ANALYSIS OF DROPLETS FALLING ON HOT VERTICAL SURFACE

A. Amoresano*, G. Langella* and C. Noviello*
amoresan@unina.it
***** Dipartimento di Ingegneria Meccanica per l'Energetica - Università di Napoli "Federico II"
Via Claudio 21 - 80125 Naples- Italy

Abstract
The situation of a droplet falling on a vertical hot surface is typical of spray cooling systems in nuclear reactor but it takes place in many other industrial applications. Two different cooling tecniques can generate such interaction. The first one is the film rewetting: a liquid film falls along a vertical surface at temperature upper than the Leidenfrost point, and a sputtering phenomenon is generated, as reported in fig.1. Sputtering is a violent evaporation that breaks the film along a quenching front into a great number of droplets which go away from the surface inpinging on other surfaces near it.
The second one is the spray cooling of vertical surface: in this case there is no film cooling, but droplets are directly generated by cooling system nozzles.
In both cases there are some droplets that have momentum enough to rebound from the surface, but there are other droplets that fall on the surface and evaporate.
The behaviour of a single droplet falling on a vertical hot surface has been investigated by a fast CCD camera device. Particularly the influence of wall temperature, drop size and velocity have been analized in order to investigate the best cooling conditions.
The creation of secondary droplet by main droplet break up has been also analized because of high thermal exchange coefficient that can be achieved by these droplets' interaction with the hot wall.
Aim of the work is the analisys of the different types of wall-droplet interaction that can be performed and evaluation of heat exchance rates through the elaboration of the frames acquired at a frequency higher than 1000 frame/sec.

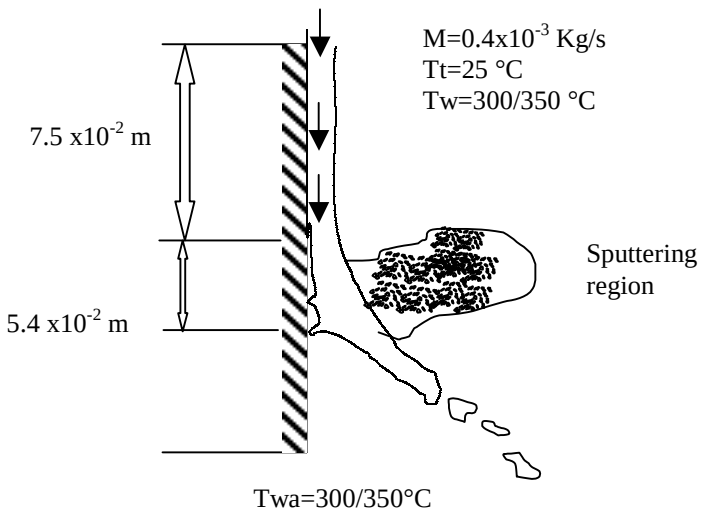
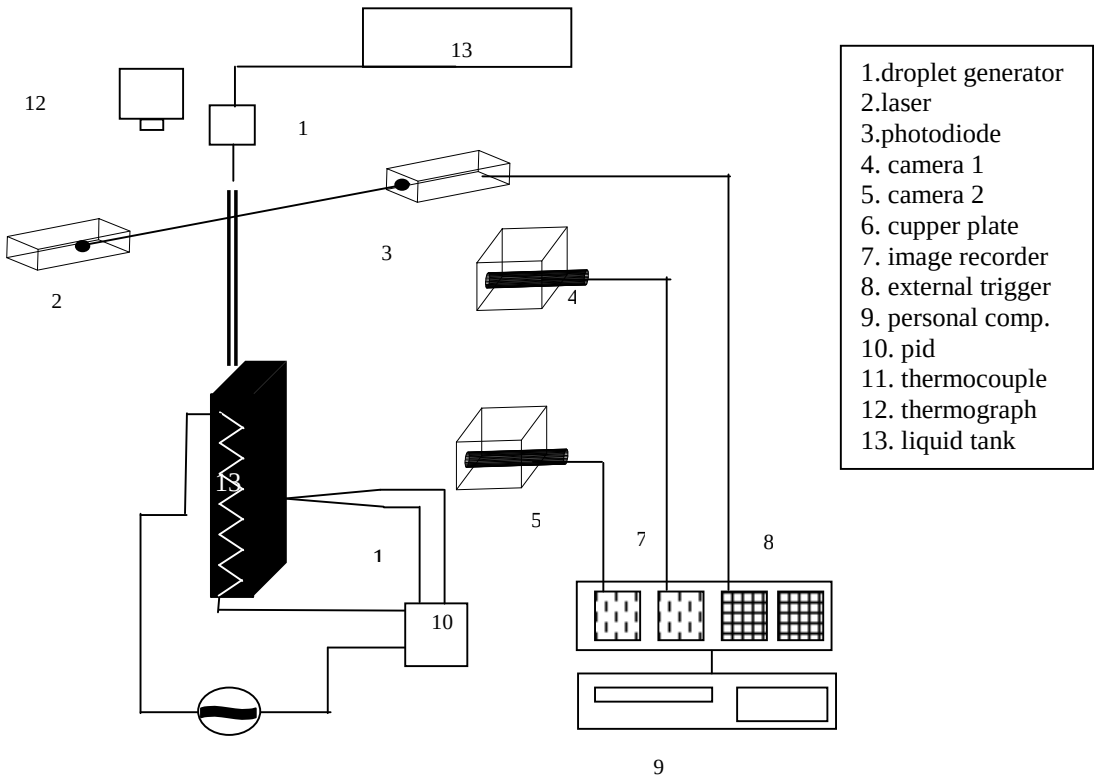


Fig. 1

Sputtering in spray rewetting cooling systems
As known two types of emergency refrigeration for nuclear plants are available: spray cooling and bottom flooding. In the analysis of interaction between droplets and vertical hot surfaces, rewetting of nuclear bars due

to gravity is a phenomenon of particular interest. It takes place in emergency cooling systems of nuclear plants, when a loss of coolant accident occurs: a cool liquid is injected on bars over Leidenfrost point by spraying rings disposed over the bars.
The liquid sprayed falls down by gravity, wetting the walls. This liquid film goes down slowly because it's obstructed by a violent evaporation along the quenching front where sputtering takes place, that is a quick boiling and separation of liquid film from the wall. In this front a great number of droplets are generated, falling down or being dragged up by vapour stream, depending on their dimensions.
The liquid film feed is mainly controlled by heat conduction in the wall.
The number and the size distribution of these droplets are very important parameters because they determine the total amount of exchange surface between liquid and gas phase.
In fig. 1 a typical sputtering situation is reported: in this figure some characteristic dimensions for light water reactors are reported.
Diagrams [1] have been traced by computation of liquid front rewetting velocity and droplet rate generating from sputtering vs liquid mass rate injected onto surface.
Droplets generated in the sputtering zone inpinge onto the high temperature wall with a certain cooling effect (precursory cooling).

Experimental facility
In this case the nozzle generates a continous water beam definined as 'rivulet', using a steel capillary pipe connected with a free surface liquid tank thousands of times bigger than single drop bulk.
Solid surface consists of a 300 mm insulated blister copper with, thickness of 5mm. To realize a steady - state operating condition, the electrical power to the plate was adjusted with a temperature feedback electronic control device so max 1 K deviation from set point was got.
Cameras store images with a frequency variable from 50 to 4000 frame/sec. Each camera was controlled by software statements which set imaging frequency, pixels number and frames number to be stored.
Up to 60 full frames (128x128 pixels) can be stored each time. Because of working with high frequencies, a short period is available to catch the whole impact, so that a synchronization system is needed.
A low power (95μW) He-Ne laser was used to excite a photodiode linked to an electronic trigger circuit. Drop passage through laser ray, stops exciting so a trigger signal is sent to cameras and acquisition begins.
The first camera is synchronized by an external trigger and it records the droplet near the injector and the radius at the instant t_1. The second camera takes place near the impact zone and by the external synchronized trigger records the frame just before the impact and the entire break-up phenomenon.



Experimental Analisys

The experimental analisys is carried out by means the CCD fast camera tecnology ([5],[6],[8]). The hot wall in this case is completely vertical and the impinging flux is continuous.

The water temperature inside the tank is about 25-27 °C. The hot wall is controlled by a PID to be sure of the accuracy of the set point temperature. The water flow rate of the impinging rivulet is fixed on 42 ml/s and the distance between hot wall and nozzle is about 150 mm. These conditions assure that the rivulet is continous before and after the wall impact.

The limit conditions of the liquid phase give the following geometrical condition of this one.

$$T_w = 300/350\ °C$$
$$\delta = 10^{-3} m$$
$$T_b = 25°C$$

It is possible to indicate the rivulet velocity knowing the value of inlet undercooling. In this case ΔT_{in} is about 75°C and the velocity of advancing of the liquid front is given [1] by the following equation:

$$Ufr = 10^{-4} \cdot (1 + \Delta Tin^{1,4}) \cdot (M \cdot 60)^{2 \cdot 10^{-3} (1 + \Delta Tin^{1,3})} \qquad (1)$$

For boundary condition of this case, the rivulet velocity Ufr = 0.2 m/s. It means, considering the thickness of the rivulet and its width equal five times its thickness, that the area to be considered for the analysis of the heat flux is given by

$$A\varphi = (Lr + Ls) \cdot 5 \cdot 10^{-3} \qquad (2)$$

To better intend the mechanisms of the impact of the free rivulet on the vertical surface it is very interesting to consider [1] that the law of rebouding of droplets on vertical wall varying the wall temperature.

If the wall temperature is about 200 °C the impinging droplets have an anelastic behaviour. So they lose the shape after the impact. If the wall temperature is included between 300 and 400 °C the behaviour of the droplets follow the elastic law, the droplets rebound on the surface and leave it recovering the initial shape. For wall temperature higher than 550 °C and low impact angles the droplets behaviour becomes anelastic again.

The behaviuor of the free liquid rivulet is very similar to the behaviuor of the impact droplet on vertical surface. In this paper is also pointed out that the behaviour of the liquid flow impinging on vertical hot surface follows the three phenomena (200 –450- 550 °C) because of the continuous cooling of the surface and the velocity of the liquid front of the rivulet.

Experimental results

A rivulet of water has been generated with a flow rate of 0.42 ml/sec and a 1x1 mm circular section. The interaction of the rivulet with a hot and vertical copper surface has been investigated, varying the plate temperature from 250 to 400 ° C , according with theoretical consideration above mentioned.

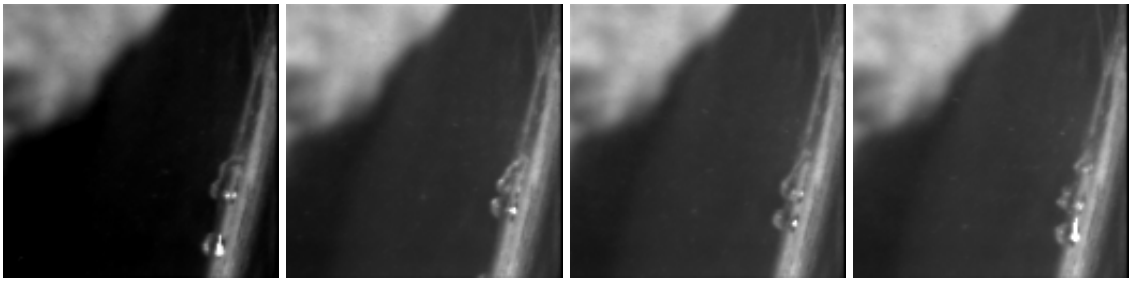
The sputterig phenomenon has been detected between 300 and 350 ° C.

For plate temperature below 300 °C, the rivulet generates a local cooling of the surface which goes down under Leidenfrost temperature so a flooded interaction takes place and water falls down along surface in a continous film.

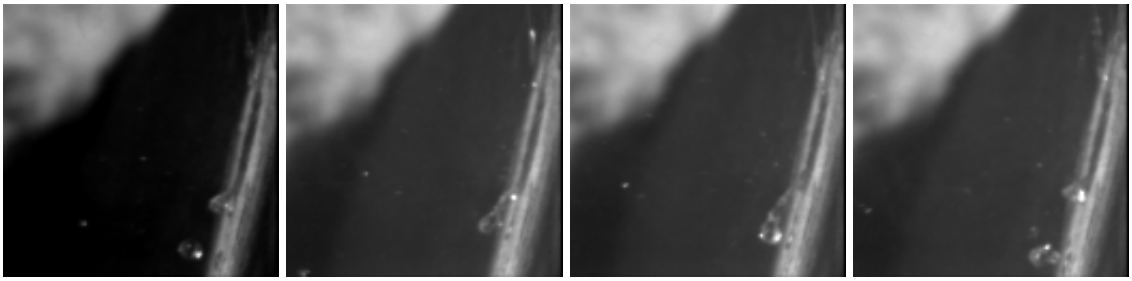
At about 300 °C the heat transfer from the plate to the water is enough to create a vapour cushion by which the film detaches from the plate generating a small number of big droplets (300μm diameter) and a great number of small secondary droplets (10 – 50 μm diameter) at the two sides of the rivulet where the thickness of the liquid film is much more less with rispect to the rivulet axis. This behaviour can be observed in impact sequence n°1.

When temperature arises to 320 ° C , a typical sputterig phenomenon takes place: in impact sequence n:2 the complete detaching of the rivulet is reported and the further breaking into a small number of droplets.

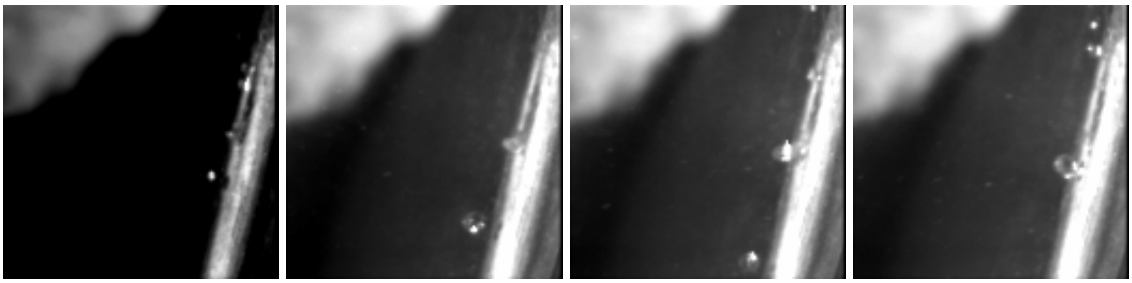
At higher temperatures the rivulet breaks up violently in a great number of small droplets (10 – 100 μm diameter) such as reported in inpact sequences n° 3 and 4.. It can be noticed that the higher the plate temperature, the greater is the number of droplets generated and the smaller their diameter. In this case the rivulet cannot keep its continuity when detached from the surface (such as for lower temperatures) and it's quickly divided into droplets.



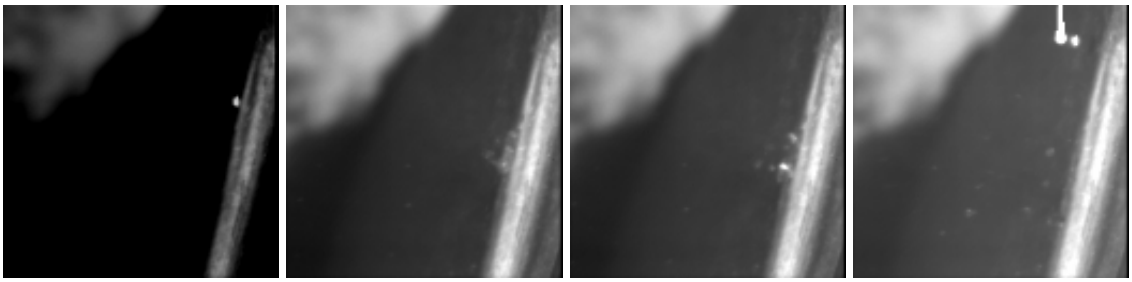
IMPACT SEQUENCE N°1
Twall = 310 °C



IMPACT SEQUENCE N°2
Twall = 320 °C



IMPACT SEQUENCE N°3
Twall = 340 °C



IMPACT SEQUENCE N°4
Twall = 360 °C

Nomenclature

A	Surface	[m^2]
M	Mass flow rate	[kg/s]
T	Temperature	[°C]
u	Velocity	[m/s]
L	Length	[m]

Subscripts

in	inlet
r	rivulet
s	sputtering
t	tank
w	wall
φ	flux

Greek letters

δ	thickness	[m]

References

[1]M.Cumo, G.E.Farello, M.Furrer, *Experimental remarks on sputtering phenomena and droplets generation in falling film rewetting,* CNEN Report RT/ING (80) 2.

[2] Wachters L.H.J., *The heat transfer from a hot horizontal plate to sessile water drops in the spheroidal states,* Chem. Eng. Sci., 1966, Vol. 21 pp. 923-936

[3] Grissom and F.A. Wierum, *Liquid Spray Cooling of a Heated Surface* Int. J. Heat Mass Transfer ,1981 Vol. 24, pp. 261-271

[3] Cappellini, V. Elaborazione numerica delle immagini Boringhieri 1985

[4] DALSA Databook, *CCD Image Sensors and Cameras* DALSA Inc. 1991

[5] A.Amoresano -G.Langella- C. Noviello, *Experimental analysis of liquid drop inpinging on hot oblique surface,* ILASS Europe ’99, Tolouse 5-7 July 1999.

[6] A.Amoresano -G.Langella- C. Noviello, *Analysis and behaviour of droplet inpinging on hot curve surface,* ILASS Europe 2000, Darmstadt 11-13 Sept. 2000.

[7] M.A.Aamir-A.P.Watkins, *Modelling of spray impingement heat transfer,* ILASS Europe 2000, Darmstadt 11-13 Sept. 2000.

[8] A.Amoresano -G.Langella- C. Noviello, *Analysis and behaviour of droplet inpinging on hot radiative surface,* ILASS Europe 2001, Zurich 2-6 Sept. 2002.