ILASS 2008
Sep. 8-10, 2008, Como Lake, Italy

Paper ID ILASS08-P-7

# EXPERIMENTAL CHARACTERIZATION OF HOMOGENEOUS FLASHING IN A LIQUID JET

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## ABSTRACT

Flash-boiling method is one of the most common current atomization methods. In most applications, the atomization unit consists of an inlet orifice, an expansion chamber and a discharge orifice. Nucleation occurs at the inlet orifice on the walls (heterogeneous nucleation), the bubbles develop in the expansion chamber, and a rapid bubble growth (flash-boiling) occurs when the mixture leaves the discharge orifice. In the present work an attempt was made to make use of homogeneous nucleation, rather than heterogeneous, in order to improve the spray characteristics while simplifying the construction of the atomization unit. We studied experimentally the characteristics of an emerging jet that undergoes homogeneous nucleation when emerges through a single orifice. We first explored the border between heterogeneous and homogeneous regimes of boiling by conducting a series of experiments using water. By observing the different flow regimes resulting from a range of temperatures and injection pressures, the borderline between the different boiling regimes was determined. The emerging jet was analyzed for its break-up distance and its opening angle. Our observations show significant differences in the characteristics of the emerging jet between the heterogeneous and homogeneous regimes. The factors that affect these characteristics have been identified.

## INTRODUCTION

The use of sprays is very common nowadays in variety fields and there are plenty of injecting methods that suits the different applications. In each process that involves spray there are different requirements from it, the most common requirements are associated with the spray angle, the average drop size and size distribution and the breaking length of the jet. During the years many methods has been developed in order to create as much tiny and uniform drops as possible. The common and effective methods are injecting in high pressure, jet spinning and jet shearing by compressed gas. New modern methods are based on injection of binary mixture (usually two components with different vapor pressure) so that a propellant undergoes an extremely rapid boiling process (flash-boiling) due to sudden pressure drop that bring it to pressure lower than the saturation pressure, the vapor embryos that appears are interrupting the jet stability. The flash boiling is infected by the liquid temperature, the orifice geometry, the pressure difference before and after the orifice etc. We can classify the flesh boiling into two main regimes, heterogeneous nucleation regime in witch the bubble creation occurs on the orifice walls and homogeneous nucleation regime in witch the bubbles creations occurs all over the jet volume. The nucleation regime affects the spray properties therefore there is significance meaning to the studies in this filed. During the last century many studies has been made in order to understand the factors that influences the nucleation regime, the nucleation rate and spray formation. In former studies (Sher & Elata 1977, Park & Lee 1994, Rashkoven at al. 2003, Bar-Kohany 2004) it has been proved that by injecting a binary mixture so that one of the components undergoes a flash boiling significantly improves the spray properties. The flash boiling phenomena is infected by many factors as the initial temperature and pressure of the liquid and the orifice geometry (Lienhard et al. 1978). The nucleation regime influences the nucleation rate (Carey 1992), therefore it seems that it will affect the spray properties. Other studies have been made in order to characterize spray formation and injectors types (Reitz 1978, Lefebvre 1989, Hiroyasu 2000) and other studies aimed to characterize the border limit between the nucleation regimes (Skripov 1974, Blander & Kats 1975, Lienhard 1982, Avedisian 1985, Carey 1992). The aim of this study is to examine the borderline between the nucleation regimes and to characterize homogeneous flashing in a liquid jet.

## EXPERIMENTAL SETUP

In order to examine the border limit of homogeneous nucleation and to characterize the spray properties in this regime, the following system has been assembled. The system was involving a refined water tank, the refined water pumped with high pressure pump through a stainless steel coil, the coil was placed in high temperature oven so that the water leaved the oven with very high temperature (above 300 [ºC]) in a liquid state (pressure above 10 [MPa]). The superheated water passed through a delicate filter and injected to the surrounding through a plain orifice (0.1 [mm] diameter). The water temperature and pressure measured near the orifice. In fig.(1) the experimental system is described schematically. Where: 1- cold water tank (about 5 liters volume), 2- water pump (7/8 hp), 3 – stainless steel tube in a coil shape that receives heat from an oven, 4 – delicate filter (15 μm), 5 – pressure probe that placed 10 cm from the orifice (7), 6 – thermocouple that placed 5 cm from the orifice(7), 7 – plain orifice (0.1 mm diameter, 0.5 mm length as shown in fig.(2)), 8 – digital camera. The water tank in the experimental system contains refined water that goes through ion exchange system that purifies the water from salts and bacteria. The first stage of the experiment was to activate the oven and wait till the wanted temperature achieved and stabilized (the temperature inside the oven reached to 300-450 [°C] during the experiments). After the temperature was stabilized, the pump was activated and the water starts to flow in the system. For each working point the pump was set to the wanted pressure, after the system reached to steady state temperature and pressure measurements and a digital picture of the spray was taken. In each working point a different initial pressure and temperature of the superheated liquid was measured.

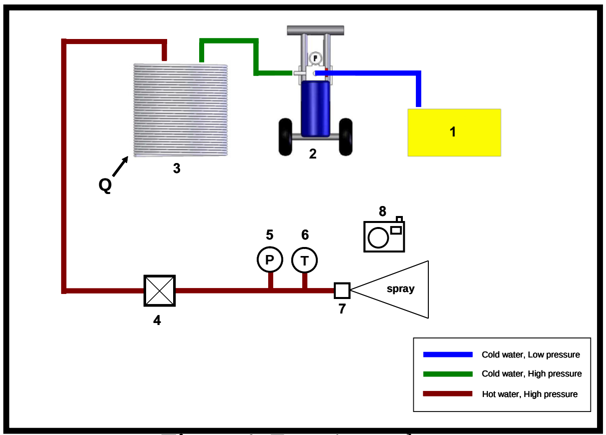

**Figure 1.** Experimental system

## RESULTS AND DISCUSSION

*The homogeneous nucleation borderline*

In the following experiments series results, the initial temperatures and pressures range was between 310 to 335 [ºC] and 10 to 15 [Mpa]. During the experiments two flow patterns were obtained. For constant pressure, in some temperatures one flow pattern obtained and above a specific temperature the second pattern obtained. In the first pattern, fig.(2), the breaking point of the liquid jet appears right thought the output section of the orifice and the spray angle are quit large. In the second pattern, fig.(3), there is a distance between the orifice and the breaking point of the liquid jet and the spray angles are smaller. By injecting the water in varies initial pressures and temperatures we were able to find the border limit between the two flow patterns. We showd in our work that the borderline between the two flow patterns is actuoally the borderline between the nucliation regims.


**Figure 2.** First flow pattern (11.25 [MPa], 310 [ºC])

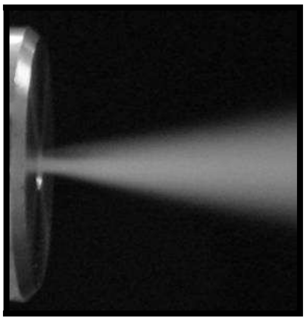
**Figure 3.** Second flow pattern (11.25 [MPa], 320 [ºC])

In fig.(4) we can see the comparison between the nucleation border that was defined by the experiments to that of some theoretical correlations. The Lienhard correlation to determine the superheating temperature (1982):

(1) $$T_{SL} \cong T_{cr} \cdot \left[ 0.932 + 0.077 \cdot \left( \frac{T_{sat}}{T_{cr}} \right)^9 \right]$$

And the Lee and Frost correlation (1997):

(2) $$T_{SL} \cong T_{cr} \cdot \left( 0.11 \cdot \frac{P}{P_{cr}} + 0.89 \right)$$

It is possible to see that the nucleation border that occurs from the experiments is quite near to the theory correlations (digression of about 5% at the absolute temperature [K]).

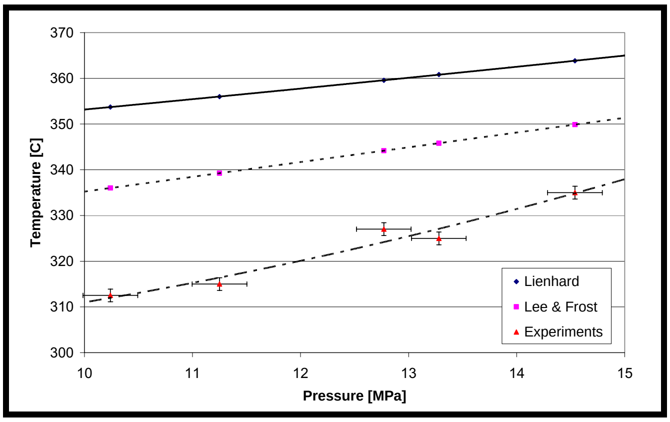

**Figure 4.** Comparison between the nucleation borderline in experiments to theory

*The breaking length of the liquid jet*

The breaking length L was defined as the maximal length that performs the condition that the jet outlines are parallel as shown in fig.(5). We saw that increasing the temperature and the pressure results an increasing of the breaking length. The extreme pressure drop results a high speed water jet, for the typical pressures that measured in our experiments it is possible to assume that the water velocity in the output section is pretty close to the sound velocity of a saturated liquid at the matching temperature. Fig.(6) illustrates the water speed of sound as a function of the pressure and the temperature, we can see that in the liquid zone the speed of sound is decreasing with the increasing of the temperature. In fig.(7) it is possible to see the dependence of the breaking length on the liquid velocity, the breaking length decreased as the liquid velocity is increased. Those results fit the Lefebvre (1989) theory, according to Lefebvre in the fully developed spray region (that fits to our experiments) the breaking length decreased exponentially with the velocity increasing. We can associate this fact to the cavitation phenomenon, the enhancement of the liquid velocity results larger whirling vapor zones near the orifice walls that produce larger interruptions for the jet stability so the breaking length is decreased.

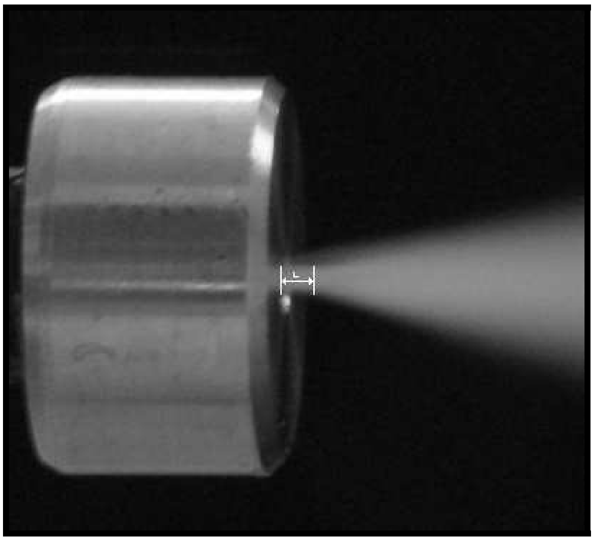

**Figure 5.** The breaking length

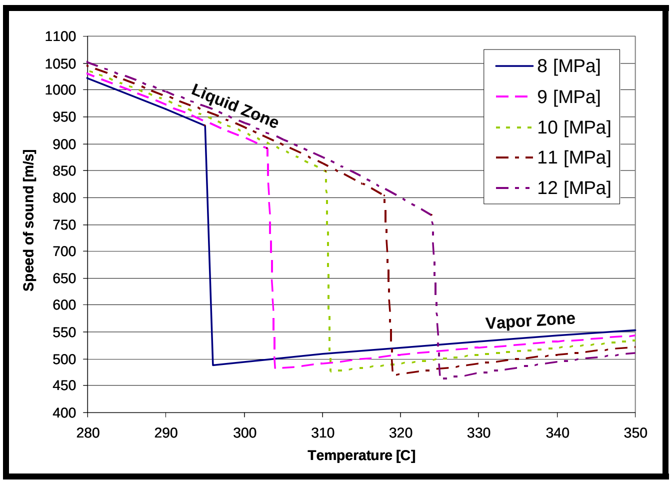


**Figure 6.** Water speed of sound as a function of the pressure and the temperature

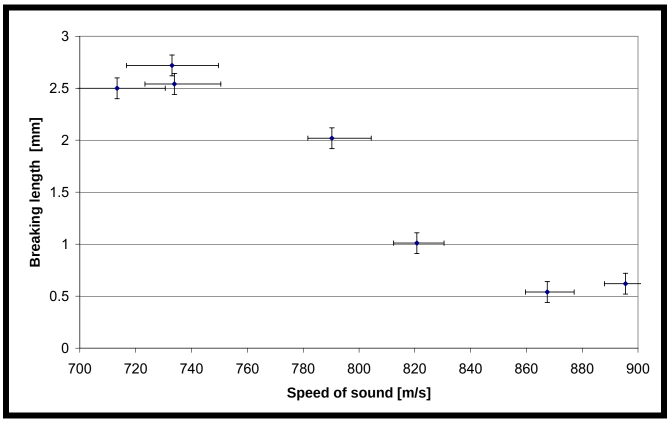


**Figure 7.** The breaking length dependence on the liquid velocity

*The spray angle*

One more element that has been examined is the spray angle . In additional experiments series a few spray angles was measured, all of them in the case of homogeneous nucleation regime. The spray angle is defined by the two obstructing outlines that include the whole spray between them. Fig.(8) reveals the different spray angles and obstructing outlines, as taken from the experiments results for deferent initial condition of the superheated water. In fig.(9) and (10) we can see the spray angle change as a function of the initial temperature and pressure of the superheated liquid. The spray angle is increased with the enhancement of the liquid pressure and temperature. We can associate this fact with the nucleation rate. According to Carey (1992), the nucleation rate is extremely depend on the superheated liquid temperature so that a little change in the liquid temperature cause an extremely high change in the nucleation rate. Therefore, increasing the temperature results higher nucleation rate that produce larger spray angle. Additionally, the velocity reduce due to the temperature rising cause larger spray angles (reduce of the inertia forces).

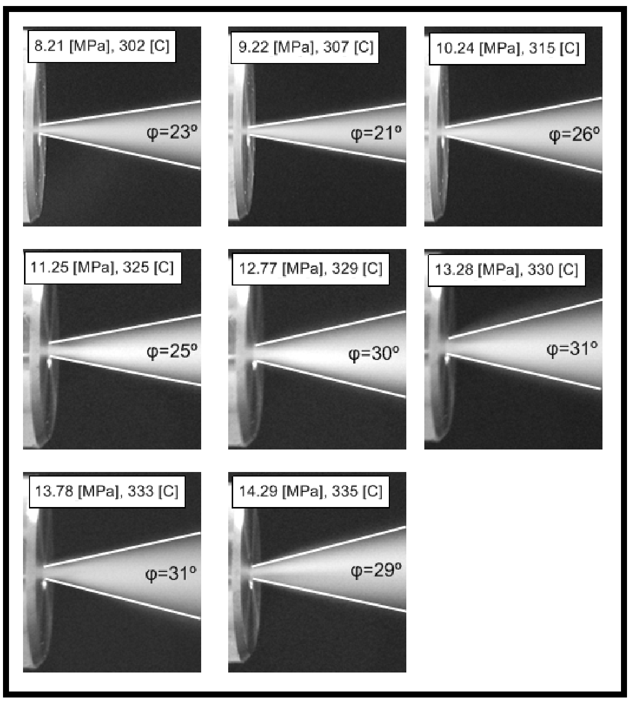


**Figure 8.** The spray angles

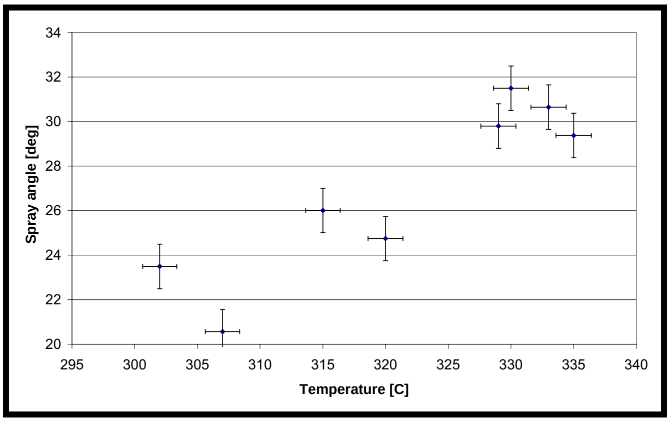


**Figure 9.** The spray angle dependence on the temperature

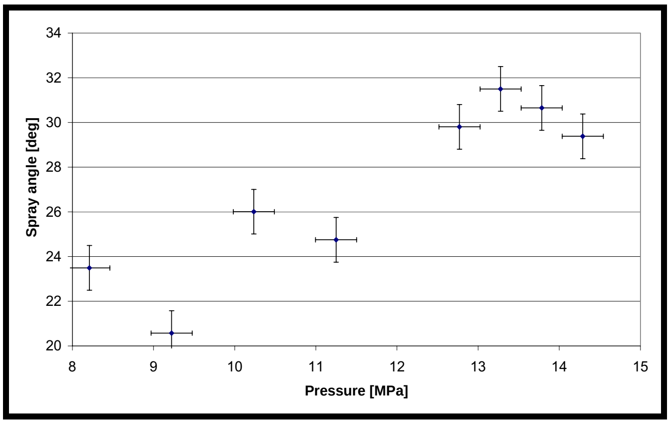


**Figure 10.** The spray angle dependence on the pressure

## CONCLUSIONS

- The borderline between the nucleation regimes is mostly infected by the superheated liquid temperature and pressure.

- The breaking length of the jet is mostly infected by the inertia forces of the liquid witch infected by the liquid temperature.

- lhe spray angle is mostly infected by the liquid temperature and inertia forces.

- The homogeneous nucleation is characterized by smaller spray angles and larger breaking lengths then the heterogeneous nucleation. That means that in the application that requires large spray angles and small breaking length, as internal combustion engines, there is priority to heterogeneous nucleation.

## NOMENCLATURE

| Symbol | Quantity | SI Unit |
|---|---|---|
| L | Breaking length | [mm] |
| P | Pressure | [MPa] |
| T | Temperature | [ºC] |
| φ | Spray angle | [deg] |

| Subscripts | Quantity |
|---|---|
| Cr | Critical |
| Sat | Saturated |
| SL | Superheated Limit |

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