Leidenfrost study of impacting droplets of n-butanol - water binary mixtures at different impact velocities

1. Introduction

When a drop of liquid strikes a surface heated to a temperature much higher than the boiling point of the liquid, the drop may levitate over the surface. This phenomenon, explained by the instantaneous evaporation and consequent formation of a thermally insulating vapor layer, causes the drop to vaporize at a significantly slower pace than in the absence of such an event. This effect is known as the Leidenfrost effect, named after the German doctor J. G. Leidenfrost, who was the first to describe it. [1] The minimum temperature at which the liquid drop impinging on the heated surface levitates is called the Leidenfrost temperature (LFT) or point (LFP).

As the Leidenfrost effect essentially decreases the rate of heat transfer between the solid and the fluid, it is desirable to delay it in many applications, including spray cooling, spray quenching, thermal management of nuclear fuel power stations [2], extinguishing fire by water sprinklers and cooling blades of turbines.

Various techniques have been employed to increase the Leidenfrost point in different solid-to-liquid heat transfer applications. Specifically, in spray cooling, Leidenfrost temperature has been enhanced by coating the solid surface with an oxide layer resulting in the formation of a porous oxide layer [3], altering the parameters of spray, including the density of water impingement, droplet size, and velocity[4], plasma-activating the coolant water [5], fabricating nano or micro-structures on the surface[6][8], induction of electric field between the hot surface and droplet[12], employing low-frequency vibrations[7] and adding polymers[9], surfactants[10][11] and salt mixtures[13] to coolant water.

Of all these methods, the most lauded is the technique to modify surface texture, as it yields a significant increase in Leidenfrost temperature. However, the method is unsuitable in various applications, including metal processing, where the surface features cannot be altered. To this end, modification of liquid properties provides a viable solution. The addition of high-alcohol surfactants to cooling fluid has been investigated [11] in which bubble coalescence and bubble bursting were proposed to be the reason for the increase in LFP. In that study, the effect of 1-octanol and 2-ethyl-hexanol on the dynamic Leidenfrost effect was explored.

Another study [14] investigated the self-rewetting nature of Water-1.5% Pentanol and Water-3% Butanol and the consequent increase in LFP. The reason proposed for such enhancement was the increase in surface tension with the rise in temperature of these self-rewetting fluids, which lead to surface tension gradients and, thus, the inverse thermal Marangoni convections. These convections were suggested to be the primary reason for the delayed LFP.

The present article focuses on the study of the dynamic Leidenfrost point (T_{DL}) of droplets of n-butanol – water mixtures at different concentrations and impact velocities on a horizontal heated surface.

2. Experimental Setup

The experimental setup is demonstrated in figure 1. A heater plate with precision control from Holmarc Opto-Mechatronics Ltd., India was used in conjunction with a digital temperature controller to heat the substrate to a temperature between 150°C to 220°C where near-constant temperature

conditions were maintained. A square stainless-steel block of dimensions 80mm x 80 mm, attached to a heating element, was used as the test surface. A thermocouple probe of T-type was inserted into the stainless-steel plate to measure the temperature and provide feed to digital hot plate controller, which could maintain constant temperature conditions with an error of ±10°C. A droplet dispensing mechanism with adjustable height and digital controller from Holmarc Opto-Mechatronics Ltd., India, was employed to drop liquid droplets from varying heights, thus providing distinct impact velocities. A micro-syringe attached to the mechanism for releasing droplets was used. A high-speed camera from Photron, UK, was utilized to capture the photographs of droplets impinging on the heated substrate. All experiments were captured at 4000 fps using a 105 mm macro lens from Nikon.
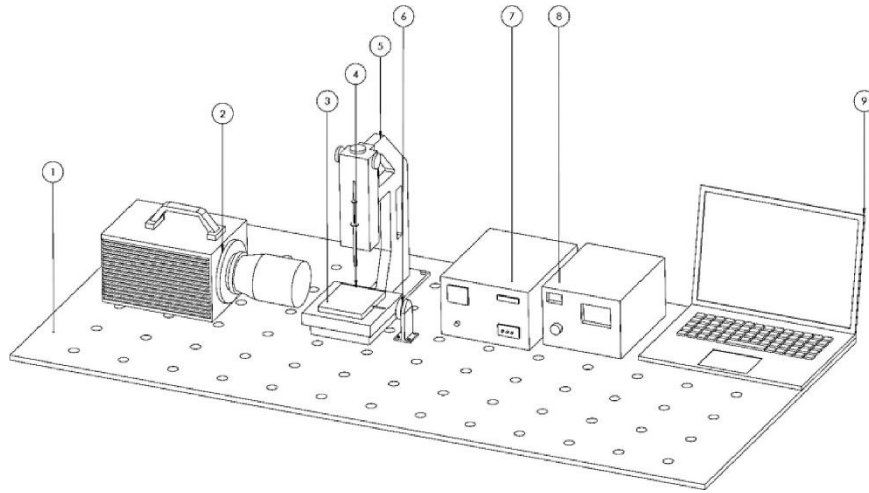

Figure 1 Diagram of experimental setup: (1) Vibration free table-top (2) high-speed camera (3) hot substrate (4) micro-syringe (5) droplet dispensing mechanism (DDM) unit (6) LED backlight (7) DDM and backlight illumination controller (8) hot substrate controller (9) computer for data acquisition and camera control

Different concentrations of n-butanol – water mixture were tested for T_{DL}: 3 % butanol-water (v/v), 5 % butanol-water, 10 % butanol-water, and pure butanol.

3. Results

The spreading dynamics and boiling behavior of impinging droplets at different impact velocities and surface temperatures were captured by a high-speed camera. Figure 2 shows a series of photographs taken during the impingement of droplets of different concentrations and different velocities taken at the Leidenfrost point. The sequence of images shows different stages during droplet impact: primary contact, spreading stage, maximum spread out, retracting, and rebounding. The Dynamic Leidenfrost Point is identified as the minimum temperature at which the drop rebounds from the heated surface without being fragmented. Weber Number (We), a non-dimensional parameter, has been used to characterize the hydrodynamics of impinging droplets at LFP.

$$We = \frac{\rho v^2 D_o}{\sigma_{drop}}$$

Where, ρ = density of liquid/mixture, v = Impact velocity of drop, D_o = Drop diameter, and σ = Surface tension of a liquid (at room temperature and atmospheric pressure).

The various thermophysical properties of test liquids are given in table 1.

Liquid	Density (g/mL)	Surface Tension (mN/m)	Drop Diameter (mm)

	ρ	σ_drop	D_o
Water	0.953	74.35	3.01
Butanol Pure	0.775	22.58	1.34
Butanol 3% (v/v)	0.948	42.10	2.36
Butanol 5% (v/v)	0.944	30.81	2.23
Butanol 10% (v/v)	0.935	23.39	2.07

Table 1 Thermophysical properties of test liquids

With the addition of butanol to water, the surface tension of water decreases, resulting in an equilibrium surface tension of the binary mixture between those of the two. This, in turn, leads to decreasing drop diameter with increasing butanol component. As seen from the table above, the equilibrium surface tension, as well as the drop diameter, are maximum for 3% butanol-water mixture, at ~42.10 mN/m and ~2.36 mm respectively, and the figures are lower for 5% and 10% butanol-water mixture.
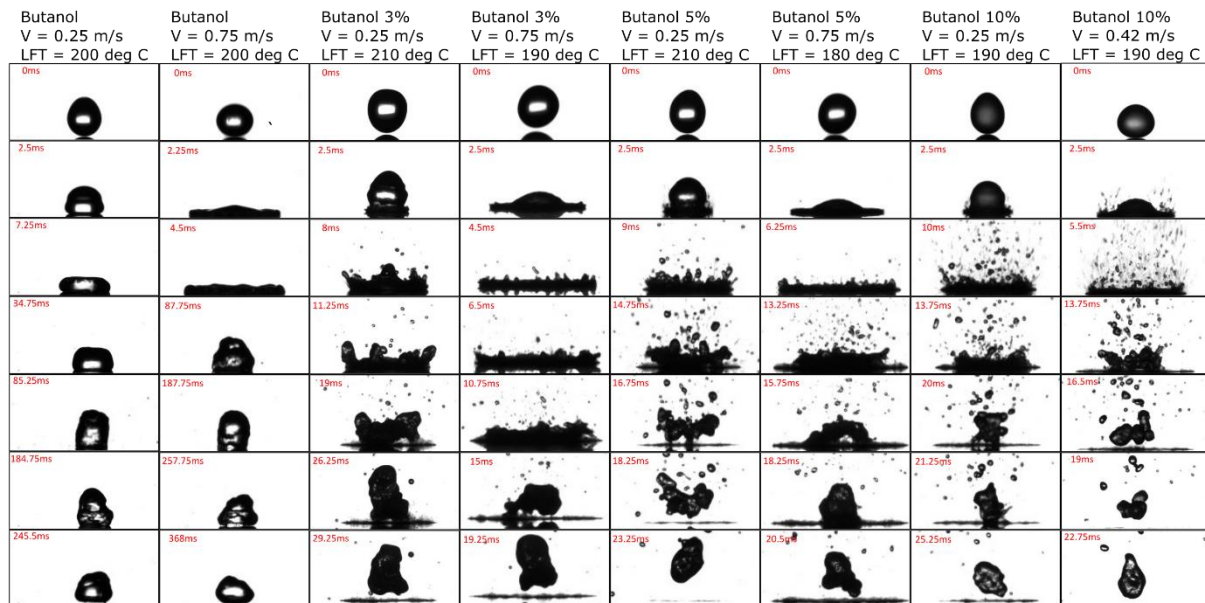

Figure 2 Dynamic behaviour of droplets with various impact heights at their respective Leidenfrost points

As for different liquid droplets impacting the surface at different temperatures, all three parameters - density, surface tension, and drop diameter are different; Weber Number is used as the non-dimensional parameter upon which the Leidenfrost point depends. As seen from Figures 2 and 3, for pure butanol, LFP is found to be virtually independent of the impact velocity at 200^{0}C, and the drops tend not to fragment even at moderately large Weber numbers (~46). Whereas for 3% and 5% butanol-water mixtures, LFP decreases with an increase in Weber number, although the drops start splitting near, We ~ 30. Furthermore, for mixtures with higher butanol content (5% onwards), numerous tiny droplets are ejected from the droplet when impacting the heated surface marking the

regime of spraying film boiling. For the 10% butanol-water mixture, the tendency to fragment is very high, and the droplets split at Weber Number ~ 15.

Impact Velocity (mps)	LDT for different liquid (binary mixture) °C				
	Water	Pure Butanol	Butanol 3%(v/v)	Butanol 5%(v/v)	Butanol 10%(v/v)
0.25	240	200	210	210	190
0.42	240	----	200	200	190
0.50	240	200	200	200	*Splitting*
0.60	240	----	200	190	
0.75	220	200	190	180	
1.00	*Splitting*	200	*Splitting*		

Table 2 Dynamic Leidenfrost Temperature (T_{DL}) of butanol-water mixtures at different impact velocities of droplets (Temperature Error: ±10 °C)

Mixture	D_{max} (mm)	Ambient Temp.	D_{max} (mm)	Boiling Temp. (°C)	D_{max} (mm)	LFT - 20°C	D_{max} (mm)	LFT - 10°C	D_{max} (mm)	LFT
Water	6.077	25	5.816	100	6.653	220	5.55	230	4.871	240
Pure Butanol	5.037	25	4.904	117	3.529	180	2.987	190	3.128	200
Butanol 3%(v/v)	4.900	25	5.994	101	7.733	190	6.220	200	4.860	210
Butanol 5%(v/v)	4.965	25	6.276	102	4.891	190	6.201	200	5.156	210
Butanol 10%(v/v)	5.107	25	6.505	105	7.868	170	6.104	180	5.427	190

Table 3 Maximum Spreading Diameter of butanol-mixtures at different temperatures and impact velocity = 0.25 mps

Mixture	D_{max} (mm)	Ambient Temp.	D_{max} (mm)	Boiling Temp. (°C)	D_{max} (mm)	LFT - 20°C	D_{max} (mm)	LFT - 10°C	D_{max} (mm)	LFT
Water	5.329	25	6.825	100	7.086	220	6.465	230	6.478	240
Pure Butanol	5.167	25	5.297	117	4.301	180	2.458	190	2.345	200
Butanol 3%(v/v)	5.363	25	6.123	101	7.090	180	7.190	190	6.332	200
Butanol 5%(v/v)	5.438	25	6.371	102	6.328	180	6.596	190	6.441	200
Butanol 10%(v/v)	5.628	25	6.549	105	6.963	170	6.018	180	6.140	190

Table 4 Maximum Spreading Diameter of butanol-mixtures at different temperatures and impact velocity = 0.42 mps
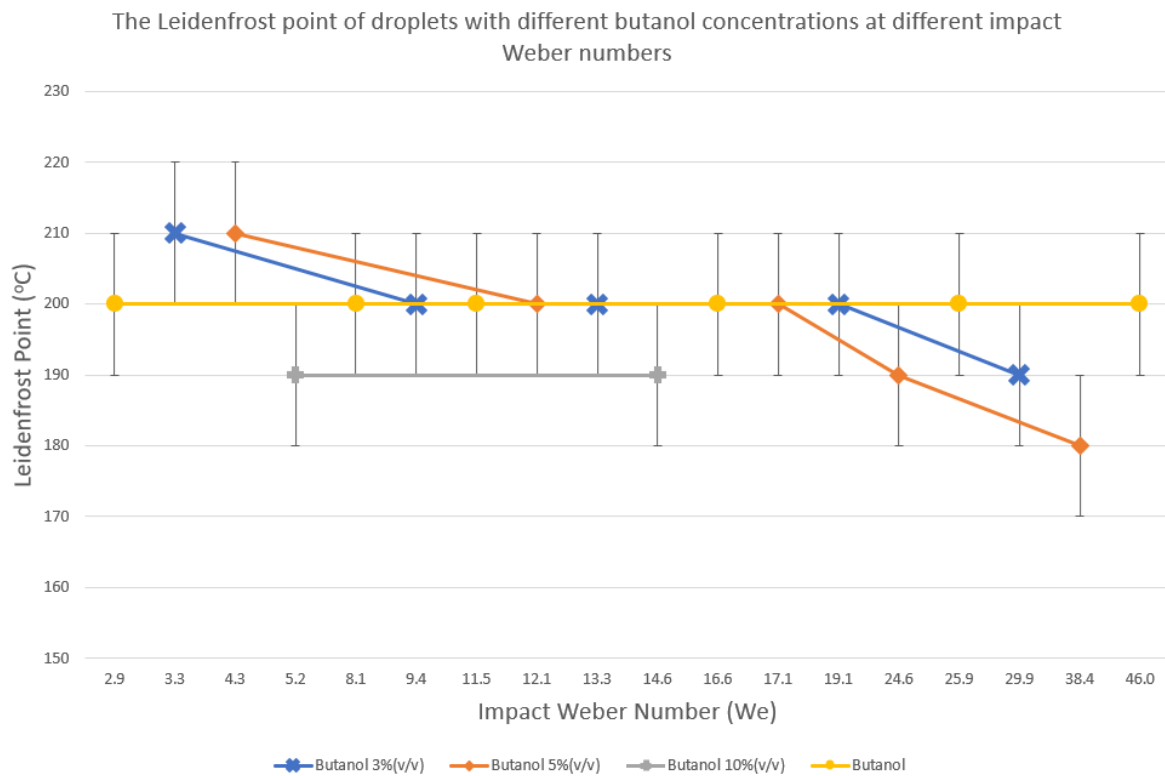

Figure 3 Dynamic Leidenfrost point variation over Impact Weber number for different concentrations of butanol-water mixture

4. References

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