ILASS Americas, 22nd Annual Conference on Liquid Atomization and Spray Systems, Cincinnati, OH, May 2010

The Effect of Flashing on Characteristics of Sprays of Splash-Plate Nozzles

R. Karami*, N. Ashgriz and H. N. Tran
Department of Mechanical and Industrial Engineering
University of Toronto
5 King's College Road, Toronto, ON, M5S 3G8

Abstract

An experimental study of the effect of flashing on sprays of splash-plate nozzles was conducted. The investigation was focused on the effect of injection temperature, pressure and delivery system on flow regime inside the nozzle, breakup mechanism and droplet size. The droplet size and disintegration mechanism were found to be very dependent on injection temperature and the internal flow regime was highly affected by both the temperature and the geometry of the system. Flashing was observed to occur few degrees above the saturation temperature. The droplet size decreased dramatically at the point of onset of flashing in a narrow range of temperature. Further increase of temperature had less effect on droplet size.

*Corresponding author

Introduction

Many nozzles operate at conditions in which the atomizing liquid may go through flash evaporation during the atomization process. If the temperature of the liquid is above the saturation temperature corresponding to the back pressure, a sudden pressure drop in the liquid would result in an abrupt nucleation of vapor bubbles in the liquid. This process is referred to as flashing. The flashing process significantly changes the atomization process by changing both the fluid properties and flow characteristics [1].

The present study is aimed at characterizing the effect of flashing in splash plate nozzles. These types of nozzles are commonly used to atomize high viscosity fluid. In splash plate nozzles a liquid jet impinges on a solid surface, forming a sheet of liquid. The liquid sheet spreads radially and eventually breaks into small droplets. The flashing process changes the breakup process of the sheet. Here we compare the liquid sheet characteristics in non-flashing and flashing conditions for various injection temperatures, pressures (or mass flow rates) and nozzle orifice sizes.

Experimental Setup

Figure 1 shows the experimental setup used in this study. A half-full tank of water was pressurized with compressed nitrogen to a desired value. An electric heater immersed in the tank heated the water. Temperature and pressure of the system were continuously monitored with thermometers and pressure gauges at various locations. The heated water was circulated from the bottom to the side of the tank using a pump to keep its temperature uniform across the tank. Once the water temperature in the tank reached a set point, the heated and pressurized water was fed to a spray nozzle via a pipe. The nozzle was a small, splash-plate type with a diameter of 5mm. The liquid flow rate was controlled using a needle valve and a flow meter. In several experiments, a transparent nozzle made of glass was also used so that the flow inside the pipe could be observed. The entire system was well insulated to minimize heat loss and temperature variation. Figure 1 also shows a sketch of the nozzle used in the experiments.

Experiments were performed at different flow rates and temperatures. Images and videos of the sprays were captured using a high-speed camera (Photron Fastcam) and a DSLR camera (Nikon D300). The liquid spray sheet was illuminated using a high intensity lamp. Depending on the shutter speed and the number of frames per second captured, the intensity of the light was adjusted to obtain the highest clarity possible.

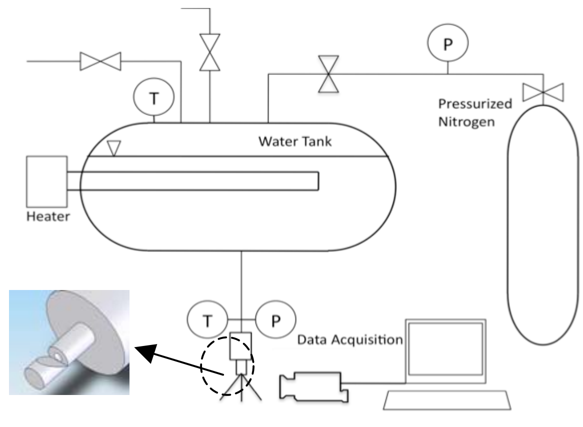


Figure 1. Experimental setup

Sheet Breakup

Figure 2 shows formation of a liquid sheet in non-flashing condition. In this case, instability of waves on the sides of the sheet result in the eventual disruption of the sheet and formation of droplets. This type of sheet breakup is referred to as “rim breakup” [2].

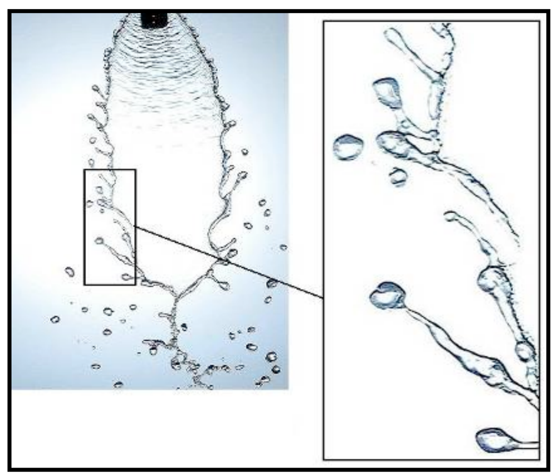


Figure 2. Disintegration of the Sheet in non-Flashing case

Figures 3 and 4 show effect of flashing on the same sheet as in Fig. 2. At few degrees above the boiling point, bubbles are observed inside the pipe and in the sheet. These bubbles disturb the sheet, resulting in the breakup of the sheet before the sheet thinning and ligament formation. Small sheet segments rapidly shrink forming ligaments, which eventually break and generate droplets. The shape of the spray at different temperatures is very different. At even higher temperatures, a fully flashing spray is formed. In this case, no sheet is formed, since the fluid exiting the nozzle is already in two phases prior to impingement on the plate. A web of interconnected ligaments is observed very close to the nozzle exit, which breaks into droplets soon after leaving the nozzle exit. At this temperature the jet velocity is very high and the nozzle is surrounded by a dense fog as a result of abrupt condensation of vapor that makes the picture fuzzy. Although at this temperature both small and large droplets are observed, it will be shown that the average size is reduced significantly.

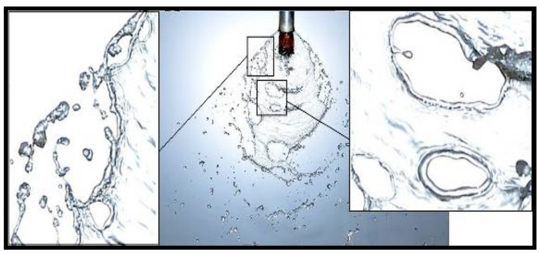


Figure 3. Flashing initiation; at 106C many perturbations in the middle and on the side of the sheet are observed. These perturbations join and break the sheet. Unlike the non-flashing case, the droplets are seen everywhere even close to the nozzle.

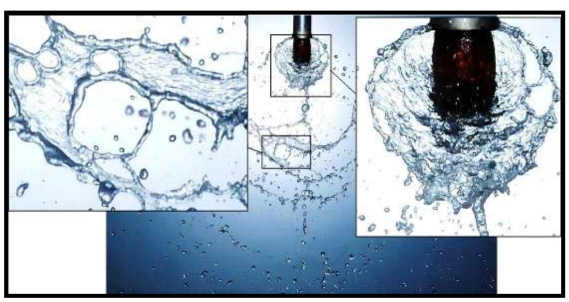


Figure 4. The sheet is already broken at 112C when it emerges from the nozzle. Small pieces of sheet travel downward while shrinking to ligaments. They also carry holes, which speed up the breakup process.

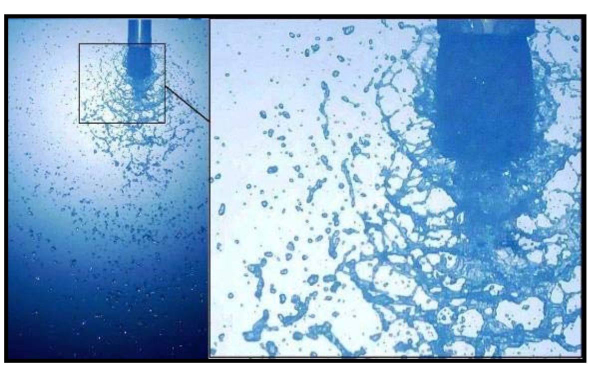


Figure 5. No intact liquid sheet is observed at 116C. At this temperature the nozzle exit is surrounded by a dense interconnected web of ligaments and small droplets. At a very short distance the spray is completely shattered.

Figure 6 compares the characteristics of the liquid sheet formed at different temperatures. As the liquid temperature is increased the breakup mechanism, sheet length, and sheet opening angle change. This sensitivity to temperature starts only few degrees above the boiling point. Above 110˚C the flow is not continuous anymore. The bubble generation in the pipe disconnects the flow frequently.

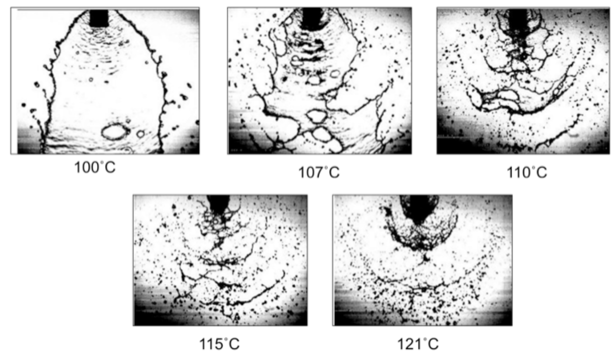
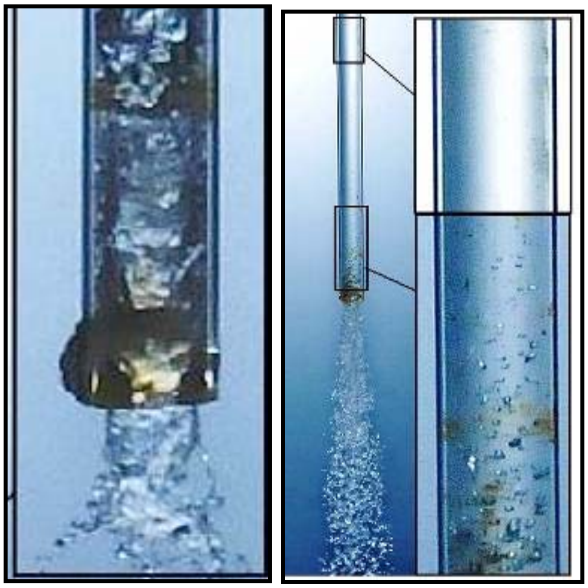


Figure 6. Change in Sheet Disintegration Mechanism, as the Temperature Increases

Internal Flow

The internal flow regime prior to the nozzle exit has a direct effect on the sheet formation and hence sheet disintegration. The internal flow regime depends on the nucleation point inside the pipe. The nucleation point depends not only on temperature, pressure and nozzle size, but also on the geometry of the delivery system. Any disturbances in the delivery system (such as sharp corners, nozzles, valves etc.) may disturb the superheated flow of liquid, and initiate the nucleation process. When the liquid is heated, at certain temperatures nucleation starts forming micro-size bubbles. This temperature highly depends on the solid surface roughness, solid content and also dissolved gas in the liquid. The bubbles are mostly generated at the solid-liquid interfaces or the interface of liquid and released dissolved gas. These bubbles do not grow in size unless the pressure of the liquid is reduced. This may happen at sharp corners or other changes in geometry, or in regions close to the nozzle exit. At this latter region, pressure drops to the surrounding pressure allowing the growth of the bubbles [3].

Figure 7a shows a case in which the flow regime inside the pipe is annular, namely, a liquid film flowing on the inner walls of the tube with a core gas flow [3]. If the system is not disturbed much, the bubbles are mainly formed close to the nozzle exit. Figure 7b shows this case, in which bubbles start to grow very fast close to the nozzle exit (approximately 25 cm/s in diameter) and make the flow turbulent and shatter the jet. The location at which the bubbles start to grow can be changed slightly by changing the pressure. Increasing the injection pressure moves the bubble growth location downstream of the flow [4].



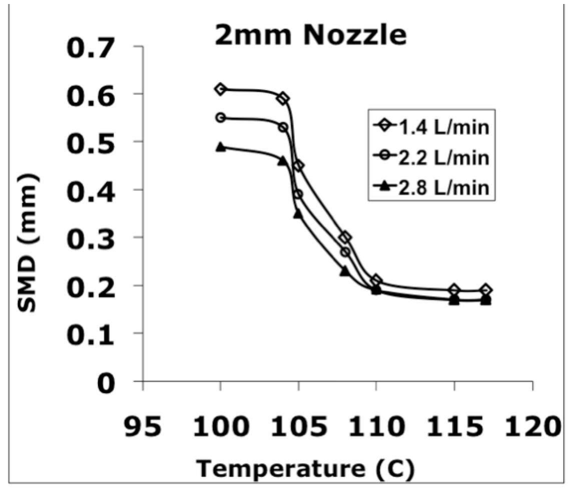
(a) (b)

Figure 7. (a) Annular Flow, (b) Bubbly Flow Close to the Tip of the nozzle

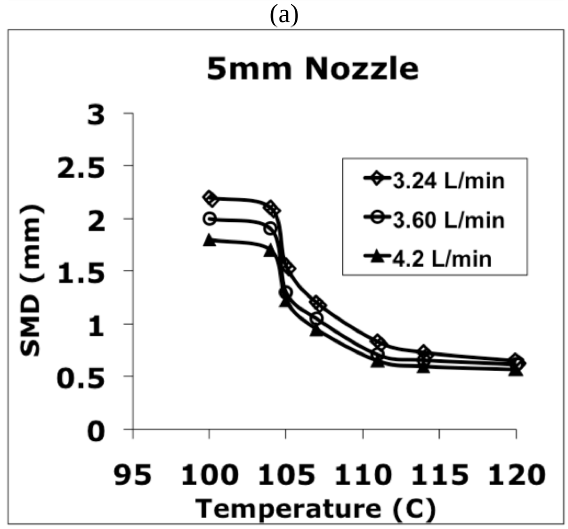
Droplet Size

Figure 8 shows the change in Sauter Mean Diameter (SMD) of sprays formed from a 2 mm and 5mm diameter nozzles, in terms of the initial liquid temperatures. The measurements were made at 5 different temperatures from non-flashing to high flashing conditions at three zones around the nozzle. The onset of flashing results in an abrupt change in droplet size. The major size reduction occurs in a narrow temperature range between 105 to 108 ˚C, which has been reported in the prior literature as well [5]. Increasing the temperature in a non-flashing jet does not reduce the droplet size significantly since changing the temperature only affects the viscosity. In order to change the viscosity enough to see a significant change in droplet size, the temperature should be increased or decreased dramatically. In the present conditions, the droplet size sensitivity to temperature is very low. However, in flashing condition, a slight increase in temperature leads to a significant change in droplet size, especially in flashing temperatures around 106 ˚C.

Figure 9 shows droplets at three different temperatures. These pictures illustrate the change in the number and size of the droplets in a certain zone. As the temperature is increased, higher number of droplets with smaller average size is produced.



(a)



(b)

Figure 8. Droplet Size vs. Temperature for a (a) 2mm Nozzle, and (b) 5mm Nozzle.

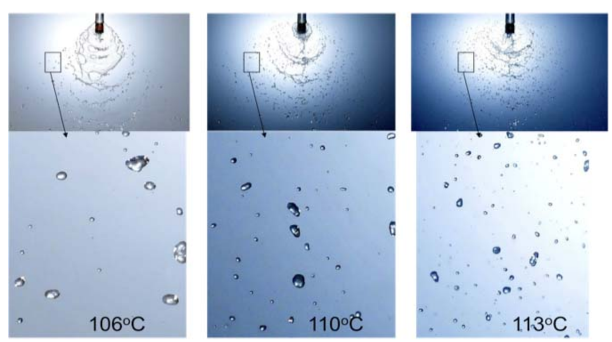


Figure 9. Smaller droplets at higher temperatures

Summary

The observations suggest that increasing the liquid temperature to few degrees above the saturation temperature initiates flashing and completely changes the breakup regime. If the difference between liquid temperature and flashing point is only1-3K, the sheet can be formed but due to slight evaporation the sheet has more perforations, more irregularities on the side and slightly more velocity. Internal flow observations suggest that this is due to low number of bubbles inside the nozzle tube. Increasing the temperature to 4-7K above the flashing point leads to a spray that is not in tact; small liquid sheet segments are observed which break and/or shrink to ligaments and droplets. Slug flow inside the nozzle tube in this temperature causes an oscillatory type of flow in the nozzle exit and hence separate sheet segments. Further increase in temperature makes the sheet completely shattered before impinging on the plate and therefore the liquid sheet is not observed anymore. The flow regime at this temperature is normally annular or wispy annular which due to high velocity and mixing with vapor cannot form an intact liquid sheet.

The initiation point of flashing is highly dependant on flow and delivery system characteristics. Increasing the injection pressure moves the nucleation point towards the nozzle orifice. At very high pressures it was observed that a part of evaporation occurs after the nozzle exit. Increasing the temperature however, takes the nucleation point to upstream of the flow. The geometry of the delivery system is also important in location of bubble formation. If the piping and connections do not disturb the system, the fluid will be delivered to the nozzle in liquid form, however, any irregularity in shape of a connection close to the nozzle can be an initiation point for vaporization and start of a two-phase flow.

Droplet size and velocity are other parameters affected by flashing. Increasing the temperature increases the droplet velocity and reduces the droplet size. When flashing occurs in a nozzle, the droplet size becomes very sensitive to liquid temperature. Although in a non-flashing nozzle the droplet size is affected by temperature too, but below the flashing point the temperature affects the droplet size only by changing viscosity and surface tension, therefore the change in temperature should be dramatic to observe a change in droplet size. However, in flashing condition even 0.5K change in temperature can have considerable effect on droplet size because little change in temperature can generate more vapor and increase the flow velocity and turbulence drastically. Some of the droplets formed in flashing condition are even larger than those of non-flashing sprays but the high number of small droplets reduces the average size. In flashing condition the velocity is increased because of evaporation. Vapor generation decreases the liquid density and due to mass conservation the velocity of liquid is increased.

References

1. Kraft recovery boilers, Adams, Terry N., Frederick, Wm. James, Grace, Thomas M., Hupa, Mikko, Iisa, Kristiina, Jones, Andrew K., Tran, Honghi, (1997). AF&PA, TAPPI PRESS, Atlanta.
2. The Characteristics of Black liquor Sprays, Pasi Miikkulainen, Ari Kankkunen, Colloquium on Black Liquor combustion and Gasification, Utah, USA, May 2003.
3. Liquid-Vapor Phase Change Phenomena, Second edition, Van P. Carey, (2007), Taylor and Francis Group.
4. The Derivation of Relaxation Time Between Two-Phase Bubbly Flow, S. A. Mohammadein, Heat Mass Transfer, 42: 364-369, 2006
5. Flashing liquid jets and two-phase droplet dispersion. Witlox, H., Journal of Hazardous Materials, 142(3), 797-809, 2007.