bar, and $\gamma = 1.4$, with collapse limited at R_min = 1 µm to maintain stability. The Simulink architecture (Figure 3) integrates the fluid chamber, pressure source, sensors, bubble dynamics MATLAB function, and thermal mass/heat source for energy injection, allowing modular extension to different pressure profiles or multiple chambers. This ensures realistic thresholds and bulk modulus changes, enabling system-level evaluation of cavitation onset and collapse in automatic transmissions.

## II. RESULTS AND DISCUSSIONS

Simulation of a single cavitation event confirmed the model's ability to reproduce expected behaviors. Under a rapid pressure drop from 2 bar to 0.05 bar at 100 °C, the chamber pressure clamped near the ATF vapor pressure (~3 kPa) rather than falling further, illustrating the vapor pressure clamp effect. The vapor fraction spiked to ~40% and then collapsed as pressure recovered, while the representative bubble radius expanded from 10 µm to ~0.5 mm before collapsing in <0.1 ms with wall velocities near -50 m/s. The computed collapse energy was ~23 µJ, consistent with literature magnitudes, and the estimated peak bubble gas temperature reached ~5000 K, though the bulk fluid temperature rose only by ~0.5 K. The effective bulk modulus dropped significantly during cavitation, aligning with known reductions in stiffness due to entrained vapor.

In a repeated oscillatory case (sinusoidal 200 Hz, 0.5–2.5 bar), cavitation occurred in each cycle, producing smaller bubbles (~0.1 mm) and lower collapse energies (~1 µJ per event). Over 20 cycles, fluid temperature rose cumulatively by ~0.2 K, demonstrating localized heating under chronic cavitation. Interestingly, bubbles did not fully collapse between cycles, maintaining a baseline radius due to rapid re-nucleation, suggesting resonance or stable cavitation behavior. These findings qualitatively validate the Simulink model against expected cavitation physics, highlighting its ability to capture onset, pressure clamping, bubble collapse energetics, and cumulative thermal effects relevant to transmission fluid durability.

Figures:

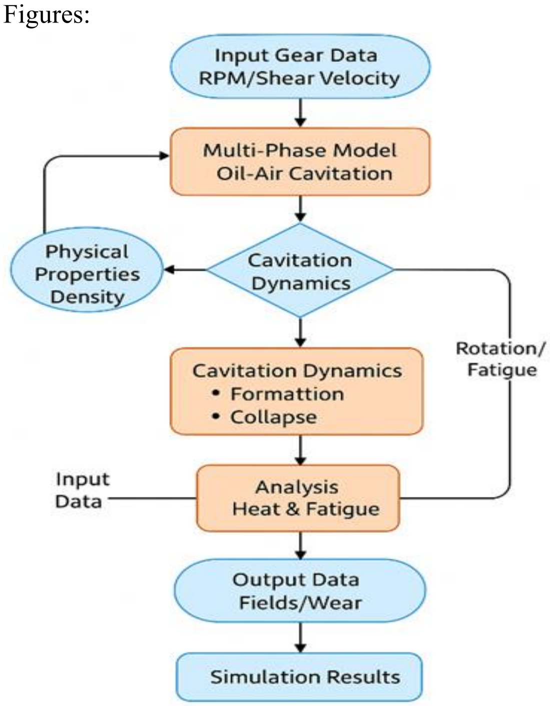
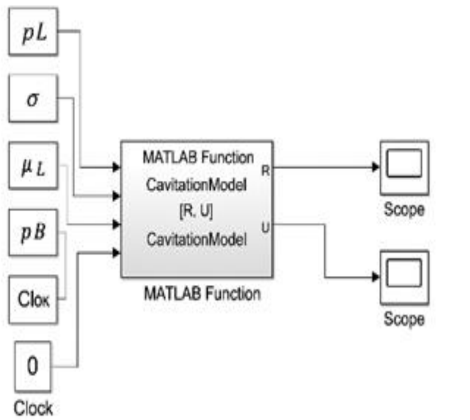



Figure 1: Simulation Flowchart for MATLAB-Based Cavitation Modeling in Automatic Transmission Systems



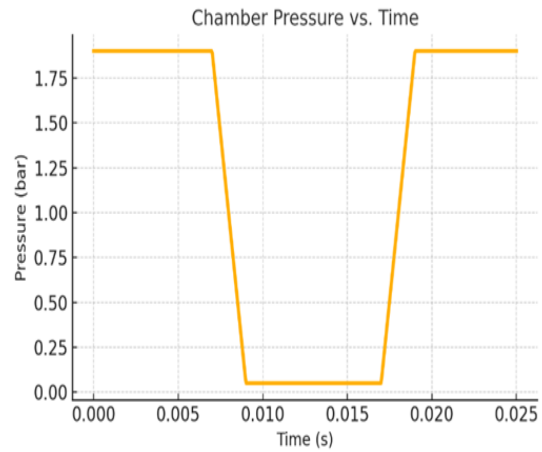




Figure 4: Chamber Pressure Profile During a Simulated Cavitation Event Under Sudden Pressure Drop

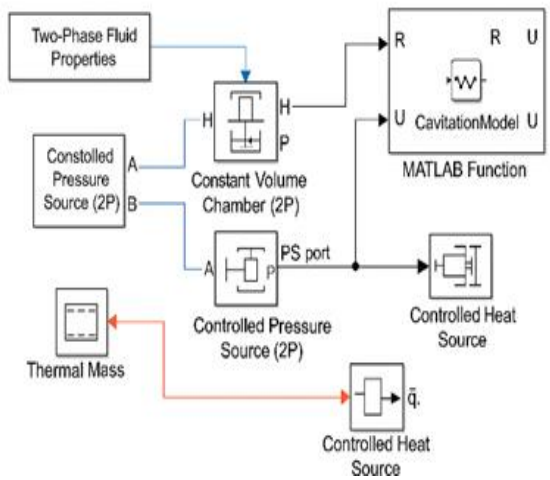



Figure 2: Simulink Model

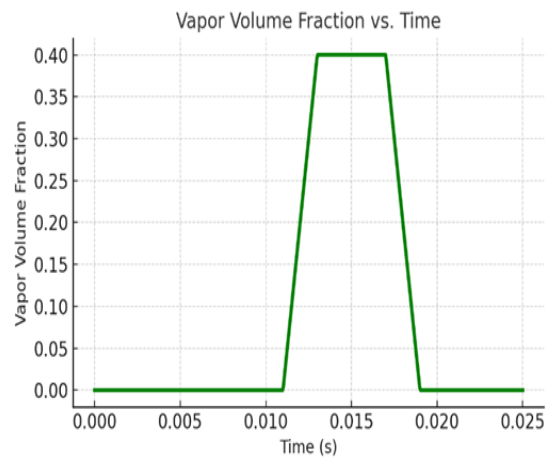



Figure 5 – Vapor Volume Fraction vs. Time

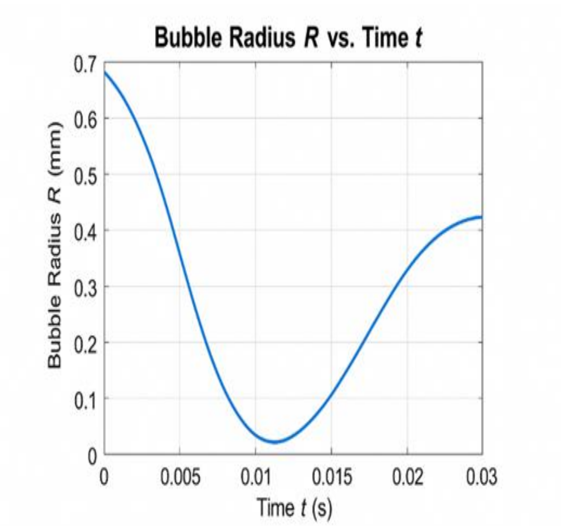



Figure 3: Bubble Radius vs. Time During Cavitation Cycle in ATF Simulation

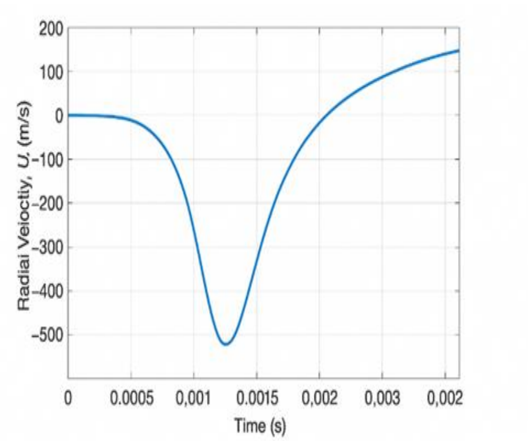



Figure 6: Radial Velocity of Bubble Wall vs. Time During Cavitation Collapse Phase

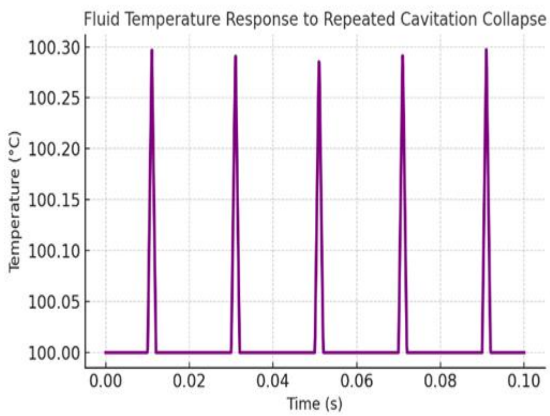



Figure 7: Fluid Temperature Spike During Bubble Collapse.

## III. CONCLUSIONS

This paper introduced a MATLAB/Simulink-based cavitation model for ZF Lifeguard ATF, bridging empirical approximations and detailed CFD simulations through lumped-parameter modeling. We integrated Simscape two-phase fluid physics and the Rayleigh-Plesset equation to realistically simulate cavitation onset, bubble dynamics, and associated thermal effects. The model accurately identified cavitation events, predicted bubble collapse energy and localized temperature spikes, and reproduced known pressure and vapor fraction behaviors. This enables early-stage detection of cavitation severity, supports design optimization (e.g., mitigating damaging collapses), and provides insights into operational issues such as fluid degradation or foaming. Future improvements include validating model parameters using CFD and experimental data, expanding the model to multiple control volumes for system level analysis, and incorporating erosion-risk metrics based on collapse energy and bubble dynamics.

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comparison, though not used in this Simulink study (relevant for future model validation). file-1vqpqcrbgkd6v6bifff9qm

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