Modelling of Spray Impingement Heat Transfer for Spray Cooling

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A new spray impaction heat transfer model has been developed from spray cooling experimental data and theoretical background. The model, incorporated in an in-house two-dimensional spray code, considers three droplet-impingement regimes and the three heat-transfer regimes. The impingement regimes considered are rebound, spread and splash, whereas the heat transfer regimes are nucleate, transition, and film-boiling. The model predicts the heat fluxes from a 40mm diameter mild steel surface, within a range of surface temperature from $100^{\circ}C$ to $250^{\circ}C$. Other variables used in the analysis are: the distance from the nozzle to the heated surface, the nozzle diameter, and the upstream pressure. The mathematical structure of the model follows a new approach in which the hydrodynamic behaviour of droplets and the heat exchange phenomenon are not coupled, but intimately synchronized. Model construction details and middle research goal results are shown in this paper.

Nomenclature

d_0	Original droplet diameter (before impaction).
D	Droplet diameter at any instant after impaction.
q_{all_layers}	Heat transferred to a droplet that has had several layers evaporated.
q_{evap}	Heat transferred to a droplet whose first layer was at saturation temperature sufficient to evaporate the layer.
q_{first_layer}	Heat transferred to the droplet when the first layer was evaporated.
q_{mth_layer}	Heat transferred to a droplet when its m^{th} layer was evaporated.
q_{Tsat}	Heat transferred to a droplet sufficient to take the first layer from its initial temperature to saturation temperature
q_1	First heat component. Heat transferred to a droplet in the first time-scale.
$T_{profile\_evap}$	Layer temperature profile of a droplet when its first layer has been evaporated
$T_{profile\_Tsat}$	Layer temperature profile of a droplet when its first layer has achieved saturation temperature condition
t_{end}	End of life time for a droplet
t_{Tsat}	Time between t_0 and the moment at which the droplet's first layer reaches saturation temperature.
t_{evap}	Time between t_{Tsat} and the moment at which the droplet's first layer becomes completely evaporated
t_0	Time at which the droplet makes contact with the hot wall.
t_{scale}	Time at which a time-scale of the droplet lifetime finishes.
$t_{b=1}$	Time at which the droplet has a contact area defined by its original diameter.
$t_{b\,max}$	Time at which the droplet has its greatest contact area.
β	Spread-ratio (d_0 / D)

1. Introduction

The mathematical structure of the model tackles the spray-cooling phenomenon with a new approach in which the impacting behaviour of droplets and the heat exchange between the droplets and the wall are characterized independently. The output information from these two phenomena is designed to be mutually compatible allowing such an intimate synchronization that would result in an accurate modeling of the spray cooling process, but without excessive computational efforts.

2. Impacting Behaviour of Droplets

Droplets change their wall impaction behaviour dependent on the wall-temperature, thus to gain independence between droplets hydrodynamics and the wall heat transfer temperature and flow regimes, two facts needed to be known:

1. The timing of the droplet's interactions with the wall, at all wall-temperatures in the temperature range considered.
2. The contact surface area between the droplet and the wall, at any time and at all wall-temperature in the temperature range considered.

The knowledge of these two facts leads to the development of a droplet's hydrodynamic timing map, for all wall-temperatures in the range $(100^{\circ}C - 250^{\circ}C)$, and for all incoming droplet's Weber numbers in the range $(20 - 220)$, and a spread-ratio curve prediction equation. Seeking to gain accuracy, the timing map was divided into three parts according to the time-scales of the life of a droplet. The definitions of the time-scales are:

1. First time-scale (fractions of millisecond; $t_0 - t_{b=1}$)
2. Second time-scale (units of millisecond; $t_{b=1} - t_{b\,\max}$)
3. Third time-scale (tens-hundreds of millisecond; $t_{b\,\max} - t_{end}$)

An example of an experimental timing map (provided by Bernardin et al[1]) is shown in Figure 1:

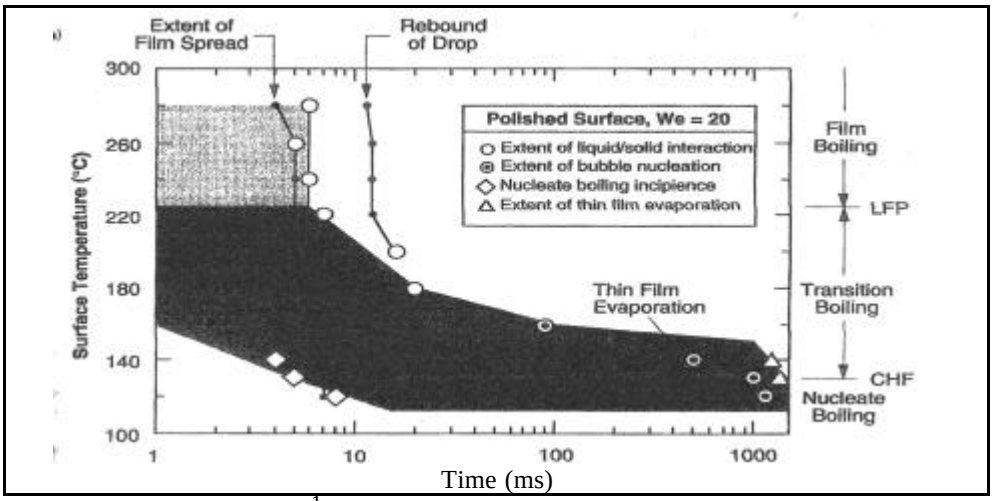
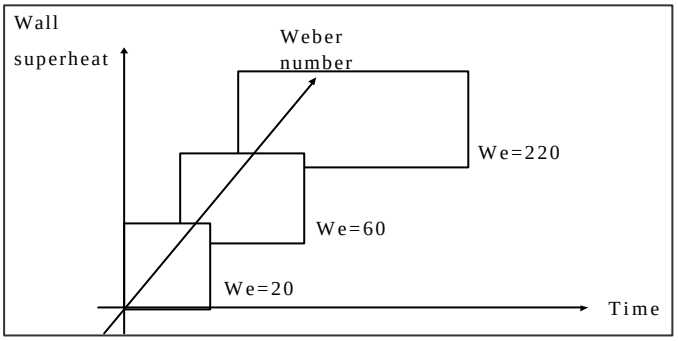


Fig.1 Bernardin et al[1] droplet regime map for a Weber=20 valued droplet

As can be seen this timing map provides information of the changes a droplet undergoes in its lifetime (the information must be read horizontally, by choosing a surface



temperature). Maps as the one shown were digitised to construct a three dimensional timing map, Figure 2.

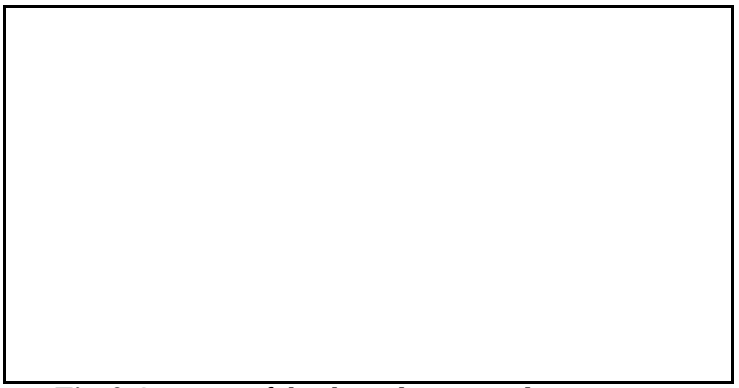


Fig. 2 Structure of the three-dimensional timing map.

The information extracted in Fig. 1 from these maps helps our third time-scale (i.e. from the line of "extent of film spread" to the end of the droplet life), given the fact that the previous time-scales are predicted by other means. The same timing map but in digitised form, is shown in Figure 3.

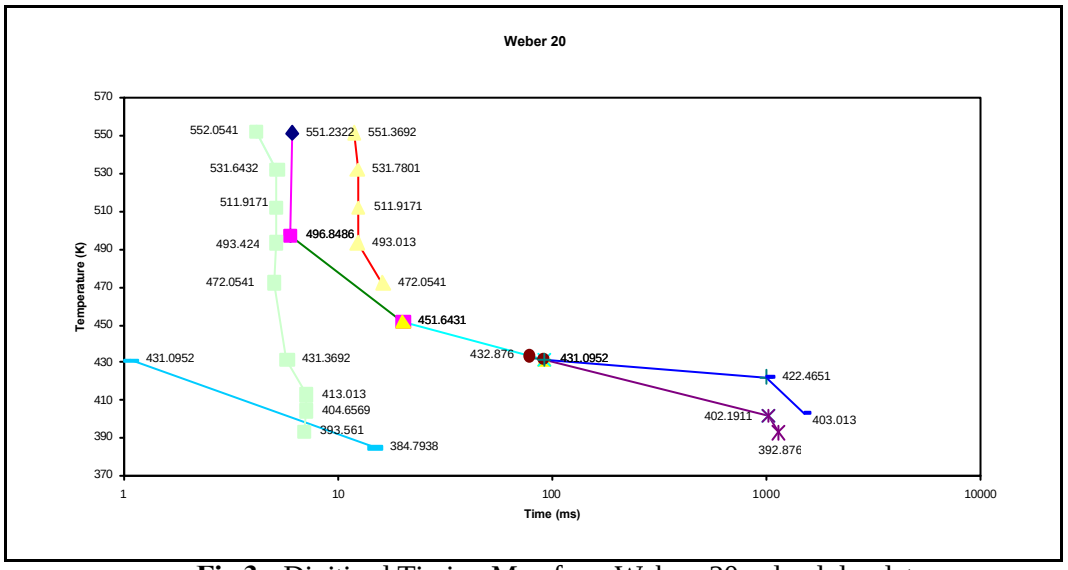


Fig.3 Digitised Timing Map for a Weber=20 valued droplet.

The first time-scale is concerned with the initial wall-droplet contact period, from the moment the droplet touches the wall to the time the droplet has a contact area defined by its original diameter. The second timescale is concerned with the spreading process the droplet will undergo if the inertial and wall-temperatures conditions allow it. And finally, the third timescale is concerned about the droplet's hydrodynamics behaviour after the

spreading process has reached its maximum value. The experimental data used for this development were taken from Bernardin et al[1], Chandra et al[2], and Pasandideh-Fard et al[3].

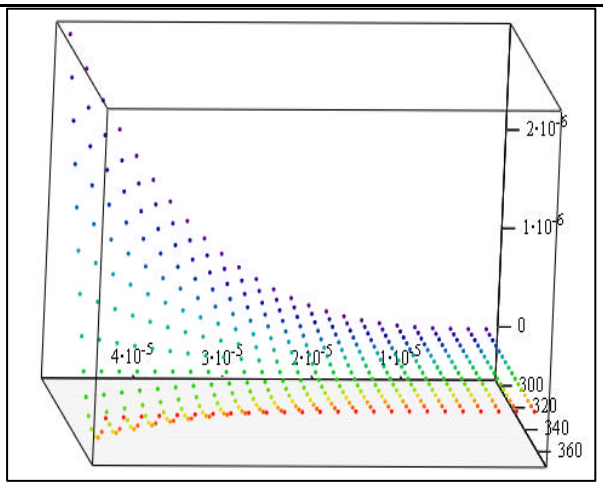
3. Heat Transfer Behaviour of Droplets

The heat transfer prediction is made in a new in-house code. The code uses two-dimensional conduction equations to predict the heat transfer of a droplet that is in contact with a hot wall. For any specific wall-temperature the code swept twenty five different droplet radii and sixteen droplet initial temperatures, in order to calculate all of the following six parameters:

- q_{Tsat} -The heat transferred to the droplet to reach saturation conditions in the first layer of the grid (the layer that is adjacent to the wall).
- q_{evap} -The heat transferred to evaporate the first layer of the grid.
- t_{Tsat} -The time needed to reach saturation conditions in the first layer of the grid.
- t_{evap} -The time needed to evaporate the first layer of the grid.
- $T_{profile\_Tsat}$ -The temperature profile within the droplet when the saturation condition in the first layer is met.
- $T_{profile\_evap}$ -The temperature profile within the droplet when the evaporation of the first layer is completed

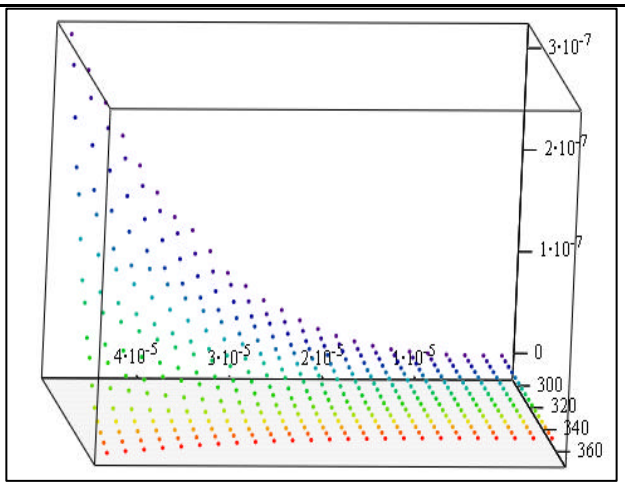
The knowledge of these parameters for any droplet radius, droplet initial temperature, and wall-temperature allowed the development of heat transfer correlations and data tables. These correlations and tables, make possible to avoid heat transfer calculations within the main spray impaction code.

Figure 4 shows planes of q_{Tsat} (vertical axis) versus initial droplet temperature and droplet radius (horizontal axes) for four different wall-temperatures.



(X,Y,Z)

WALL TEMPERATURE 373 KELVIN



(X,Y,Z)

WALL TEMPERATURE 423 KELVIN

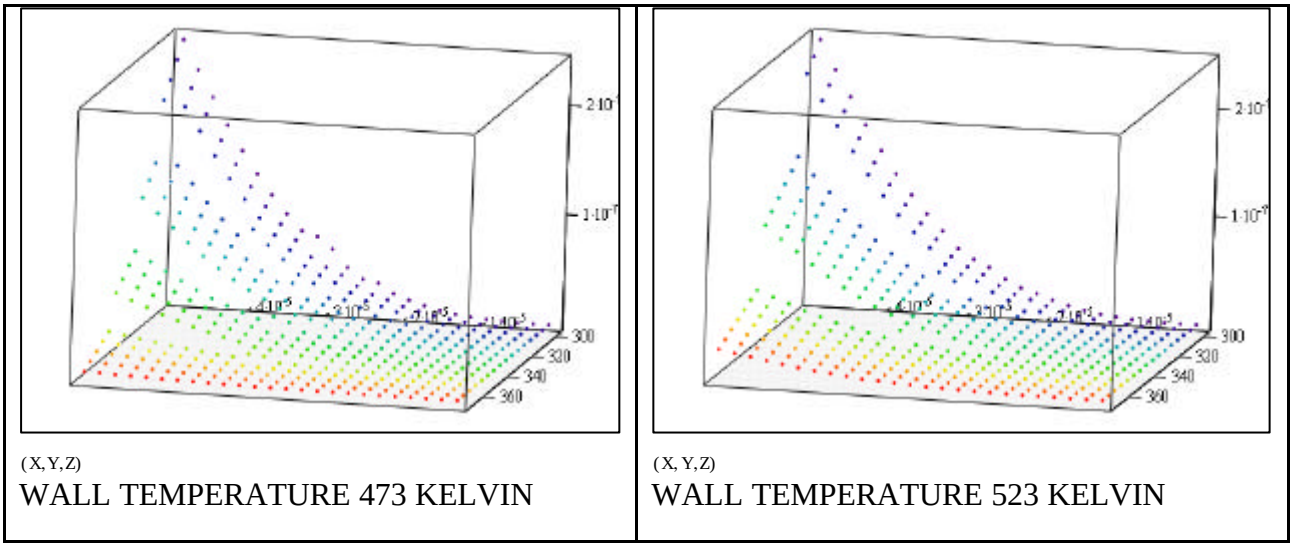


Fig. 4 $\frac{q_{Tsat}}{2p}$ (J) in the vertical axis versus initial droplet temperature (K) and droplet radius (m), horizontal axes, for four different wall temperatures..

4. Spray Cooling Model

The spray cooling phenomena are divided into six heat transfer modules, accordingly to whether the near wall cell is flooded or not, and to which of the three heat transfer regimes is occurring. The flow diagram of the spray cooling model is shown in Figure 5.

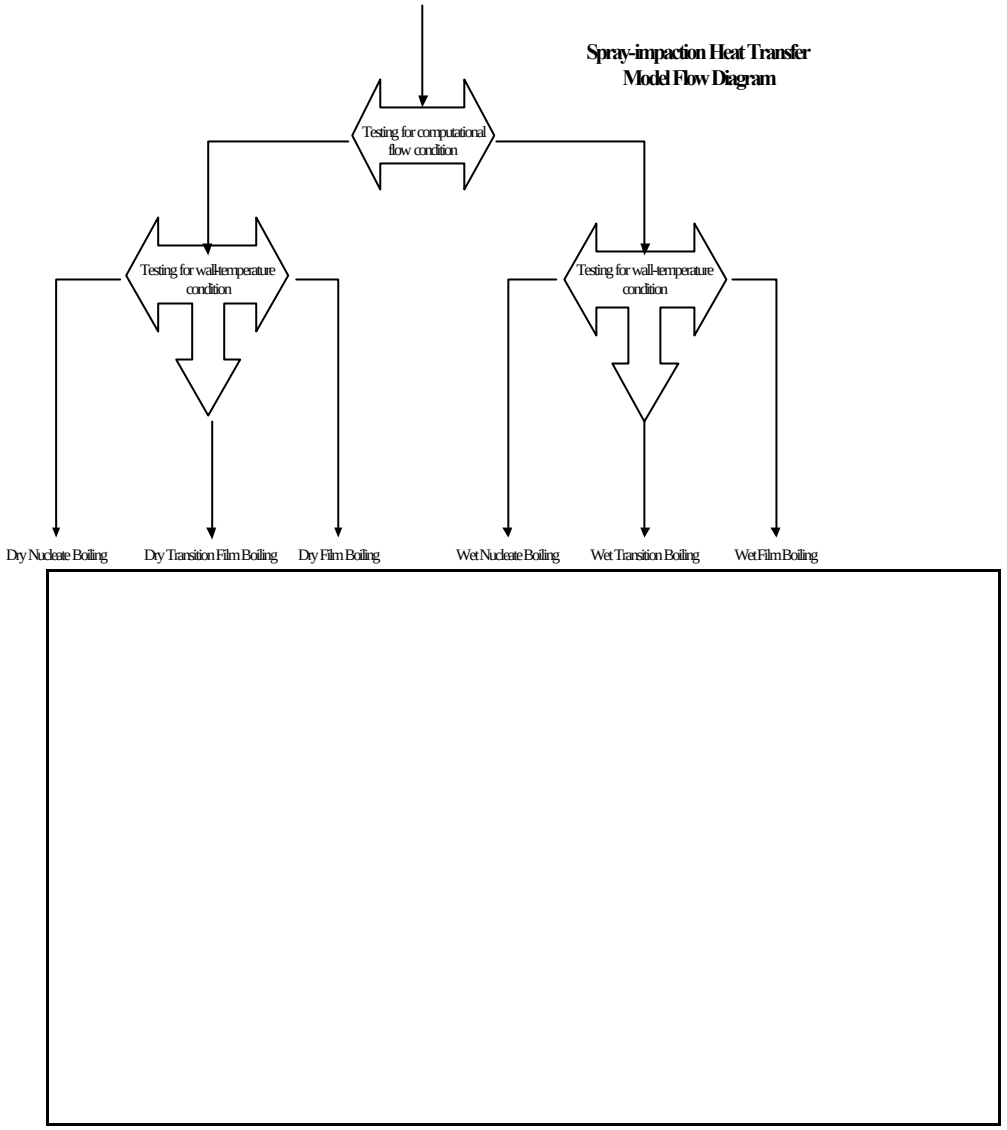


Fig.5 Spray Cooling Model Flow Diagram

Having tested for the flood condition of the wall cell (by comparing the height of the column of liquid in the cell against a $2mm$ height), the model determines by the knowledge of the wall-temperature, which of the three heat transfer regimes is taking place. The six heat transfer modules are:

1.Dry Nucleate Boiling (DNB)
2.Dry Transition Boiling (DTB)
3.Dry Film Boiling (DFB)
4.Wet Nucleate Boiling (WNB)
5.Wet Transition Boiling (WTB)
6.Wet Film Boiling (WFB)

Calculations for modules number two and five (both are transition boiling regimes) are done following the approach of Aamir and Watkins [4]. Since the transition boiling regime expresses features of its neighbouring boiling regimes a probability function is use for choosing randomly either nucleate boiling or the film boiling equations. Module number six has an independent mathematical model since it is the only module in which a permanent vapour layer exists between the wall surface and the liquid layer. Modules one, three and four use the impacting behaviour and heat transfer behaviour of droplets predictions already discussed, and therefore they have very similar mathematical solutions. The mathematical model for the dry nucleate boiling regime will be presented as an example.

Mathematical Model For Dry Nucleate Boiling Regime (DNB).

According to the model, any droplet has:

- A hydrodynamic life, which is described by the timing map. This map is divided into three time-scales for the sake of precision.
- A heat transfer life, which is composed by three heat transfer statuses and two transient heat transfer events.

Changes in the droplet's hydrodynamic life and heat transfer life rarely occur at the same time, so all the possible combinations between a change of time-scale and changes of heat transfer status must be considered. Once a change happens it is necessary to process the heat transfer information, save it, and pass it appropriately to the next time-step.
For any given time-scale the following combinations may occur:

Case 1-($t_{scale} < t_{Tsat} < t_{Tsat} + t_{evap}$). The time-scale t_{scale} is shorter than the time needed for the contact-layer to reach saturation temperature t_{Tsat}.
Case 2-($t_{Tsat} < t_{scale} < t_{Tsat} + t_{evap}$). The time-scale t_{scale} is larger than the time needed for the contact-layer to reach saturation temperature t_{Tsat}; but not large enough to evaporated the layer t_{evap}.
Case 3-($t_{Tsat} < t_{Tsat} + t_{evap} < t_{scale}$). The time-scale t_{scale} is large enough for the contact-layer to reach saturation temperature at t_{Tsat}, and to be evaporated at t_{evap}, and allow a new contact-layer to start heating.

The Dry Nucleate Boiling regime occurs when the wall superheat condition is low (nucleate boiling regime), and a non-flooded condition exists in the computational wall-cell. The heat transfer module predicts the heat transferred to the liquid as the result of three heat components. Each heat component determines the heat transferred within a time-scale.

- First Heat Component-First time-scale ($t_{scale} = t_{b=1} - t_0$)
- Second Heat Component-Second time-scale ($t_{scale} = t_{b\max} - t_{b=1}$)
- Third Heat Component-Third time-scale ($t_{scale} = t_{end} - t_{b\max}$)

First Heat Component Calculation q_1 .First time-scale $t_{scale} = t_{b=1}$.

The first heat component accounts for the heat transferred within the first time-scale period (from the moment the droplet touches the wall at t_o to the time the droplet has a contact area defined by its original diameter at $t_{b=1}$).

Case 1($t_{scale} < t_{Tsat} < t_{Tsat} + t_{evap}$)($t_{scale} = t_{b=1}$)
The contact-layer gets heated but does not reach saturation temperature ($t_{b=1} < t_{Tsat}$). Then the heat that has entered into the droplet is calculated as a time proportional quantity,

(1)

$$q_1 = \frac{t_{scale} \; q_{Tsat}}{t_{Tsat}}$$

Case 2($t_{Tsat} < t_{scale} < t_{Tsat} + t_{evap}$)($t_{scale} = t_{b=1}$)
The contact-layer reaches saturation temperature but does not completely evaporate (i.e. $t_{Tsat} < t_{b=1} < t_{Tsat} + t_{evap}$).

(2)

$$q_1 = q_{Tsat} + \frac{(t_{scale} - t_{Tsat}) q_{evap}}{t_{evap}}$$

Case 3($t_{Tsat} < t_{Tsat} + t_{evap} < t_{scale}$)($t_{scale} = t_{b=1}$)
The contact-layer reaches the saturation temperature, is evaporated and a new layer starts heating ($t_{Tsat} < t_{Tsat} + t_{evap} < t_{b=1}$).

(3)

$$q_{first\_layer} = q_{Tsat} + q_{evap}$$

The second layer is expected to be at a much higher initial temperature (somewhere near the saturation temperature) because it has been in contact with the first layer. It is then expected that it will reach saturation temperature and will evaporate sooner than its predecessor layer, but it also has less time in order to change its heat transfer status. The heat transferred to all layers that would have been in contact with the wall within the first time-scale is,

(4)

$$q_1 = q_{all\_layers} = \sum_{m=1} q_{mth\_layer}$$

These three cases include all the possible outcomes for the first time-scale. Similar treatments are given to the second and third time-scales. In the second time-scale special treatment is given to the spreading process. A customised spreading curve (spread-ratio versus time) is generated taking into account the wall temperature and the droplet Weber number. This curve allows the knowledge of the contact area at any time, which is a parameter that greatly influences the heat transfer phenomenon. After the three heat components are calculated, they are added to evaluate how much heat was removed from the wall by the droplet in its lifetime.
For Dry Nucleate Boiling Regime (DNB), and Dry Film Boiling Regime (DFB), the wall cell is non-flooded and it is assumed to interact with discrete droplets, therefore the process explained above is calculated for each individual droplet in the wall-cell. On the

other hand, when Wet Nucleate Boiling Regime is present, the wall-cell is flooded and is therefore assumed to be covered by a liquid-film. Under this assumption equations 1-4 are applied to the whole wall cell, as if it were a very large droplet.

5. Summary and Conclusions

- A new spray impingement heat transfer model has been presented.
- The model predicts the heat transferred from the hot wall to the fluid using as parameters the droplet incoming Weber number, the droplet diameter, the initial droplet temperature, and the gaseous phase temperature.
- The model is able to predict heat transfer taking into account the flooded condition of the near cell wall, and solves for the corresponding heat transfer regime according to the wall temperature.
- The mathematical structure of the model is divided into hydrodynamic impacting behaviour and heat transfer behaviour of the droplets. These two phenomena are then intimately associated and synchronized in order to correctly simulate the actual spray-cooling phenomena
- Some preliminary results have been shown, and examples of the model calculation procedure given.
- Future work will be devoted to implement the model in the spray impaction code and run comparisons with experimental data.
- Some other possibilities are:
    - to extend the model for different fluids and wall materials.
    - to test the model for non-homogeneous temperature surfaces.
    - to test the model in transient temperature surfaces.

6. References

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[2] S. Chandra, and C.J. Avedisian (1991). On the collision of a droplet with a solid surface. Proc. R. Soc. London A 432, Pp. 13-41.
[3] M. Pasandideh-Fard, S.D. Aziz, S. Chandra, and J. Mostaghimi (2001). Cooling effectiveness of a water drop impinging on a hot surfaces. International Journal of Heat and Mass Flow 22, Pp. 201-210.
[4] M.A. Aamir, and A.P. Watkins (2000). Modelling of Spray Impingement Heat Transfer. ILASS-Europe, VII.2.1-6, Darmstadt.