

# Analytical Prediction of Transient Spray Cooling

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## Abstract

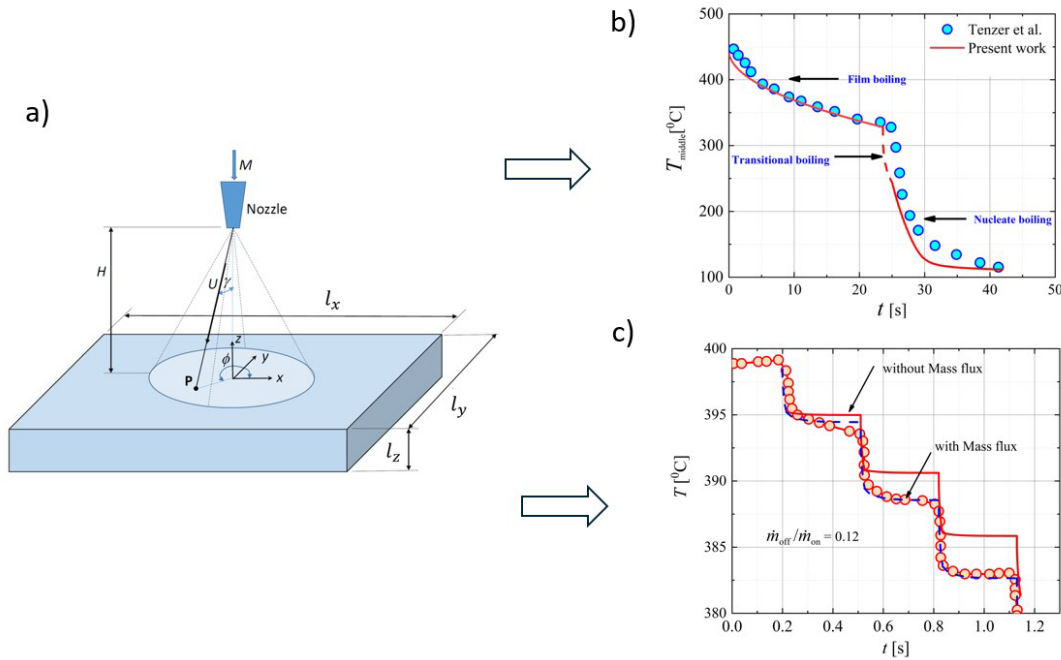
Spray cooling is a well-established technique for high-flux thermal management in applications ranging from metal quenching and turbine blade protection to the cooling of compact, high-power electronics [6, 5, 3]. A critical challenge in optimizing spray cooling lies in accurately modeling the transient thermal response of the substrate, especially as it passes through different boiling regimes: film boiling, transitional boiling, and nucleate boiling. This study presents a physics-informed, computationally efficient framework to simulate such transient spray cooling under a single nozzle, offering predictive insights that complement experimental investigations.

The model is grounded in analytical expressions that describe the heat transfer from individual droplet impacts in each boiling regime. These expressions are sourced from validated literature and incorporate regime-specific physical mechanisms. The transition between boiling regimes is governed by temperature-based thresholds, allowing the simulation to dynamically adapt as the substrate cools. By applying the principle of superposition, the model aggregates the contribution from all impacting droplets based on their spatial and temporal number flux to calculate the instantaneous heat removal rate from the surface.

A full conjugate heat transfer problem is solved using a finite difference approach, enabling time-resolved prediction of the temperature distribution within the substrate [1].

This modeling framework is further extended to evaluate the performance of Intermittent Spray Cooling (ISC), where cooling is applied in bursts rather than continuously [4]. ISC is characterized by two key parameters: duty cycle ( $\phi$ ) and cycle frequency ( $f$ ).

The study demonstrates that by adjusting these parameters—particularly increasing the spray-on phase duration ( $t_{on}$ )—ISC can achieve faster and more efficient cooling than continuous spray cooling, especially in the film boiling regime where droplet-induced vapour disruption is most beneficial.



**Figure 1.** a) Sketch of the geometric parameters defining the geometry of the substrate and spray cooling. b) Validation of transient behaviour of temperature at the center of the heated surface performed in [7] using the parameters  $D0 = 50 \mu\text{m}$ ,  $U0 = 13 \text{ m/s}$ ,  $T_{w0} = 450\text{-C}$  and mass flow rate  $\dot{M} = 0.1 \text{ kg/s}$ . c) Comparison of experiment performed in [2] with predictions. Substrate surface temperature is shown as a function of time. Cycle time of the intermittent spray is 300 ms and duty cycle is  $\phi = 0.05$ . Solid red line is with zero mass flux during  $T_{off}$  period. Dashed blue line corresponds to a mass flux of 12% of the  $t_{on}$  mass flux during the  $t_{off}$  period. Input conditions are:  $\dot{M} = 0.5 \text{ kg/m}^2\text{s}$ ,  $U0 = 5 \text{ m/s}$ ,  $D0 = 50 \mu\text{m}$ ,  $H = 0.15 \text{ m}$ , and  $\gamma_{max} = 12.5^\circ$ .

Model validation is performed using published experimental data [7, 2], confirming its ability to capture the thermal response of the substrate with high fidelity. A comprehensive parametric analysis is then conducted to examine the influence of spray characteristics—including droplet size, velocity, and flux—on the substrate cooling behavior. The results reveal that ISC offers not only energy and fluid savings but also improved control over surface temperature trajectories, making it particularly attractive for applications requiring precision thermal management.

Overall, this study contributes a versatile, physics-based modeling tool for engineers and researchers, providing deep insights into spray cooling dynamics across all boiling regimes.

The framework offers a valuable foundation for optimizing ISC strategies and guiding future experimental and industrial developments in advanced cooling technologies.

**Keywords:** intermittent spray cooling, duty cycle, film boiling, frequency.

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