MULTIPLE TEMPERATURE DROP STUDY IN THE WATER THIN LAYER FOR A PLATE WITH INTERNAL HEAT SOURCES

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Abstract: *The problem of cooling flat surfaces with thin jets of fluid is common in various technical fields. In the present study, a thin flat plate is considered to be heated uniformly and one of its sides insulated from the environment, to avoid heat losses. The other side of the plate is cooled in multiple points by small water jets. The flat surface area is much greater than the plate thickness, which permits to assume unidirectional conductive heat transfer. State of the art technological applications often require determining the optimal water jet dimensioning so as not to generate a significant temperature drop on the plate. In this case the considered behavior is that of a quasi-isothermal plate. For the present work, the temperature drop was determined numerically in the case of a one-dimensional heat flow for an insulated-type surface and a multi-point network, at different heat fluxes. The obtained results allow determining the temperature field in the case of multiple thin areas cooled by water jets.*

Keywords: *pelicular heat transfer, temperature drop, multi-point network, heat sources.*

1. Introduction

The use of liquid jets for surface cooling is common in many technological applications because the heat transfer capacity is high. This type of cooling can be optimized by changing certain parameters such as dispersion angle, nozzle types, type of fluid and size of the liquid jet.

In this study liquid jets are considered to be symmetrical in relation to the plate they come in contact with as Md Lokman Hosain shows in [1] and they are uni-axial as shown in Figure 1.

The temperature variation resulting from the dispersion of thin liquid jets on an inclined flat plate and the interaction of the liquid jets between them (considering that the plate is constantly heated to a temperature of 140° *C*) will be studied.

The plate is assumed to be thin with a length and width much larger than the thickness. It is also considered that the heat flow is high enough to provide a uniform heating of the plate. In this case, the heat exchange regime is a stationary one. As stated, it results that the lower part of the plate is in an adiabatic regime and the upper one is subjected to a cooling regime. The cooling system is assimilated to a matrix-type one, based on several thin liquid jets flowing at a speed of 3 *m/s*. The temperature of the liquid jet is considered to be close to that of the environment.

According to the researches carried out so far, [5], when the liquid jet hits the flat surface it takes a circular flat form with less than 4 mm of thickness. For the simulations, a cylindrical shape was used. The right shape will be analyzed in further researches.

Figure 1 shows a liquid jet sent through a thin nozzle (3 *mm* in this case) onto a thin plate (200x200x4 *mm*).

The common characteristic of uni-axial jets can be identified as three different areas; free jet area of the radial flow stagnation region. There is a zone in the jet shear layer of the jet where the interaction between the core and the peripheral lead to division of fluid mass and energy [2].

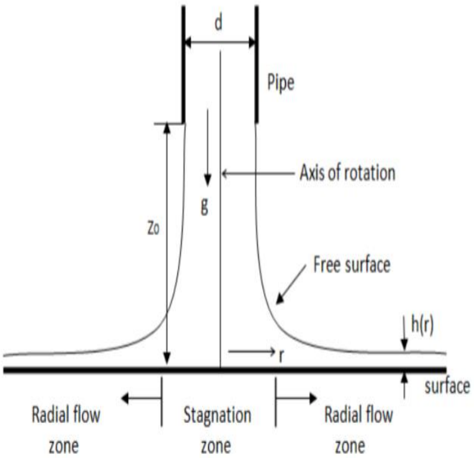


Figure 1: *Uniaxial jet [1]*

Based on the assumptions made, taking into account the actual dimensions of the plate, the nature of the material, etc., the purposes of this study are:

- to obtain the variation of the temperature through the plate at the moment of the impact with the cooling agent;
- to study by simulation the convective way of changing of the liquid's phase in the immediate proximity of the plate.

2. Description of the principle of the experimentation installation

The main structure of the experimental installation is shown in Fig. 2 where a system for spraying coolant consists of five transport ramps (1) fitted with a series of nozzles denoted by (2). Through these nozzles, cooling liquid flows on a flat plate (3). The plate is heated by an electrical resistance system (4) to a temperature of 140°*C*. In order to create an adiabatic environment, the lower side of the plate is thermally insulated (5). A trough (6) located at the lower end of the plate allows the collection of the solids extracted through a process of pseudo-sublimation of the liquid jets sprayed on the plate. Solids accumulate in the tank (7). Outside the installation there is a steam collection system (8) made on the upper side, like a hood, in order to improve steam circulation.

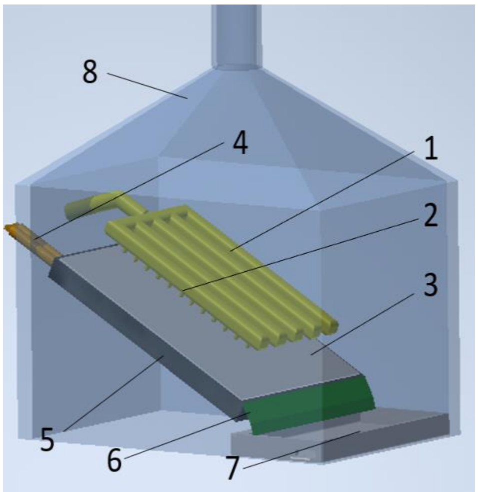


Figure 2:*Experimental installation structure*

3. Temperature drop equations for a thin plate with internal sources cooled by multiple jets of water

A 4 mm thick plate 200x200 *mm* in size is considered. On one side, an internal heating source made by an electrical resistance system with very close loops that allows a quasi-uniform heat transfer, the first step of this study is carried out to analytically determine the variation of the plate temperature on the opposite side of the heating source at the moment of the impact with multiple cold liquid jets.

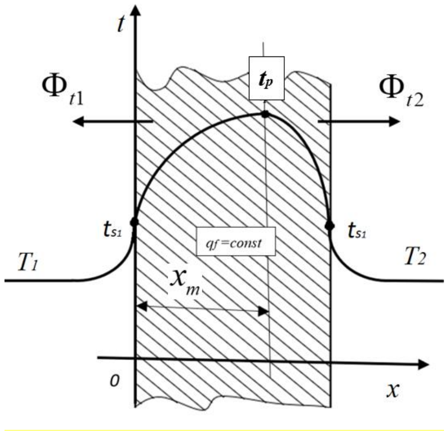


Figure 3: *Temperature distribution in a flat wall with uniform sources of heat with different cooling conditions on the two surfaces, [3].*

A liquid pumping system, with multiple nozzles, will spray water jets on the thick plate inclined at 35 degrees to the horizontal. It is assumed that the power density (given by the internal heat source) and the thermal conductivity of the plate material are constants. Fig. 3 shows a unidirectional distribution of the heat, parallel to the x-axis.

The heat flow dissipates in both directions but the thermal insulation placed on the lower side of the plate makes it to move mostly on the upper side. The differential equation of temperature variation *t*, in stationary mode, unidirectional on direction *x*, on a flat surface parallel to internal heating source q_f, knowing that λ is the coefficient of thermal conduction, is:

$$\frac{d^2t}{dx^2}+\frac{q_f}{\lambda}=0 \tag{1}$$

Integrating twice, the equation of temperature variation is:

$$t=-\frac{q_f{}^2}{2\theta}+C_1x+C_2 \tag{2}$$

Determining the C_1 and C_2 constants in the boundary conditions:

$$\begin{aligned} x&=0,\ t=ts_1 \\ x&=2\delta,\ t=ts_2 \end{aligned} \tag{3}$$

Thus, results the temperature distribution in the wall:

$$t=-\frac{q_f x^2}{2\lambda}+\left(\frac{(ts_2-ts_1)}{2\delta}+\frac{q_f\delta}{\lambda}\right)x+ts_1 \tag{4}$$

The maximum temperature in the wall is achieved at the elevation x_m resulting from the condition: $dt/dx = 0$, [3]:

$$x_m=\frac{q_f}{\lambda}(\delta-x)+\frac{ts_2-ts_1}{2\delta} \tag{5}$$

The maximum temperature point is inside the plate if the following condition is met:

$$-1\le\frac{\lambda}{2q_f\delta^2}-(ts_2-ts_1)\le 1 \tag{6}$$

The thermal flow denoted by Φ expressed in [W], on each side of the plate is:

$$\Phi_{t1}=-q_f S\,x_m=-\lambda\,S\left(\frac{ts_2-ts_1}{2\theta}+\frac{q_f\delta}{\lambda}\right) \tag{7}$$

$$\Phi_{t2}=q_f S(2\delta-x_m)=\lambda S\left(\frac{q_f\delta}{\lambda}-\frac{ts_2-ts_1}{2\delta}\right) \tag{8}$$

Total transmitted heat flow is given by:

$$\Phi_{tot}=\left|\Phi_{t1}\right|+\Phi_{t2}=2q_f S\delta \tag{9}$$

3.2 Results of the analytical model for determining the temperature drop

Using the Mathcad programming environment [4], analytical calculations were performed to determine the temperature variation resulting from the impact of multiple jets of liquid with a hot surface.

Case I shown in figures 4-5 presents the results of the temperature calculation for a flow rate of the liquid jet of 0,02 *kg/s* (lowest) at a speed of 3 *m/s*.

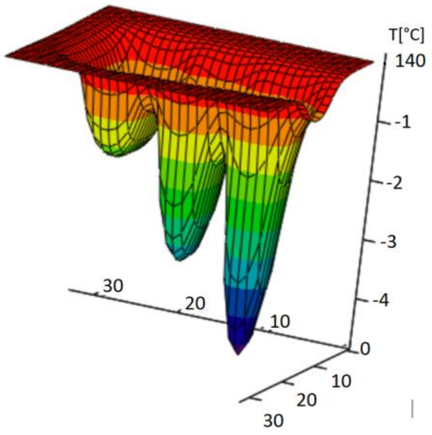


Figure 4: *Temperature variation in the case of three successive jets of liquid with a flow rate of 0,02 kg/s at a speed of 3 m/s.*

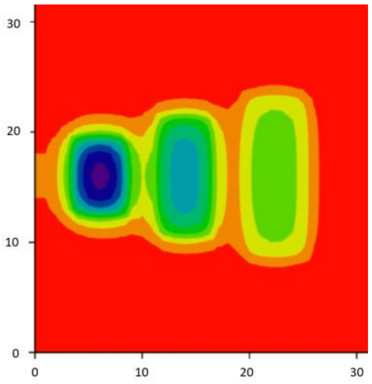


Figure 5: *Top view of the temperature variation in the case of three successive liquid jets with a flow rate of 0,02 kg/s at a speed of 3 m/s.*

Case II shown in figures 6-7 presents the temperature variation of the plate cooled by three successive jets at a flow rate of 0.08 *kg/s* (maximum flow rate) and speed of 3 *m/s*.

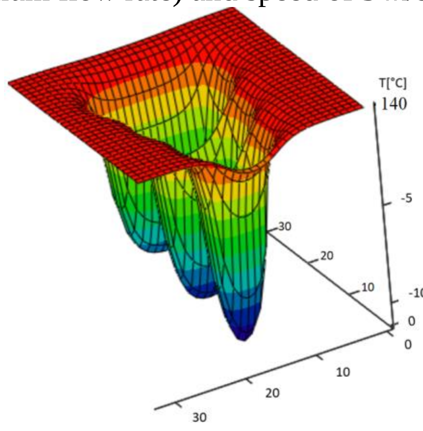


Figure 6: *Temperature variation in the case of three successive jets of liquid with a flow rate of 0,08 kg/s at a speed of 3 m/s.*

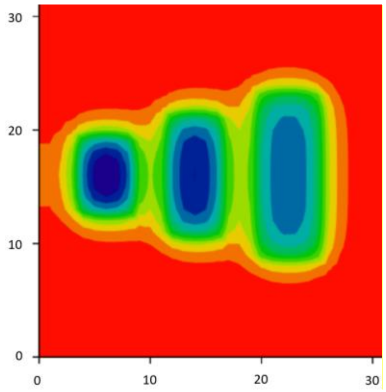


Figure 7: *Top view of the temperature variation in the case of three successive liquid jets with a flow rate of 0,08 kg/s at a speed of 3 m/s.*

4. Vaporization simulation of multiple jets of water on a hot plate

This chapter presents the simulation method used for four liquid jets sprayed on a heated surface. The aim is to analyze the results of the heat transfer through the plate compared to the theoretical results presented above. The process of vaporizing a sample of liquid on the surface of a flat plate will be simulated as well.

Using the ANSYS Fluent simulation program [5], the principle of volume fractions determination (VOF) based on Realizable K-Ɛ turbulence model was chosen as a method. A uniform fluid spraying speed of 3 *m/s* and a constant plate temperature of 140° *C* were assumed.

The settings and the steps followed to obtain the simulation are:

- the geometry was created as shown in Figure 8;

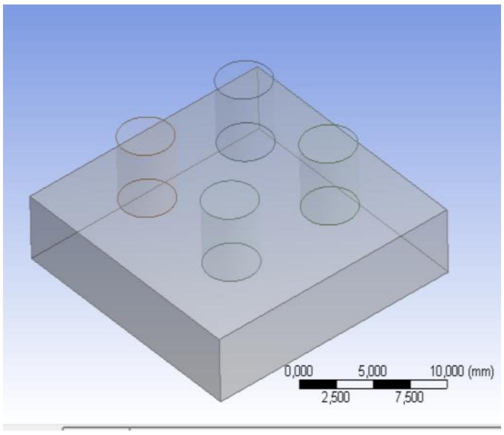


Figure 8: *Simulated assembly geometry.*

- in order to observe the variation of the liquid temperature, flowing from four nozzles, the dimensions of the plate (20x20x4 *mm*) were chosen;

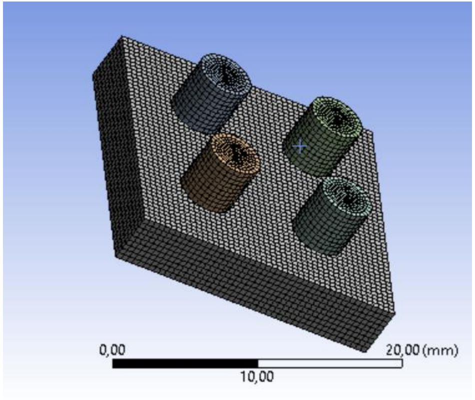
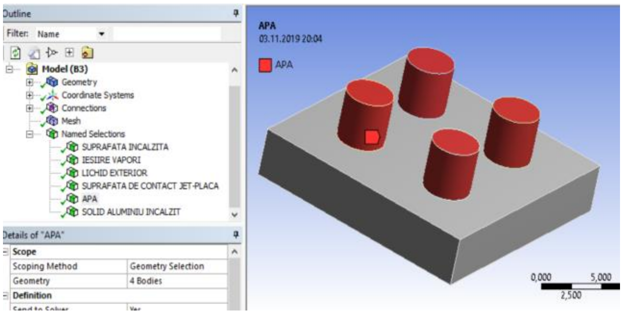


Figure 9: *Creation of meshes.*

- the mesh shown in Figure 9 was created: the liquid jets were represented as four cylinders and the metal plate as a parallelepiped;
- the number of points and nodes that allow to perform an optimal simulation was established;
- contact surfaces, jet input surfaces and heated surface were established as shown in Fig. 10;
- the parameters used for the simulation were selected as given by Table 1;



Scope
Scoping Method: Geometry Selection
Geometry: 4 Bodies
Definition

Figure 10: *Setting surfaces.*

Table 1: *Parameters used for the simulation.*

Plate temperature	413 K
Liquid temperature	293,15 K
Air temperature	293,15 K
Solid material	Al
Liquid	Water
Phases	Phase 1- Air Phase 2 - liquid-water Phase 3 - liquid vapor
Phase interaction	vaporization-condensation
Viscosity	1,7894 x 10^5
Density	1,225

- the simulation program was run using a number of 20 iterations of 20 steps. The results can be seen in Fig. 11.

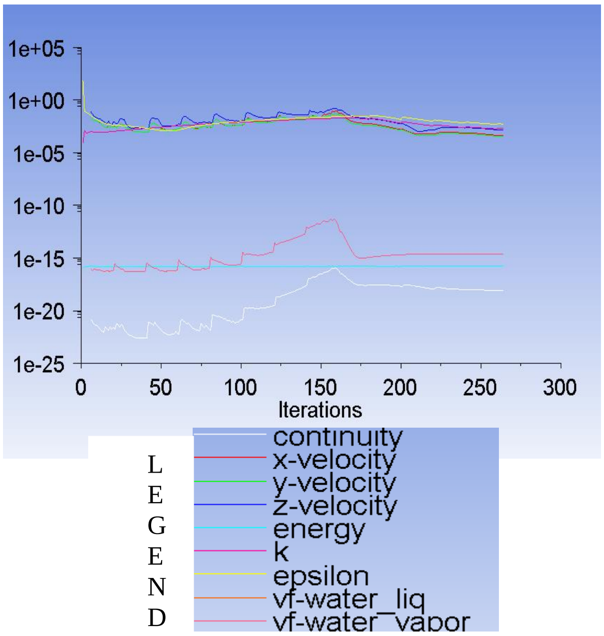


Figure 11: *Simulation plot.*

According to the simulation, a temperature drop of 13° *C* was obtained compared to 13.2°*C*, obtained by analytical calculation. Figure 12 shows the influence of the four jets of liquid when in contact with the heated surface.

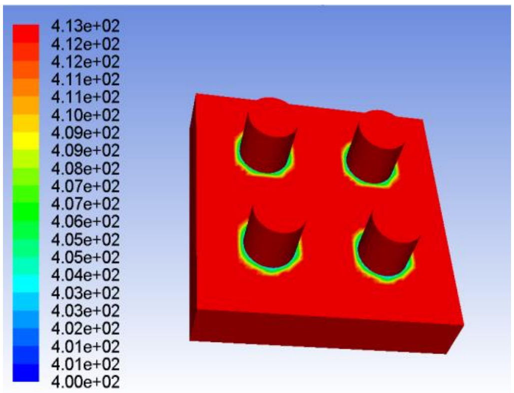


Figure 12: *Temperature variation from simulation.*

In Fig. 13 the evolution of the temperature field inside the jets is observed.

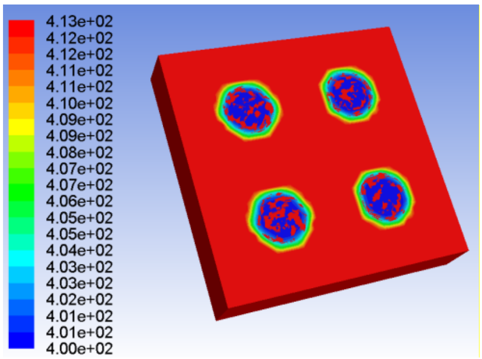


Figure 13: *Top view of the temperature variation.*

A cross section of the temperature evolution at the impact of the liquid jet with a hot surface can be seen in Fig. 14.

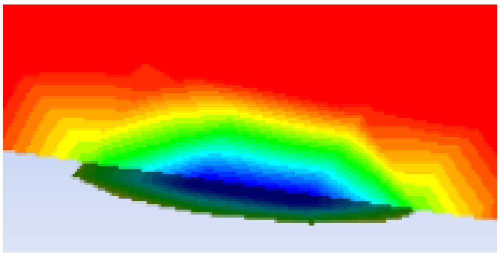


Figure 14: *The temperature variation of the section of the jet.*

At the local level, in Fig. 15 it is possible to observe the distribution of the volume fractions of the liquid in contact with the hot surface, observing the evolution of the vapors at the time of boiling.

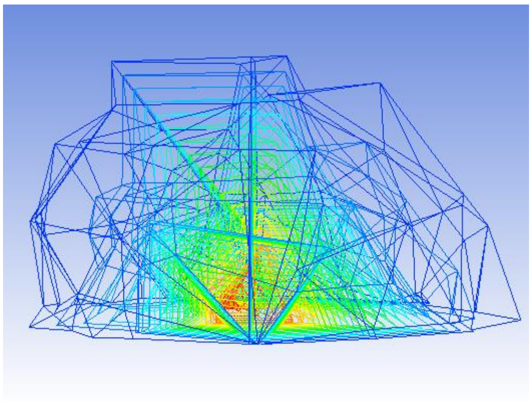


Figure 15: *Distribution of volume fractions.*

5. Conclusions

The aim of this study is to determine the temperature drop of a plate cooled with multiple liquid jets.

The cooling fluid is injected using calibrated nozzles on a heated surface.

Considering a flat plate with a quasi-isothermal side and the other one cooled by water jets, analytical calculations were first performed. Calculations were made taking into account the flow rate through the cooling system nozzles.

The first conclusion reached is that the temperature drop is directly proportional to the injected flow rate. Thus, for a plate heated to a temperature of 140° *C*, for the lowest flow rate (0,02 *kg/s*) at a cooling jet speed of 3 *m/s* and a temperature of the jet close to that of the environment, the temperature drop is about 5° C. Under the same conditions, if the flow rate is maximum (0,08 *kg/s*), a temperature drop of 13,2° *C* is obtained. This first conclusion indicates that the right balance between flow rate and heating temperature of the plate must be chosen in order to maintain the surface at values that allow the formation of crystals in a pseudo-sublimation process.

The temperature drop was also studied for a “chessboard” like configuration of the cooling system.

Considering the heated plate inclined at 35 degrees by report to the horizontal it was assumed that the liquid flowing from the top nozzles will flow towards the lower ones. The graphs in figures 4 and 7 were analytically determined using this configuration of the installation. The paraboloids obtained represent the temperature drop for three jets of cooling water that flows on the inclined plate. It can be noticed that there are different temperature drops. This is due to the incomplete vaporization of the liquid coming from the upper nozzles. This liquid, flowing on the other nozzles, will cool the area of the lower ones.

To simulate the processes, ANSYS simulation environment was used [7].

Four thin liquid jets sprayed onto a hot surface, with the mentioned characteristics, have been studied. Considering the higher flow rate, a temperature drops of 13° *C* resulted from the simulation.

Results obtained by numerical simulation show good agreement with those obtained analytically.

References

1. [Md Lokman, 2014] Lokman Hosain M.D., Anders Daneryd, Rebei Bel Fdhila, Anders Daneryd, *Multi-Jet Impingement Cooling of a Hot Flat Steel Plate***,** 2014.
2. [Mohammad, 2013] Mohammad Jahedi, *Computational study of multiple impinging jets on heat transfer*, University of Gavle, January 2013.
3. [Isachenko, 1975] Isachenko V.P., Osipova V.A., Sukomel A.S., *Heat transfer, MIR Publischer, Moskaw, 1975.*
4. [Solodov, 2005] Solodov A. Ochkov V., *Differential Models An Introduction with Mathcad*, Springer Berlin Heidelberg, 2005.
5. [Molana, 2013] Molana M., Banooni S., *Investigation of heat transfer processes involved liquid impingement jets: a review, 2013.*
6. Mathcad 14, Licensed to: Stefan cel Mare University, Partially Product Code JE140709XX2311-XXD9-7VXX.
7. Annual lease of ANSYS Academic Teaching with Civil FEM, 701359 inv. no., Stefan cel Mare University of Suceava, (2018).