ONGOING MODELING AND EXPERIMENTAL SPRAY COOLING STUDY

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Abstract: *This work proposes a numerical and experimental study of spray cooling using single-droplet models extended to sprays via the Monte Carlo method. A MATLAB code estimates transient heat flux fields, validated by synchronized high-speed and infrared imaging. The approach aims to improve heat transfer prediction based on physical droplet parameters.*

Keywords*: Heat transfer regimes. Atomization. Quenching.*

1. INTRODUCTION

Spray cooling is a very attractive method because it achieves high heat fluxes with low overheating, compared to other cooling methods (Cheng et al., 2016). Despite being widely used in many industries, such as high-power electronics, nuclear systems, gas turbines, secondary refrigeration systems, and metallurgical processes (Liang & Mudawar, 2017a, 2017b), there are still many theoretical gaps that prevent a full understanding of the process.

Spray cooling is studied through experiments (Estes & Mudawart, 1995; Zhao et al., 2024), numerical simulations (Liu et al., 2024; Zhang et al., 2024) and theoretical models (Castanet et al., 2020; Qenawy et al., 2024). Experimental techniques include high-speed imaging, infrared thermography, and optical diagnostics to analyze droplet behavior and heat transfer. Numerical studies use Computational Fluid Dynamics (CFD) with models for multiphase flow, droplet impact, and phase change. Lastly, theoretical models seek to relate the heat flow to measurable spray parameters.

Although there are several studies on spray cooling, there are limitations such estimation of steady heat fluxes in experimental works, high computational cost in numerical investigation, and specific models that dependent on the process parameters, such as the type of nozzle used or the material and fluid used. Therefore, this work presents a proposal for a spray cooling study, which uses single-droplet impact models and then extends them to a spray model using the Monte Carlo method.

2. MATERIALS AND METHODS

As an initial proposal, we will review hydrodynamic and heat transfer models for both single droplets and sprays from the existing literature to support the simulation of our heat flux. After that, the temperature distribution of the substrate can be estimated by solving the transient three-dimensional heat conduction equation in cartesian coordinates, assuming no internal energy generation, as given by:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)=\rho c_p\frac{\partial T}{\partial t} \tag{1}$$

where λ is the thermal conductivity, ρ is the density of the material, c_p is the specific heat, T is the temperature in and t is the time. This equation can be solved by finite difference method as follows:

$$\frac{1}{\lambda_{ijk}^{n+1}}\frac{\partial\lambda}{\partial x}\Big|_{ijk}^{n+1}\frac{\partial T}{\partial x}\Big|_{ijk}^{n+1}+\frac{\partial^2 T}{\partial x^2}\Big|_{ijk}^{n+1}+\frac{1}{\lambda_{ijk}^{n+1}}\frac{\partial\lambda}{\partial y}\Big|_{ijk}^{n+1}\frac{\partial T}{\partial y}\Big|_{ijk}^{n+1}+\frac{\partial^2 T}{\partial y^2}\Big|_{ijk}^{n+1}+\frac{1}{\lambda_{ijk}^{n+1}}\frac{\partial\lambda}{\partial z}\Big|_{ijk}^{n+1}\frac{\partial T}{\partial z}\Big|_{ijk}^{n+1}+\frac{\partial^2 T}{\partial z^2}\Big|_{ijk}^{n+1}=\frac{1}{\alpha_{ijk}^{n+1}}\frac{\partial T}{\partial t}\Big|_{ijk}^{n+1} \tag{2}$$

where i,j, and k are the indices of the x-, y-, and z-directions respectively, n indicates the time step, and $\alpha=\lambda/\rho c_p$ is the thermal diffusivity of the material.

A MATLAB code will be employed to solve the inverse problem and estimate the transient heat flux field on the sprayed surface. A new MATLAB code will be developed, employing the Monte Carlo method to simulate the spray's droplets impact on a surface, considering both the hydrodynamics of impact and a transient heat flux field per droplet. Therefore, we aim to develop a tool for estimating heat flux in spray cooling processes by simulation the impact and heat transfer droplet by droplet. The results will be validated experimentally using the setup shown in Fig. (1). The nozzle support will be adjustable to vary the height from the surface (h). A high-speed camera (Photron NOVA S6, equipped with a CMOS image sensor offering a resolution of 1024 x1024 pixels at 6,400 fps) will be positioned horizontally to capture the droplets impacting the hot surface. An infrared camera (FLIR X6582sc, with a maximum frame rate of 355 Hz at its highest resolution of 640 x 512 pixels) will be placed at a lower level, using a mirror to capture the bottom temperature of the heated wall and a thermocouple will be employed to calibrate the infrared camera, following the procedure by (Peña Carrillo et al., 2019). The bottom of the heated plate is painted with matte black ink to improve the surface emissivity and, consequently, the signal-to-noise ratio of the infrared thermography. Both cameras will be synchronized to ensure we can analyze the two images together for a better analysis of the entire spray cooling process. Finally, a TDK-Lambda programmable power supply of 7500 W at 7,5 V and 1000 A will be used to heat the test surface by Joule effect. All the equipment will be mounted on an optical table and is already available in the laboratory.

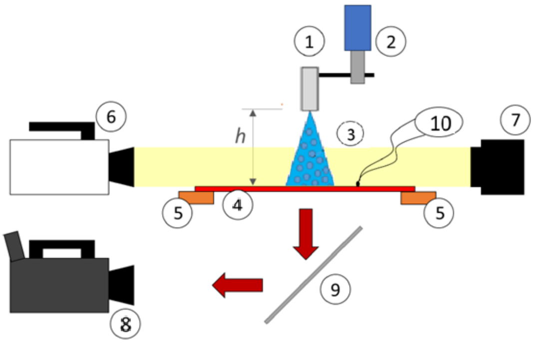

Figure 1. Experimental setup: 1) Spray nozzle, 2) Nozzle support, 3) Spray, 4) Hot surface, 5) Electrical suppliers, 6) Speed camera, 7) Reflector, 8) Infrared camera, 9) Mirror, 10) Thermocouple. Authors' own work.

3. EXPECTED RESULTS

The main expected result is an experimentally validated MATLAB code capable of accurately predicting heat flow in a spray cooling process, especially the temperature evolution of the cooled part. The focus will be in the Leidenfrost regime, where, normally, the droplet rebound after impacting the heated plate. Different hydrodynamic and heat transfer models will be tested as boundary conditions, so the most appropriate set of models will be employed. Then, numerical and experimental results will be confronted and, if needed, model improvements will be proposed.

5. REFERENCES

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7. RESPONSABILITY TERM

The authors are solely responsible for the information included in this work.