Air Atomized Spray with Additives: A Novel Cooling Methodology for the Development of Nanosteel

A thesis submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology
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Submitted
by
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of

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CERTIFICATE

This is to certify that the project report entitled **"Air Atomized Spray with Additives: A Novel Cooling Methodology for the Development of Nanosteel"** submitted by Mr. **Rashmi Ranjan Behera, Roll No: 111CH0062** in partial fulfilment of the requirements for the award of B.Tech Degree in Chemical Engineering at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the report has not been submitted to any other University/Institute for the award of any Degree.

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ABSTRACT

The effect of varying liquid-solid contact angle on the evaporation time of a single droplet of water deposited on a (AISI-304) steel surface is studied. Mathematical modelling for the evaporation life time of a water droplet added with additives is done. Conventional cooling methodology cools at the rate of around $30^{o}C$ which is not sufficient enough for the production of Nanosteel. Contact angle is varied in experiments by adding varying amounts (500, 1000 and 1500 ppm) of surfactant, salt and alcohol to the water. The contact angle is measured by Goniometer. Reduction in the contact angle results in increase of the contact area between the droplet and solid surface. Reduction in the contact angle also reduces droplet thickness, enhancing heat conduction through the droplet. Both the effects increase the droplet evaporation rate. Reduction in droplet evaporation life time is achieved by varying the contact angle from 90^{0} to 49^{0}. Different types of additives were added to water and their effect on the contact angle was calculated.

Key words- Nanosteel, water droplets, Contact angle, additives

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NOMENCLATURE

m = Mass of the plate (kg)

ṁ = Mass of the droplet (kg)

C_p = Specific heat of the plate (J/kgK)

T = Temperature of the plate (K)

T = Time (s)

h = Heat transfer coefficient of (AISI-304) stainless steel (W/m^2K)

A = Surface area of the plate (m^2)

σ = Stephan-Boltzmann constant (W/m^2K^4)

F_{12} =View factor

^0C = Degree Centigrade

CA =Contact angle (^{0})

Chapter 1

1: Introduction

Steel has long been the backbone of civilization. Nanosteel is nano-structured high strength alloy. It forms amorphous microstructures with grain and phase sizes refined to a nanoscale. The available methods for production of nanosteel are:

(i) NdYAG pulsed laser irradiation
(ii) Mechanical alloying
(iii) Thermomechanical treatment
(iv) Severe plastic deformation
(v) Surface mechanical attrition
(vi) Annealing
(vii) Arc discharge method

Thermo mechanical treatment method is of a chemical engineers interest. In the thermo mechanical process microstructures are formed by hot rolling and subsequent cooling. Events like precipitation and hardening are at the nanoscale level of control. The smaller becomes the grain size the harder becomes the steel. To achieve very small grain size we need to do fast cooling. The conventional laminar cooling system produces slow cooling rate of around 30^0c – 50^0c which is not adequate for the production of high tensile strength steel. The biggest challenge for achieving high cooling rate at high surface temperature is the Leidenfrost phenomenon.

One of the most effective ways of cooling a hot solid surface is to spray it with liquid droplets. Water sprays can be widely used in fire suppression; Efforts to maximize the efficiency of spray cooling have led to the formulation of models that can predict heat transfer from a hot surface to an impinging spray. Several experimental studies have been carried out to observe droplet evaporation.

Thorough knowledge about boiling heat transfer is required in understanding the transfer of heat between the coolant and test surface from which high amount of thermal energy is extracted. To achieve effective cooling some surfactants are added to the water. Surfactant added water is more effective because it makes better contact with the surface than that of pure water and leads to higher wettability of water on the impinged surface. With addition of surfactant the splashing and bouncing behaviour of the water gets minimized. The final mechanical properties of steel can be altered by controlling the cooling rate between 900^0 C and 600^0 C range on the ROT of a hot strip mill to form the desired microstructure [7].

In the case of air atomized spray cooling fine water droplets are sprayed by using compressed air on the surface to be cooled.

A study of effect of the contact angle on droplet evaporation is very important in formulating accurate models and in putting forward the strategies to improve the cooling efficiencies by enhancing surface wetting [2]. Using both numerical modelling and experiments the effect of changes in contact angle on heat transfer is examined during evaporation of water droplets on a hot surface [2].

Chapter 2

2.1: Literature survey

Evans and di Marzo [5] suggested a model that can be applied to droplets evaporating on a high temperature thermal conductive surface below the temperature that is desired to initialize nucleate boiling. The solid surface temperature was assumed to be constant during water droplet evaporation. The shape; of a droplet deposited on a surface was assumed to be that of a spherical cap, whose geometry is completely specified. The radius of the surface area wetted by the deposited droplet is termed as the spread factor. The assumption that the steel-water droplet contact diameter is constant cannot always be accurate.

Receding contact angle is the minimum contact angle beyond which there will be no more reduction in contact angle. Once the receding contact angle has been reached the contact angle remains constant (144 S. Chandra et al) [2]. In the model it is assumed that the contact angle remains constant during the evaporation process, which is an perfect description of the last stage of droplet evaporation after the receding contact angle have been reached.

The contact angle may also get affected by incident thermal radiation upon the droplet; di Marzo et aL [2] found that heating and reduction of the surface tension of the water droplet happens because of the absorbance of infrared radiation on the surface of an evaporating droplet. This is why droplets spread out more which in turn increase the liquid-solid contact area and decrease the droplet evaporation time. Such effects are significant for modelling fast cooling by water droplets.

It is known that the addition of surfactant reduces the surface tension, this addition drastically increases the fast cooling capabilities of the water droplet. Studies have shown that the addition of a additives or a wetting agent lowers the volume of water required to reduce the temperature of the plate. It has been 60 years since the use of wetting agents but little information is available in open literature about the mechanism by which surfactant enhances heat transfer from a hot surface to impinging droplets in water sprays. The dissolved surfactants makes the droplets spread out more, increasing the liquid-solid contact area which in turn enhances surface cooling.

Chanra et al [2] used stainless steel as the plate surface because it resists oxidation when heated and can be cleaned easily afterwards. Stainless steel has a relatively low thermal conductivity. Chandra et al reduced the contact angle from 90 ° (the equilibrium contact angle value for pure water) to 20 ° by adding different kinds of surfactant to the water.[2]

Ravikumar et al[8] studied the effect of different type of surfactants and the jet height on cooling of a hot steel plate and found that for a particular surfactant type, up to a particular concentration of the surfactant the surface heat flux and cooling rate of surfactant added increase and further increase in concentration of surfactant results in decrease in the heat flux and cooling rate. Ravikumar et al [8] also found that among all the varieties of surfactants present, nonionic surfactants are the best because they give high heat transfer rate at low surfactant concentration.

The splashing behaviour of water droplets on solid surfaces was studied by Worthington [10]. He concluded that with lower surface tension the conversion of impact energy into radial flow on the surface tends to vary inversely with surface tension. Higher surface tension initiates radial flow with a high upward velocity component.

Bhunia and Lienhard [1] suggested that the liquid jets undergoes splashing, this results in breaking away of the spray of the droplets from the liquid surface. This splashing of liquid distorts the effectiveness of cooling. In turbulent jets, liquid fluctuations in pressure occurs which causes disturbance due to which splashing happens. The point at which disturbances become very high, the waves break into smaller a droplet which gets expelled from the surface resulting in splashing. The liquid droplets are stable at small disturbances and unstable at large disturbances. Splashing is a nonlinear phenomenon. For the case of laminar impinging jets, the disturbance is due to the capillary instability. The fraction of liquid mass splattered into the boundary of the surface gets increased with the increase in jet height.

Jha et al [9] studied the ultrafast cooling rate in a hot steel plate by an air-atomized spray with different surfactant additives [9] and concluded that with the increase of surfactant concentration surface tension and contact angle will decrease. Jha et al [9] also found that the droplet width increases with increased concentration in the case of surfactants. This results in increased contact area for heat transfer. For anionic surfactant, increase in viscosity is encountered with increasing concentration; on the contrary for non-ionic and cationic surfactant viscosity tends to decrease with increase in concentration. A surfactant microlayer increases the wettability of the surface and makes evaporation of coolant faster**.** The heat flux and cooling rate increase with increase in concentration up to certain level. Beyond the optimum concentration level, excessive foaming occurs which results in decrease in heat flux.

Sinha et al [9] studied the experimental effect of spray inclination on ultrafast cooling of a hot steel plate and found that for the cooling of AISI 304 steel plate using pure water the cooling rate and critical heat flux increase with an increase in spray inclination up to an optimum angle of 30^0[9]. The reason behind this is the increase in spray impact area as well as the effective rolling of droplets. As inclination goes on increasing up to 60^0, decrease in the heat transfer is being observed. This is plausible reason behind this is that at high spray inclination, a stable water film gets developed on the test surface due to which the droplets slip effectively instead of rolling on the surface. This slippage effect decreases the contact time of the droplet which results in decrease in heat removal rate. In the case of surfactant added water spray cooling, the cooling rate decreases continuously when the spray inclination is increased from 0^0 to 60^0.The reason behind this is the addition of surfactant decreases the surface tension. Lower inclination of spray increases the slippage effect of droplets from the surface. When surfactant is used the contact time of spray becomes less compared to that of pure water as surfactant increases the rate of formation of liquid film.

Cornet & Hermann [10] investigated on the ultra-fast cooling and suggested a definition for ultra-fast cooling. According to this definition when the product of the thickness of the plate and the surface temperature on the plate crosses 800 ultra-fast cooling is said to be achieved.

2.1: Advantages of spray cooling

(i) Air atomized Spray cooling produces uniform cooling.

(ii) At the time of air atomized spray cooling high volumetric flow of air sweeps away the partially evaporated droplets by this film boiling can be prevented.

(iii) The heat transfer coefficient in air atomized spray cooling is 3 times higher than conventional spray cooling.

2.2: Objectives

Based on the aforesaid literature review, the followings are the current objectives:

(i) To study the effects of different types of additives on the droplet life time

(ii) Development of droplet evaporation model in the film boiling regime

Chapter 3

3: Materials and Methods

3.1: Sample preparation

Samples were made with volume of each sample 100 ml. Three different types of additives were used. Three different samples of three different surfactant concentrations were prepared. The additives used are Sodium dodecyl sulphate, Ethyl alcohol, Sodium chloride.

Sea water was collected from the Bay of Bengal at Puri. Samples were collected 4kms off the sea shore. It was made sure that the sea water has very less amount of sand particles and dirt.

Samples of 500 ppm, 1000 ppm and 1500 ppm Sodium dodecyl sulphate were prepared. 500 ppm Sodium dodecyl sulphate was made by mixing 0.05 g of Sodium dodecyl sulphate in 100 ml of distilled water. !000 ppm solution was made by adding 0.1 g of Sodium dodecyl sulphate in 100 ml of distilled water. A solution of 1500 ppm was made by adding 0.15 g of Sodium dodecyl sulphate in 100 ml of water.

Samples of 500 ppm, 1000 ppm and 1500 ppm Sodium chloride solution were prepared. 500 ppm Sodium chloride solution was made by mixing .05 g of Sodium chloride in 100 ml of distilled water. 1000 ppm solution was made by adding 0.1 g of Sodium chloride in 100 ml of distilled water. A solution of 1500 ppm was made by adding 0.15 g of Sodium chloride in 100 ml of water.

Samples of 20% v/v, 40% v/v and 60% v/v Ethyl alcohol solutions were prepared. 20% v/v Ethyl alcohol solution was prepared by adding 20 ml of ethyl alcohol in a 100 ml tube using a pipette afterwards filling the tube up to 100 ml mark with distilled water. 40% v/v Ethyl alcohol solution was made by adding 40 ml Ethyl alcohol and then filling the rest of the space with distilled water. Similarly 60% v/v Ethyl alcohol solution was made by filling the 100ml tube up to 60 ml mark and then filling the rest of tube with distilled water.

All the samples were collected in 50 ml centrifuge tubes. The samples were shaken thoroughly to achieve better mixing and were kept in master stand. The concentrations of the sample have been kept below the critical micellar concentration of the surfactant.

3.2: Surface tension measurements and droplet contact angle measurements

By using Surface Tension meter, the surface tensions of the aforesaid solutions were measured and with the help of a Goniometer contact angles were also calculated. For each sample, measurements were taken thrice and the average values of the measurements have been presented in the results and discussion section.

Figure -1: Photograph of the Goniometer

Chapter 4

4: Results and Discussions

Surface tension is the force exerted by the molecules present in the bulk fluid on that of the molecules present on the surface of the fluid. It is a surface phenomenon and it can be changed by changing the followings additives which are added to the water droplets for the fast evaporation.

(i) Surfactant concentration
(ii) Salt concentration
(iii) Alcohol concentration

In the present study, Sodium dodecyl sulphate as surfactant, Sodium chloride as salt and Ethyl alcohol as alcohol have been used. By using a surface tension meter, surface tensions at the various concentrations of the aforesaid additives were measured and the obtained values have been presented in Table.1.

4.1: Influence of surfactant and salt concentrations on surface tension

Table.1 depicts that with increase in surfactant concentration and alcohol concentration surface tension of the resultant droplet shows a decreasing trend. The dissolved surfactant in the water droplet decreases the attractive force on the surface as a result the surface tension decreases. However, the dissolved salt increases the surface tension by increasing the attractive force on the surface.

Table-1: Influence of surfactant and salt concentrations on surface tension

Sample number	Description of the sample	Surface tension (newton/metre)×10^{-3}
1	500 ppm Sodium dodecyl sulphate	55
2	1000 ppm Sodium dodecyl sulphate	52
3	1500 ppm Sodium dodecyl sulphate	46
4	500 ppm Sodium chloride	78
5	1000 ppm Sodium chloride	82
6	1500 ppm Sodium chloride	87

4.2: Effect of surface tension on the contact angle of the water droplet

Surface tension directly affects the contact angle. The literature reveals that droplet contact angle shows a decreasing trend with increasing surfactant concentration. The same trend lines have also been observed in the current case (Table-2).

Table-2: Effect of surface tension on the contact angle of the surfactant and salt added water droplets

Sl No	Description of the sample	Surface tension (newton/metre) x10^{-3}	Contact angle (^{0})
1	500 ppm Sodium dodecyl sulphate	55	71.95
2	1000 ppm Sodium dodecyl sulphate	52	59.55
3	1500 ppm Sodium dodecyl sulphate	46	49.65
4	500 ppm Sodium chloride	78	72.7
5	1000 ppm Sodium chloride	82	80
6	1500 ppm Sodium chloride	87	84

4.3: Variation of contact area with contact angle

The dissolved surfactant in the water droplets enhances the wettability characteristics and as a result droplet spreads more on the solid substrate during the deposition. But, the reverse case has been observed in the case of salt added water droplet deposition on a solid substrate (Table-5). In addition to the above, the diameter, contact area and the contact angle of the alcohol added water droplet increase with the increasing concentration.

Although the salt added water droplet shows a decreasing contact area with the increasing concentration, the reverse trend has been noticed for the case of sea water (Table-3).

Table-3- Effect of contact area on contact angle

Sl No	Description of the sample	Diameter of the droplet (metre)$\times 10^{-2}$	Area of the droplet (metre)$^2\times 10^{-4}$	Contact angle (^{0})
1	500 ppm Sodium dodecyl sulphate	3.078	7.44	71.95
2	1000 ppm Sodium dodecyl sulphate	3.386	9	59.55
3	1500 ppm Sodium dodecyl sulphate	3.494	9.588	49.65
4	500 ppm Sodium chloride	2.88	6.51	72.7
5	20% v/v Ethyl alcohol	2.64	5.47	74.6
6	40% v/v Ethyl alcohol	2.76	5.98	73.5
7	60% v/v Ethyl alcohol	3.281	8.1	63.35
8	Seawater	3.311	8.61	59.66

The images obtained from the Goniometer for the various additives at the different concentration have been shown in Fig 2(a-g).

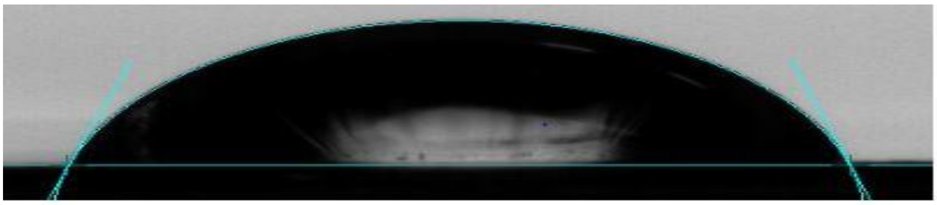

Figure-2(a): 500 ppm SDS CA-71.95

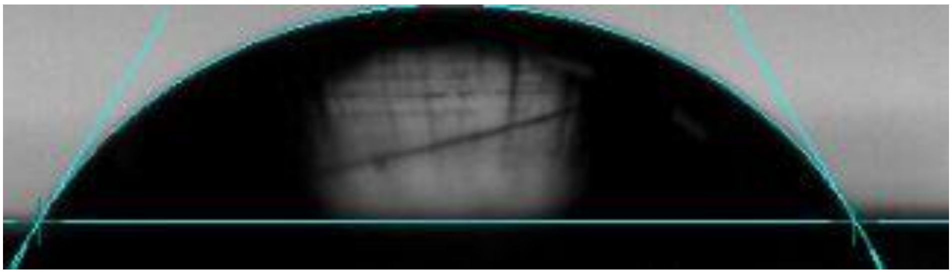

Figure-2(b): 1000 ppm SDS CA-59.55

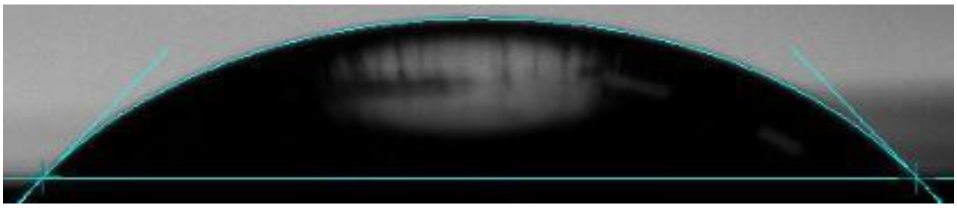

Figure- 2(c): 1500 ppm SDS CA-49.65

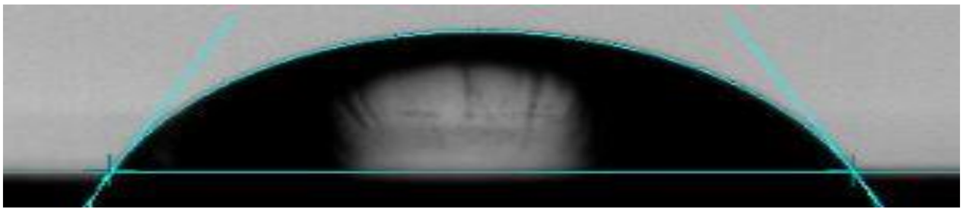

Figure-2 (d): 60% V/V Ethyl alcohol CA-63.35

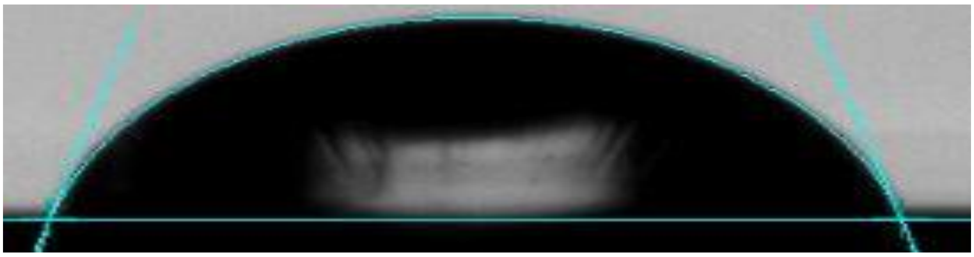

Figure-2(e): 40% v/v Ethyl alcohol CA 72.7

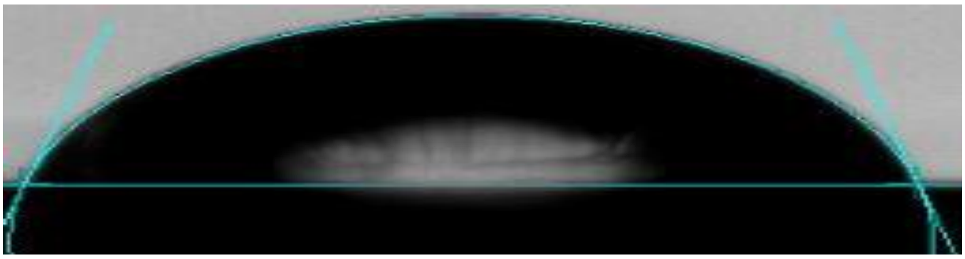

Figure-2 (f): 20% v/v Ethyl alcohol CA 74.6

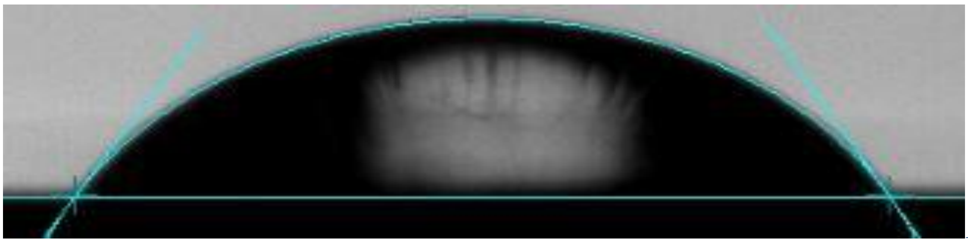

Figure-2 (g): Sea water

4.4: Development of droplet evaporation model for fast cooling operation

For the development of mathematical model several assumptions are being considered

(i) Heat transfer occurs only by the mode of convection and radiation

(ii) The whole surface of the hot steel plate is uniformly cooled

(iii) K, ρ, Cp, and h are not the function of temperature

4.4.1: The temperature distribution model on the surface of the plate

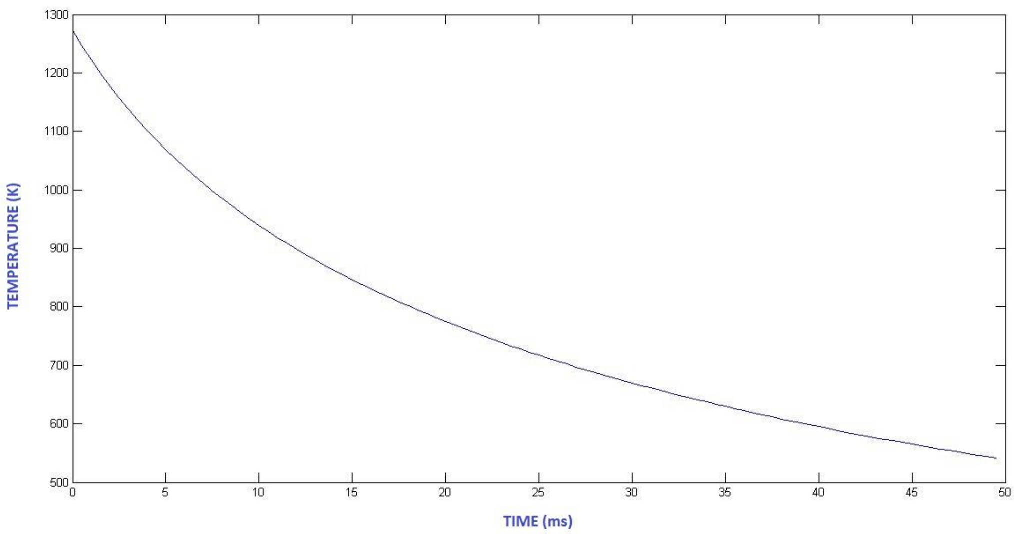

Figure-3: Temperature profile of the hot plate for the fast cooling operation

The mathematical model for cooling of hot steel plate (AISI-304) using water droplets kept at a temperature of 298K has been presented in equation 1. Bu using MATLAB the below developed model has been solved and the obtained temperature profile has also been presented in Figure. 3.

$$-\dot{m}Cp\frac{dT}{dt} = hA(T-T_0)+\sigma AF_{12}(T^4-T_o^4) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

4.4.2: Droplet evaporation model

The mathematical model for calculation of salt and surfactant added water droplets at various concentrations have been presented in equation 2. For this model, the assumptions have been given in section 4.4.

$$-[\dot{m}\lambda + \dot{m}Cp\frac{dT}{dt}] = hA(T-T_0) + \sigma AF_{12}(T^4-T_o^4) \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Case-1: SDS

(A) For 500 ppm (A=7.44×10⁻⁴)

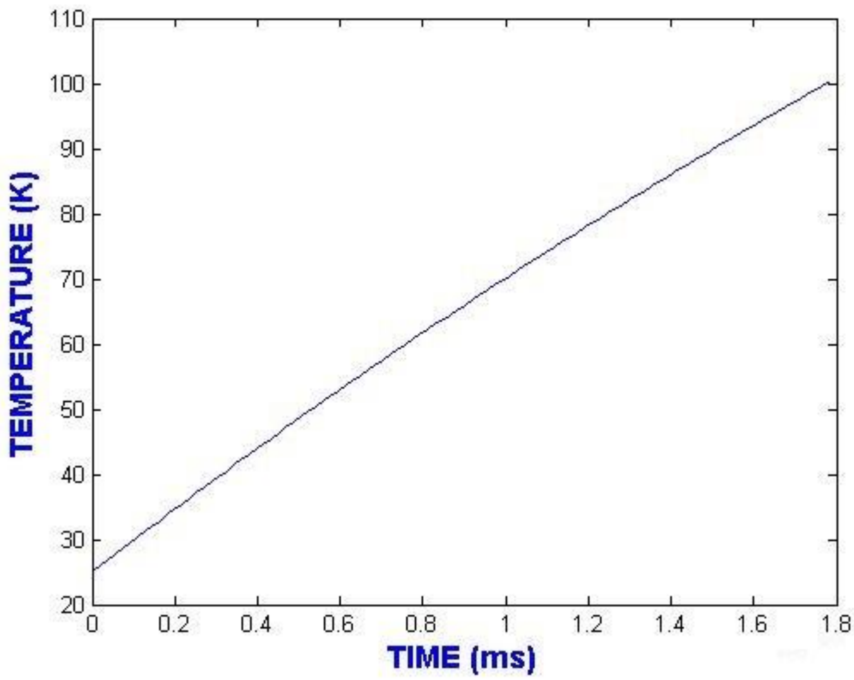

Figure-4: Droplet life time of 500 PPM SDS

The life time of surfactant added water droplet with respect to time has been shown in (Figure 3). From the figure:-4, the droplet evaporation time is found to be 1.78 ms.

Furthermore, the droplet life times of 1000 PPM and 1500 PPM cases have been given in Figures 5 and 6, respectively.

(B) For 1000 ppm SDS ($A = 9\times10^{-4}\ m^2$)

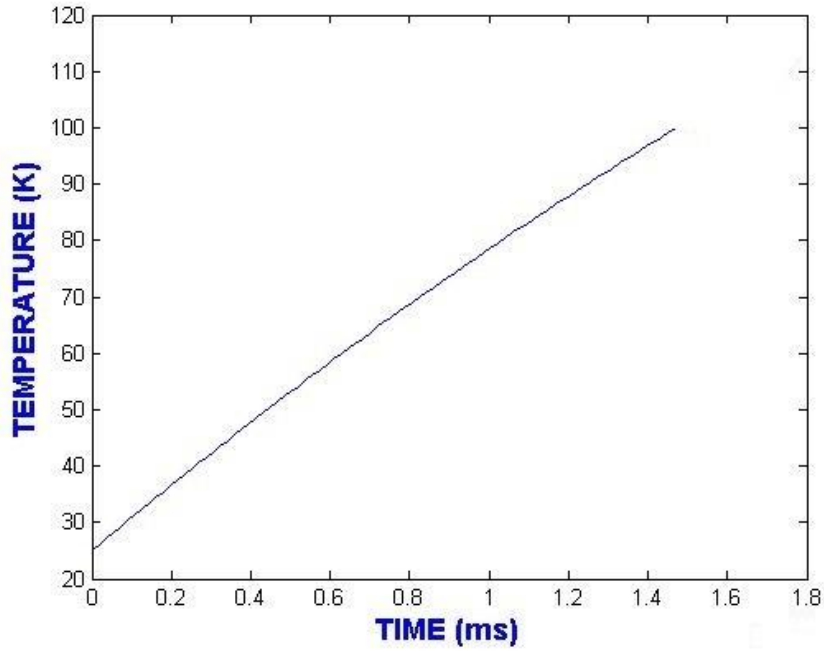

Figure-5: Droplet life time of 1000 PPM SDS

(C) For 1500 ppm SDS ($A = A=9.588\times10^{-4}$)

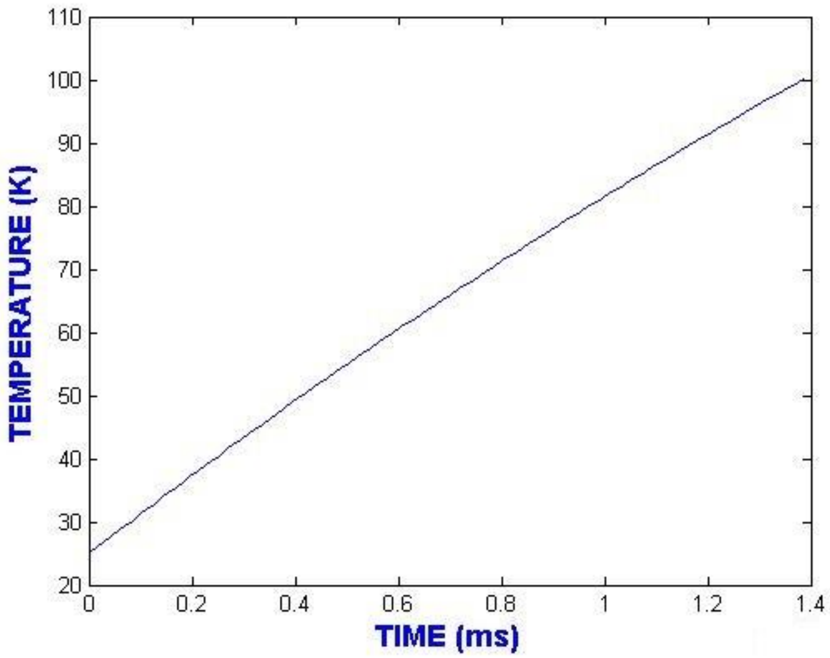

Figure-6: Droplet life time of 1500 PPM SDS

Case-2:- NaCl

(A) ***For 500 ppm NaCl (*A = 6.51×10^{-4} m^{2})**

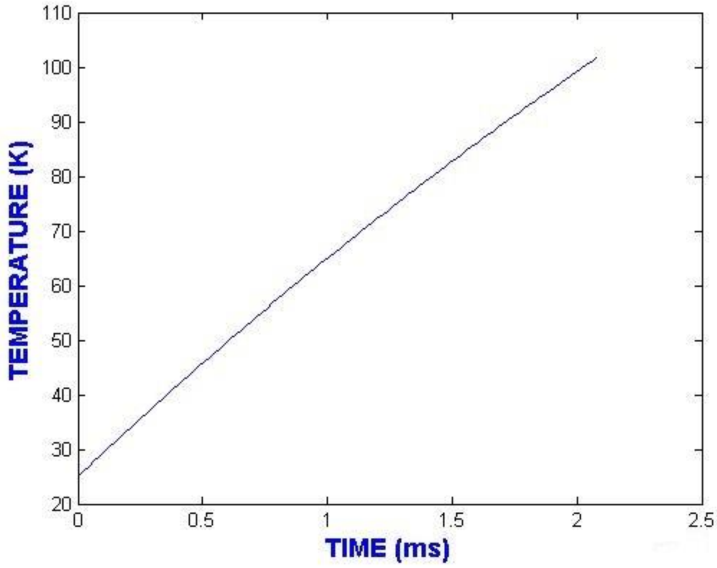

Figure-7: Droplet life time of 500 PPM NaCl

From the figure-7, the evaporation time of salt added water droplet is found to be 2 ms. This droplet evaporation time is higher than the surfactant added water droplet case.

Case-3:- (Alcohol)

(A) ***For 20%* C_2H_5OH *(*A=5.47×10^{-4})**

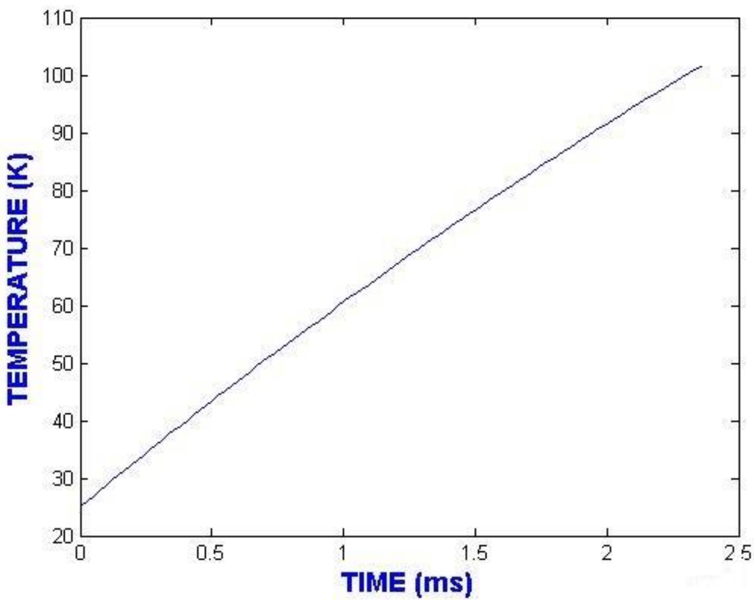

Figure-8: Droplet life time of 20 % C_2H_5OH

(B) ***For 40%*** **C_2H_5OH** ***(***A=5.98×10^{-4})

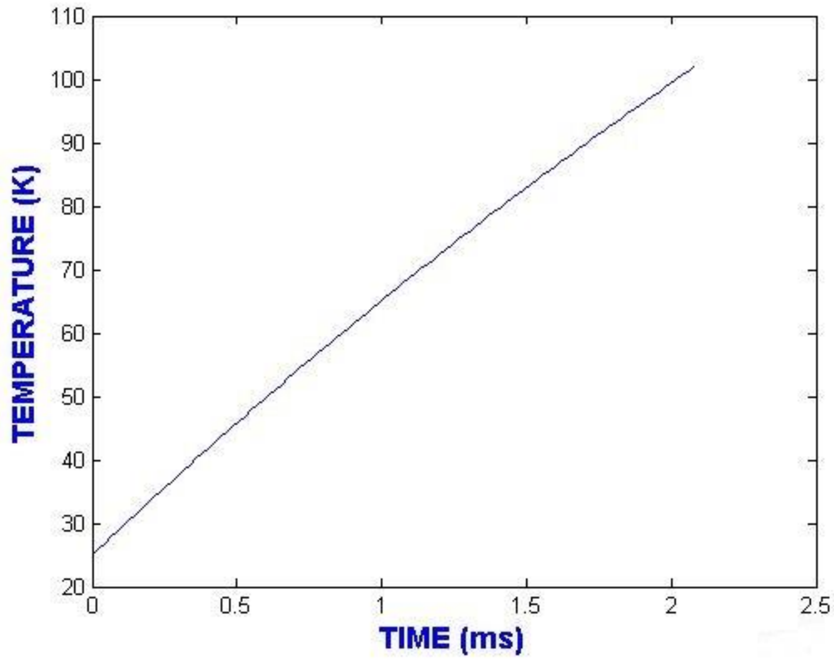

Figure-9: Droplet life time of 40 % C_2H_5OH

(C) ***For 80%*** **C_2H_5OH** ***(***A=8.1×10^{-4})

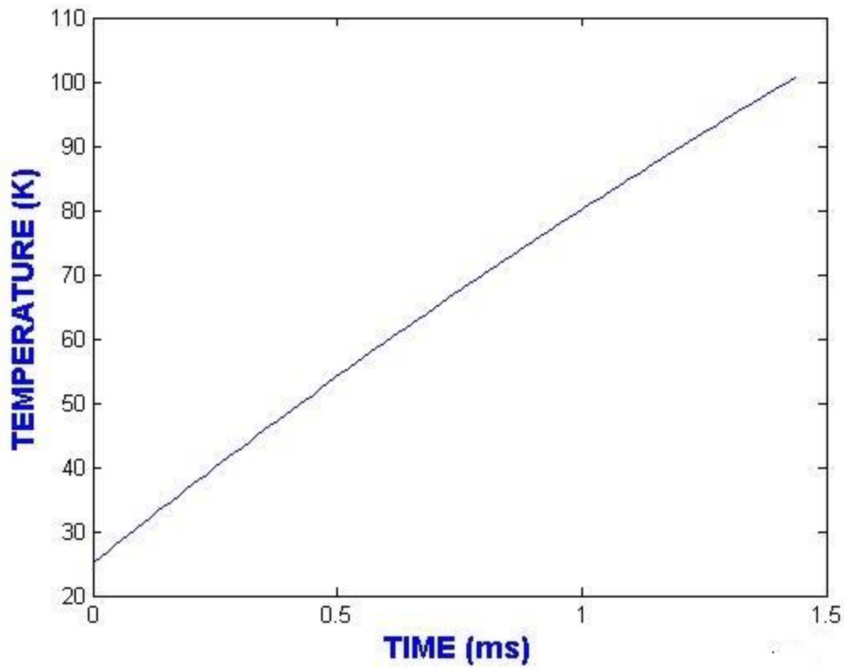

Figure-10: Droplet life time of 60 % C_2H_5OH

The evaporation times of alcohol added water droplet have been shown in Figures 7-10 and from the aforesaid figures, it is found that with the increasing alcohol concentration the life shows a declining trend. However, the achieved life time is not higher than that of surfactant case.

Case-4:-Sea water

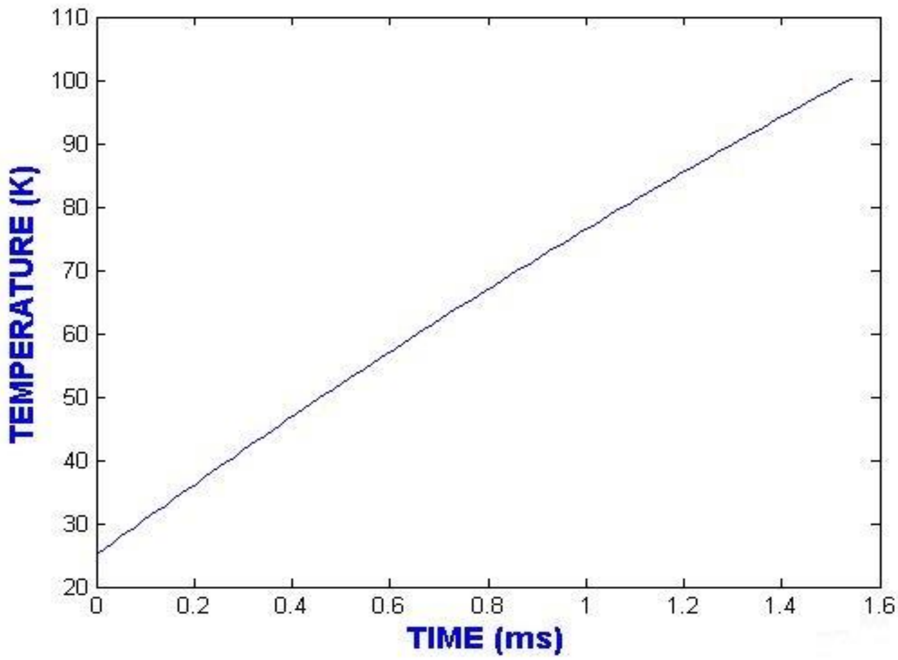

Figure-11: Droplet life time of sea water

For the sea water droplet case, the achieved life time is found to be 1.54 ms (Figure. 11) and this value is more significant than the alcohol case and pure salt case. This happens because of the sea water contains organic salts which reduce the surface tension and contact angle.

4.5: Comparative study

The evaporating life time is dependent on the area occupied by the droplet. High contact area leads to higher heat interaction which in turn reduces the droplet life time. The same trend lines have also been observed in the current case (Table-4).

Table-4 - Effect of contact area on evaporation life time

Sl no.	Description of the sample	Area of the droplet(m^2)$\times 10^{-4}$	Life time (ms)
1	500 ppm (SDS)	7.44	1.78
2	1000 ppm (SDS)	9	1.48
3	1500 ppm (SDS)	9.588	1.4
4	500 ppm(NaCl)	6.51	2
5	20% C_2H_5OH	5.47	2.27
6	40% C_2H_5OH	5.98	2.0
7	60% C_2H_5OH	8.1	1.43
8	Seawater	8.61	1.54

Chapter 5

5: Conclusions

The evaporation time of a water droplet with different types of additives have been studied in detail for the fast quenching operation. The detailed conclusions drawn from the investigations made on the cooling methodology are summarized below.

(1) The life time of 500 ppm, 1000 ppm and1500 ppm SDS water droplet are found to be 1.78 ms, 1.48 ms and 1.4 ms, respectively.
(2) The life time of 500 ppm NaCl is found to be 2ms.
(3) The life time of 20% C_2H_5OH, 40% C_2H_5OH and 60% C_2H_5OH are found to be 22.27 ms, 2.0 ms and 1.42 ms.
(4) Seawater has a life time of 1.54 ms.

From the above data, it can be concluded that among all the coolants, sea water is the best for the fast cooling operation.

5.1: Future work

(1) Study on single droplet evaporation.
(2) Validation of theoretical results with experimental data.
(3) Collection and comparison of droplet life time of samples of seawater from different locations on the shore of Bay of Bengal.

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