A Thesis on

Role of Water Temperature in a Spray Cooling of a Hot Steel Plate at Different Initial Temperatures

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In partial fulfilment of the requirements of

Master of Technology (B.Tech & M.Tech Dual Degree)

in

Chemical Engineering

by

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CERTIFICATE

This is to certify that the project report titled "**Role of Water Temperature in a Spray Cooling of a Hot Steel Plate at Different Initial Temperatures**" submitted by **Dheeraj Chouhan (711CH1157)** in partial fulfilment of the requirements for the award of degree of **Master of Technology (B.Tech & M.Tech Dual Degree**) in Chemical Engineering at National Institute of Technology Rourkela, is an authentic work carried out by him under my supervision and guidance.

To best of my knowledge, the content embodied in this thesis has not been submitted to any other university or institute for the award of any degree.

Date

Place: NIT ROURKELA

Dr. S.S. Mohapatra
National Institute of Technology
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Abstract

Water Spray cooling is an important technology used in the steel industries for the cooling from a temperature of 900 ^{o}C .The final mechanical properties of the steel are directly proportional to the quenching rate. Spray cooling is an important technique to achieve very high cooling rate .However, the achieved cooling rate is not sufficient for the metal which are used in some specific applications such as steel used for the production of surgical tools, fabrication of the rail track for the high speed train and also for light weight aircraft. Hence ,this methodology needs to be tried enhanced .In the current work by decreasing sensible heating time which is achieved by increasing water temperature, water the spray cooling is fixed to enhance .In the current work spray cooling experiments were conducted at various water temperature on a square shape (100 × 100 × 6) AISI-304 steel plate at different initial temperatures. To understand the heat transfer mechanism with respect to water temperature, first spray characteristic were studied then the water properties at different temperatures were determined. The result shown that an increasing water temperature, the heat removal increase due to decrement of evaporation period. The average heat flux obtained in case of water temperature 50 ^{o} C is 1.4 times of average heat flux obtained at water temperature of 900 ^{o} C .The same trade line also has been observed for the 600 ^{o}C and 300 ^{o}C.

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NOMENCLATURE

ROT	Run-out table
CHF	Critical heat flux
SCFB	Sub-Cooled flow boiling
TC1	Thermocouple 1
TC2	Thermocouple 2
TC3	Thermocouple 3
DAS	Data Acquisition System
S1	Surface Region 1
S2	Surface Region 2
S3	Surface Region 3
OES	Optical Emission Spectrophotometer

Chapter -1

Introduction

1. Introduction

High cooling rate on Run-out table (ROT) of a hot strip mill in a steel plant is one of the important criteria for the production of high tensile strength steel [1-2]. The conventional laminar cooling system, which is usually equipped with the ROT, cannot provide the cooling rate for achieving the said mechanical property. The Leidenfrost effect has been the biggest barrier for generating high cooling rate by the conventional cooling system. Due to this effect, a vapour layer covers the hot surface and drastically reduces the heat transfer rate from the hot steel plate. So, high cooling rate at high surface temperature has been a challenging area of research since last two decades.

From the recent research on cooling methods of metal, it is found that spray cooling produces better cooling rate than the conventional water jet at high surface temperatures. The work reported by Mohapatra et al [3] corroborates the aforesaid information. The major disadvantage of spray cooling is the formation of vapour film at very low initial surface temperatures. This phenomenon occurs due to the effect of vapour pressure and the formation of liquid film over the hot surface. So far many researchers have tried to enhance the spray cooling in different ways. Qiao and Chandra [4] investigated the surfactant added spray cooling. In their study, they considered substrate surface temperature up to 240 ^{o}C. They found that the addition of surfactant enhanced the nucleate boiling heat flux by up to 300%. Furthermore, in the follow up research by Cui et al. [5], the study was further carried out to investigate the effect of dissolving salt during water spray cooling. The experiments were performed on a copper surface which was heated to a temperature of 240 ^{o}C. Different types of salt was also considered in this study and their implication on surface heat flux is also studied. They found that heat transfer rate in case of dissolved salt of $MgSO_4$ increased both in nucleate and transition boiling regimes. Among all types of salt considered, $MgSO_4$ produced the largest increase in heat transfer rate. The flux showed an increasing trend with increasing salt concentration of 0.2 mole/litre and thereafter depicted a decreasing trend.

For the generation of fast cooling rate by any cooling process, high critical heat flux at very high surface temperature and the minimum film boiling effect are the two desired criteria.

The information provided by researchers on the sub cooling effect in case of water spray cooling reveals that heat flux decreases with decreasing sub cooling. According to them, by decreasing the degree of sub cooling of water, the total heat flux removed by the liquid at the surface is reduced. This observation evidences the heat transfer enhancement when sensible cooling is combined with phase change.

In open literature, Visaria and Mudawar [6] reported that increasing the sub cooling delayed the onset of boiling but decreased the slope of the nucleate boiling regime of the spray boiling curve. The enhancement in critical heat flux (CHF) was relatively mild at low sub cooling and more appreciable at high sub cooling. The CHF was enhanced by about 100 % when sub cooling was increased from 22 to 77 ^{o}C. But, all the discussed information were provided for only at low substrate temperature. Refiners et al. [7] studied heat transfer during cooling in continue casting by water spray at various water temperatures. They noticed that the heat transfer coefficient showed an increasing trend with the increasing degree of sub cooling and also increasing spray mass flux.

During the evaporation of a water droplet on a hot plate in film or transition boiling regime, a vapour layer is formed between the hot plate and the droplet. For fast cooling, the droplet residence time and the droplet evaporation time must be very low. If the droplet requires high sensible heat then the residence time increases for a constant heat transfer coefficient. This high sensible heat is directly proportional to the water temperature. On increasing water temperature, the sensible heat required to evaporate one droplet decreases and as a result the droplet residence time and life time also decreases. Due to the aforesaid two phenomena, the film boiling phenomenon which occurs due to the formation of a stable water film on the hot surface also decreases. As high mass flux spray operates in the temperature range of 900-600 ^{o}C in transition boiling and below 600 ^{o}C in nucleate boiling regime, the cooling enhancement is also expected in case of cooling by hot water. However, the information on the cooling enhancement by the hot water in the case of spray in film/transition boiling regime has not been studied so far and therefore further investigation is required in this regard.

In the current work spray cooling experiments were conducted at various water temperature on a square shape (100 × 100 × 6) AISI-304 steel plate at different initial temperatures. To understand the heat transfer mechanism with respect to water temperature, first spray characterisation was and done then the water properties at different temperatures were determined. The result shows that on increasing water temperature, the heat removal rate increases due to decrement of evaporation period

Chapter-2

Literature Review

2. Literature review

Spray cooling has high heat flux when compared with other cooling techniques. Jet impingement, miniaturized scale channel cooling, and sub cooled flow boiling (SCFB) can accomplish comparable heat fluxes. Nevertheless, spray cooling has a few significant advantages over many of the other high heat flux cooling techniques. The main advantage is that spray cooling permits a uniform temperature over the cooled surface M.R. Pais [8, 9].

The second point of interest of spray cooling over another high heat flux cooling methods is that of its lower associated flow rates. Flow rates directly affect close loop framework parts, fundamentally on the limit of the pumps and the span of the related tubing. In small scale cooling applications with low heat loads, the distinctions in pump size between SCFB, small scale channel cooling, and spray cooling can be ignored.

Another point of interest of spray cooling has over other high heat flux cooling methods is that of a higher heat rejection temperature. Close loop spray cooling frameworks' use a condenser to reject heat; though, single phase heat impingement, single phase small scale channel and SCFB uses a heat exchanger. The upside of utilizing a condenser as a part of the cooling framework rather than an exchanger is that a condenser has a related size because of its higher heat dismissal temperatures.

It is additionally demonstrated that the lower chip intersection temperatures created by spray cooling decrease transistor leakage currents, bringing about diminished force utilization and higher reliability. Spray cooling has the lack of understanding about its operational characteristics in variable and microgravity environments. Until now, only Baysinger and Yerkes [10] have concentrated on the impacts of microgravity on the heat exchange qualities of spray cooling. Another point of interest of a spray cooling frameworks is the capacity to kill the spray on and off. The Intel bunch demonstrated this capability with their inkjet helped spray cooler, which just connected coolant when expected to a microchip [11].

From the above literature, it is concluded that the effect of water in spray boiling process at high initial surface temperature is never been studied and hence the followings are the current objectives:

- To study the effect of substrate temperatures on spray boiling heat transfer
- To study the effect of water temperature on spray boiling heat transfer

Chapter-3

Experimental Set-up

3. Experimental Set-up

For all type of experimentation, a square shape stainless steel plate (100 mm x 100 mm) of 6mm was utilized. The plate was heated to various temperatures as 360, 660 and 980 ^{O} C in a furnace. Temperatures were measured during the experimentation by using three sub surface thermocouples (TC1, TC2, and TC3). The thermocouples were placed parallel to the quenching surface to avoid the thermocouple orientation effect and hole diameter effect. During the experimentation, the time – temperature histories were recorded with the help of a data acquisition system with a sampling rate of 3 samples per second.

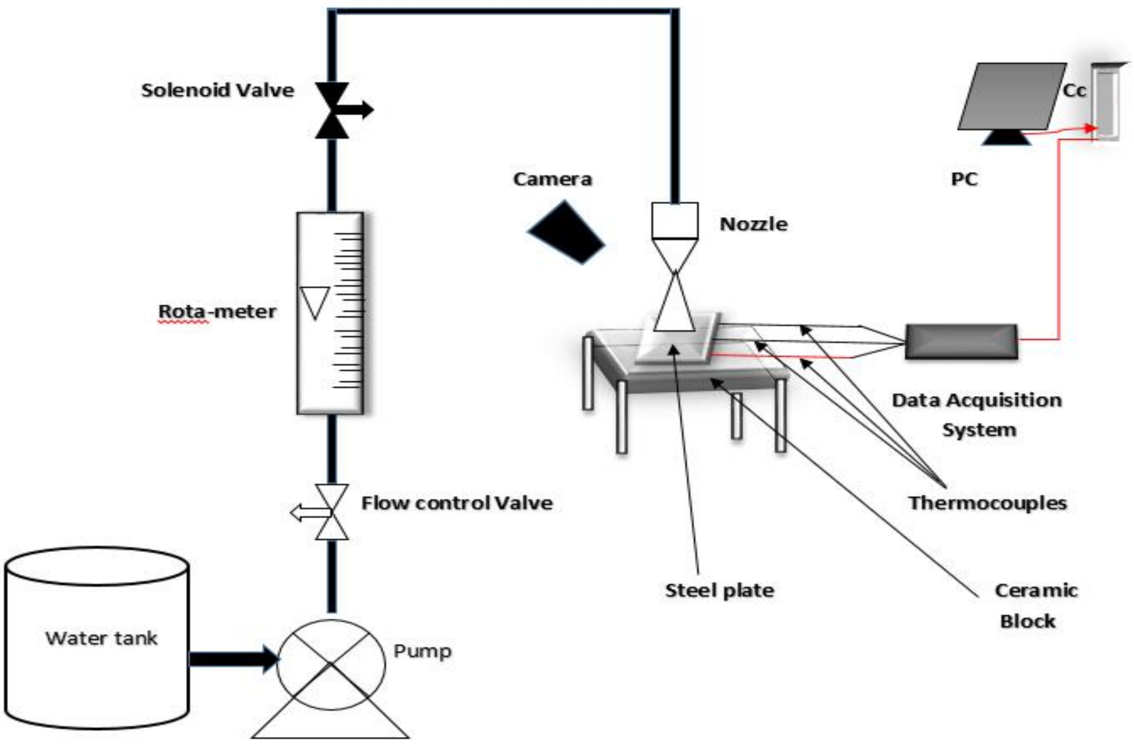


Fig.3.1 Schematic Diagram of the Experimental Set-up

After proper thermal soaking of the steel plate inside the muffle furnace at 1050^0C, the spray was made ready for the cooling experimentations by the help of valves, and the rota meters. The spray was initially covered and during this period the hot steel plate was taken out from the muffle furnace and placed on the cooling pad. Then, the spray was uncovered and the plate was exposed for the cooling. During the cooling, the entire temperature histories were recorded by the help of a data card (DAS) and saved in the PC for further analysis. The schematic diagram of the current experimental setup is shown in Fig.3.1.

3.1 Prediction of Surface Heat Flux and Surface Temperature

In the current work, by using INTEMP software, the prediction of surface heat flux and the surface temperature have been carried out (Trujillo and Busby (2003 For the prediction of surface heat flux and surface temperatures, the plate geometry has been discretised in to 3340 quadratic elements with four nodes per element. Except the quenching surface, all other surfaces are assumed to be adiabatic. For the accurate prediction of the flux, the quenching surface has been divided into three flux sections.

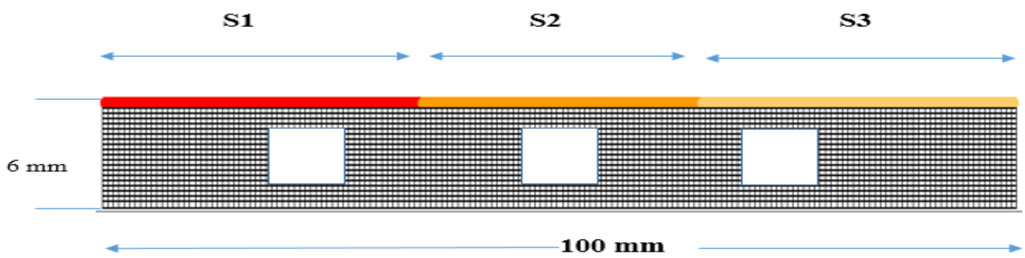


Fig.3.2 Computational Domain of the Steel Plate for INTEMP

3.2 Material Characterisation

Before the experimentation, in the current case, first the composition of the steel plate was examined by (OES) optical emission spectrophotometer. The obtained composition is shown in below (Table 3.1) and the obtained compositions confirm the AISI standard. According to composition, the material is AISI-304 type. In addition to the above, the material properties of (Table 3.2) AISI-304 steel are taken for the calculation.

Table 3.1 Composition Analysis of Material used in Experimentation (% weight)

C	Cr	Fe	Mn	Ni	P	S	Si
0.08	18.20	66.74	1.8	8.5	0.043	0.03	0.95

Table 3.2 Material Properties at 25 ^{o} C

Density (ϱ)	8000 kg/m^3
Thermal Conductivity (K)	16.2 W/mk
C_p (Specific Heat Capacity)	0.5 KJ/^{o} C

3.3 Spray Characterisation

In the case of spray cooling, the rate and mechanism depend on the spray impingement density, droplet moment, droplet diameter and the direct impingement area. To understand the heat transfer mechanism during spray cooling at different water and substrate temperatures aforesaid variables need to quantify at different conditions and this quantification process is called the spray characterisation.

3.3.1 Droplet Diameter, Velocity and Pressure

From to the data supplied by the manufacturer the droplet diameter variation with flow rate is shown in Fig.3.3.Fig.3.3 depicts an increasing trend with the increasing water flow rates. The droplet velocity and spray pressure shown the same trend with the increasing water flow rate.

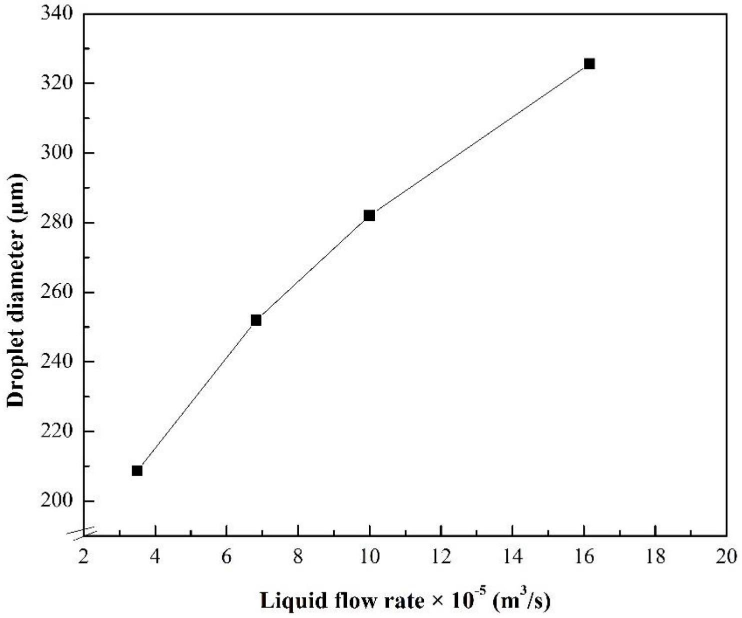


Fig.3.3 The Variation of Droplet Diameter with liquid Flow rate

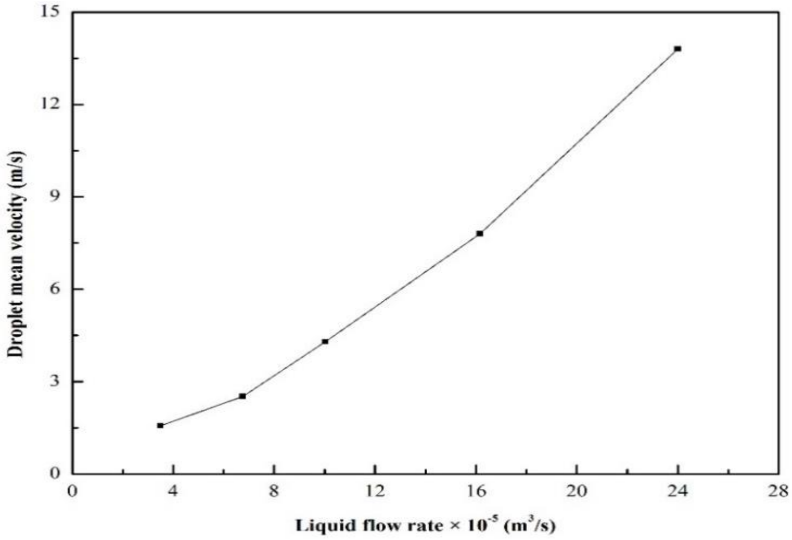


Fig.3.4 The Variation of Droplet Mean Velocity with Liquid Flow Rate

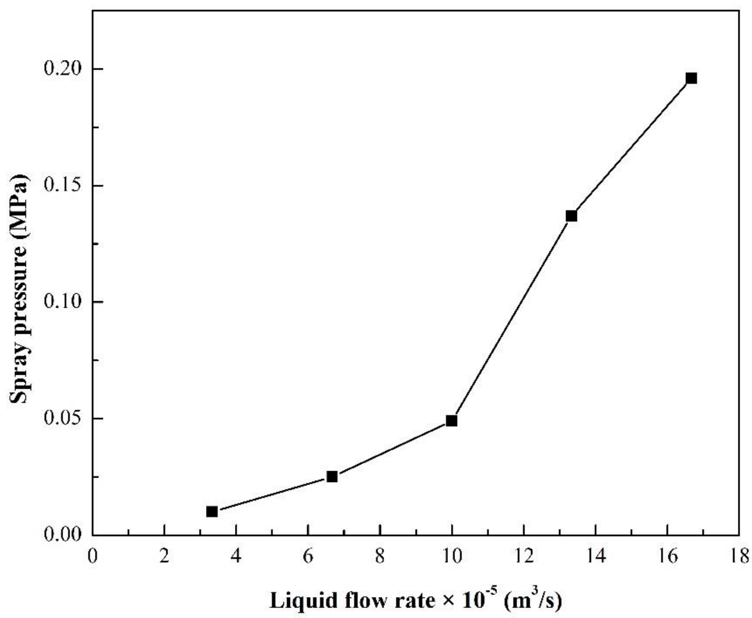


Fig.3.5 The Variation of Liquid Pressure with Liquid Flow rate

3.3.2. Spray Impingement Density

For the measurement of spray impingement density, an indigenously designed and fabricated patternator was used. Here, it is seen that the local spray impingement density increases with the increasing water flow rate at any location on the plate.

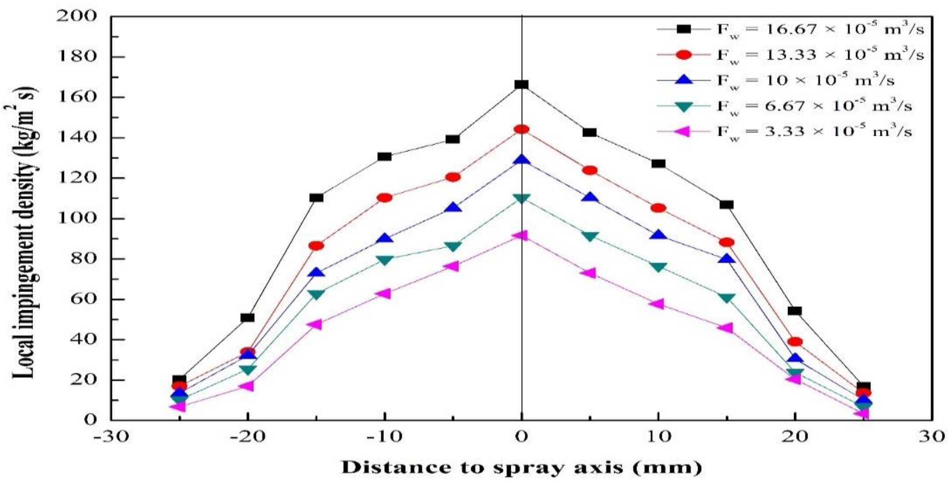


Fig.3.6 The variation of Local Impingement Density with Distance from Spray Axis

Chapter-4

Results and Discussion

Results and Discussion

4.1 Single Droplet

Experiments were done with single droplets to understand the mechanism. A total 6 numbers of experiments were done with different coolant temperatures and surface temperatures. Coolant temperature was varied from 20 ^{0}C to 40 ^{0}C while temperature of steel sample was varied from 200 ^{0}C to 300 ^{0}C. Photograph were taken and the photograph from droplet evaporation time and vapour formation time were calculated.

4.1.1 For Initial Surface Temperature of 200 ^{o}C

The droplet lifetime depends on the latent heating time and sensible heating time by droplet. The variation of droplet lifetime with coolant temperature at sample temperature of 200 ^{0}C is shown in Fig. 4.1.From fig. It is clearly evident the plot that as coolant temperature increases, droplet lifetime decreases. It is due to reduction in amount of sensible heating time required by the droplet to reach boiling point.

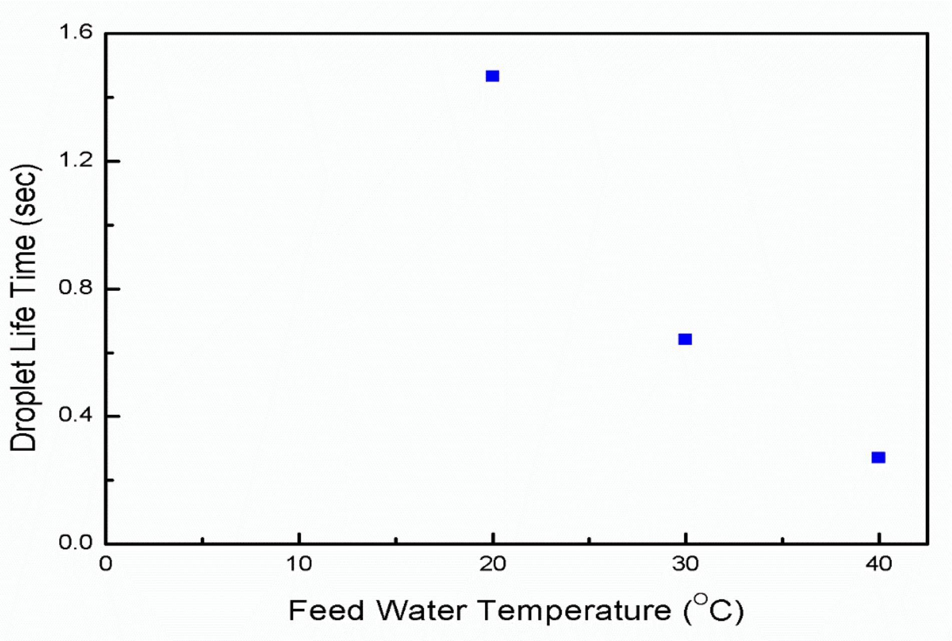


Fig.4.1 The Variation of Droplet Life Time with Water Temperature

Film boiling is an important phenomenon affecting the cooling rate. To study this effect, the time of film boiling is calculated and plotted against the coolant temperature at sample temperature of 200 ^{0}C as shown in Fig.4.2.The Fig. shows a straight decline in film boiling time with increasing coolant temperature.

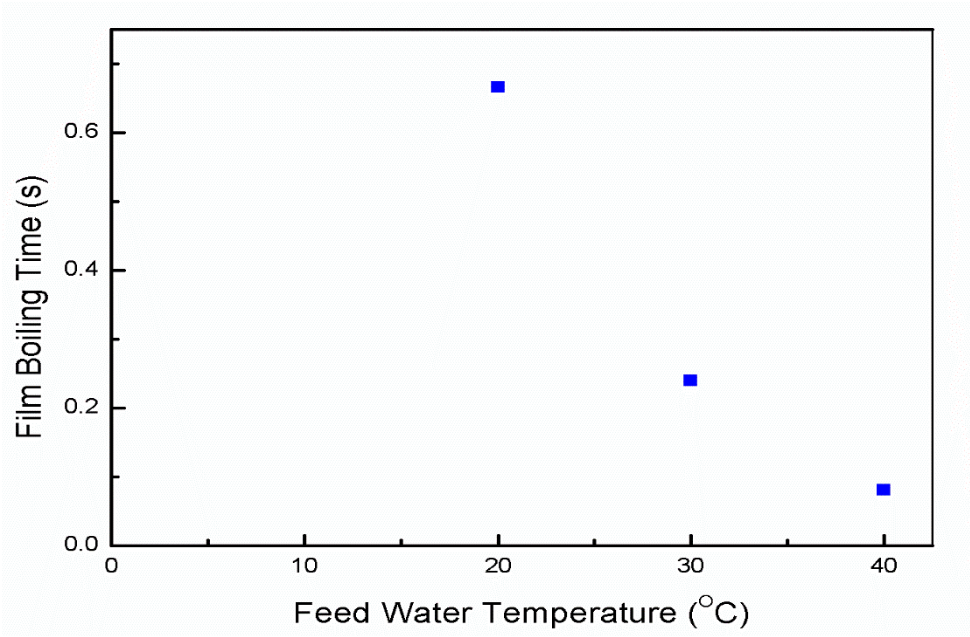


Fig. 4.2 The Variation of Film Boiling Time with Water Temperature

4.2.1 For Initial Surface Temperature 300 ° C

The droplet lifetime variation with coolant temperature at a sample temperature of 300 ^{0}C is shown in Fig.4.3.There is clear decrease in droplet lifetime with increasing coolant temperature. This is because of sensible heat effect. As the sensible heat increases, the droplet lifetime decreases.

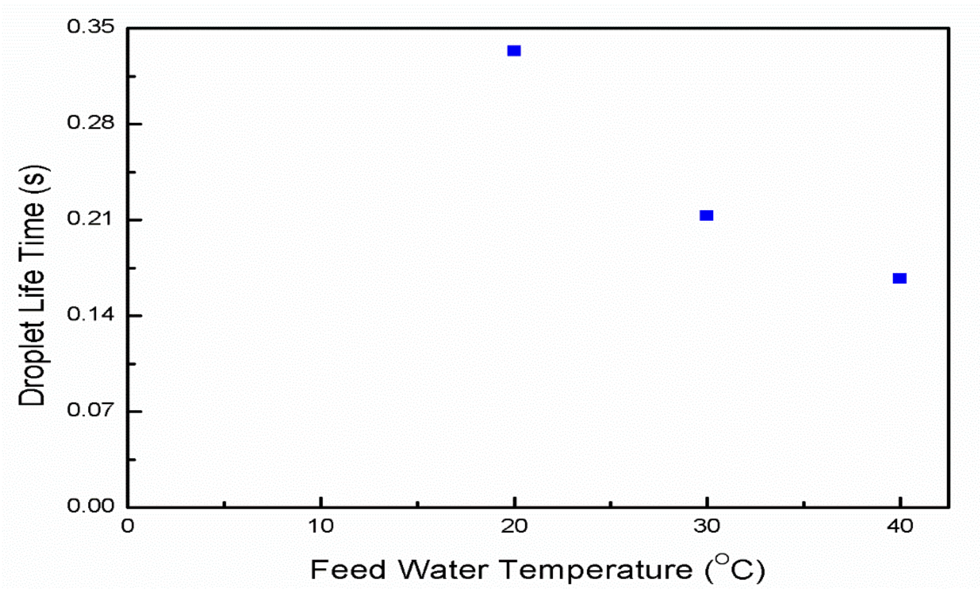


Fig.4.3 The Variation Droplet Life Time with Water Temperature

The film boiling time depends on the sensible heat significantly. This is evident from the trend shown in Fig.4.4.This Fig. shows the decreasing trend of film boiling time with increasing coolant temperature.

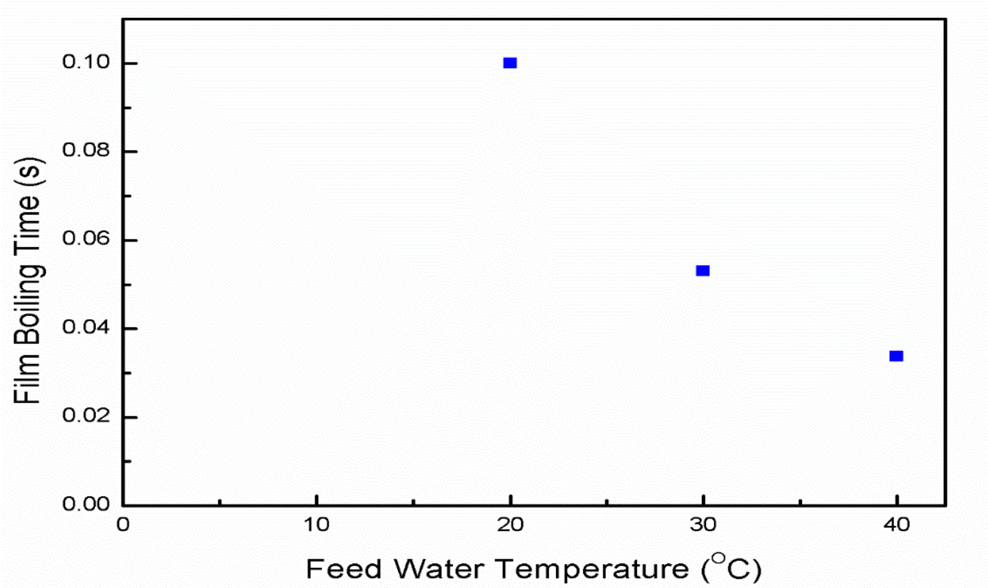


Fig.4.4. The Variation of Film Boiling Time with Water Temperature

4.2 Spray Cooling

4.2.1 For Initial Surface Temperature of 300 ° C

The variation of temperature with time for surface temperature of 300 ° C is shown in Fig.4.5. A constantly decreasing trend with time is observed for each case. However, the slope increases suddenly after a certain point of time because of alteration of boiling regime. The highest cooling rate is observed in case of water at temperature of 40 ° C. It is due to the less required sensible heating time to reach the boiling temperature.

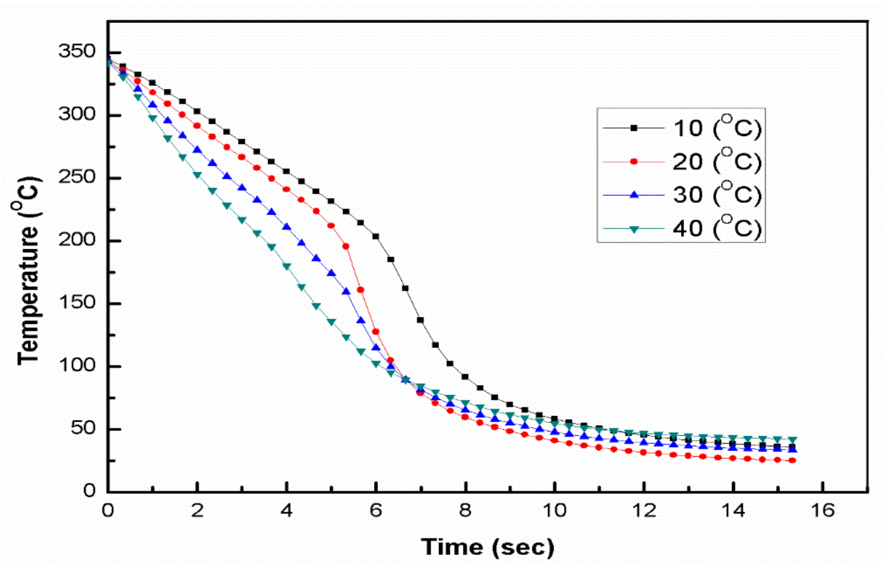
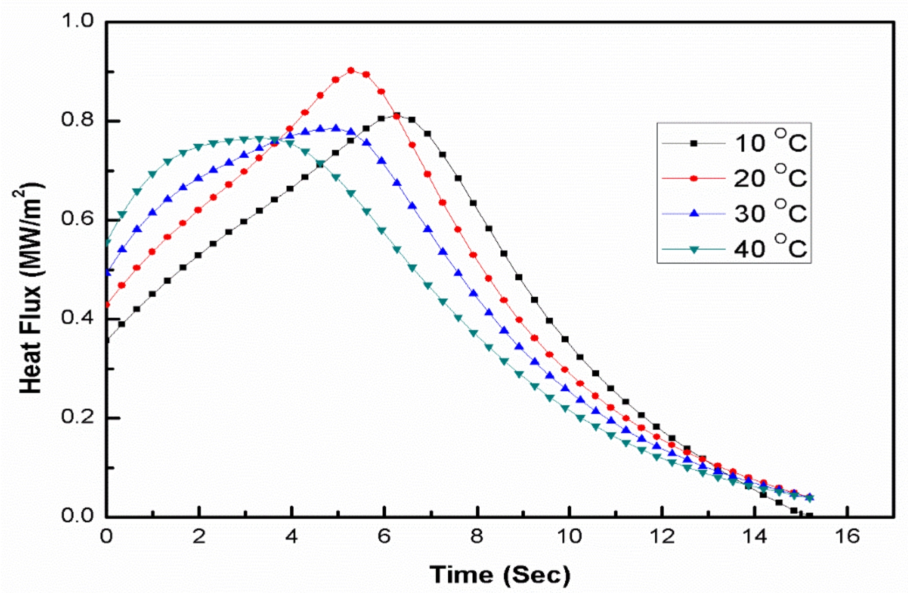


Fig.4.5 The Variation of Surface Temperature with Time at Different Water Temperature

The variation of surface heat flux with time is shown in Fig 4.6. There is an increment in surface heat flux observed with time in the starting of cooling in case of water temperature of 10 ° C and with increasing time. It attains a critical heat flux value and there after the surface heat flux decreases constantly with time. Similar trends are also found in case of coolants with higher temperatures. Critical heat flux of coolant with 20 ° C temperature is found to be more as compared to others. This is because initially the heat removal rate is slow. This allows a larger amount of heat available for removal at a later stage, resulting into a higher peak or critical heat flux.



. Fig.4.6 The Variation of Surface Heat Flux with Time at Different Water Temperature

The heat flux shows an increasing trend up to surface temperature of 150^{o} C and there after depicts a decreasing trend. All the curves show the same trend. The trends obtained with other coolants at lower temperatures also shows similar behaviour. The initial surface heat flux and the rate of increment is maximum in the case of coolant at 40 ^{o} C. A decrease in aforesaid quantities is observed as the coolant temperature decreases. This is solely because the increase in the amount of sensible heating period with decreasing coolant temperature.

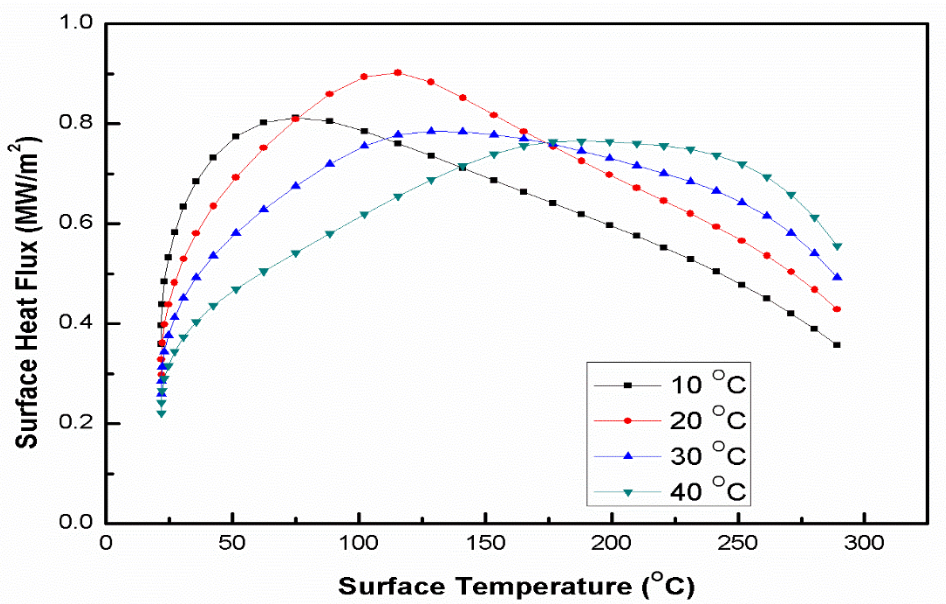


Fig.4.7 The Variation of Surface Heat Flux with Surface Temperatures at Different Water Temperature

4.2.2 For Initial Surface Temperature of 600 ^{o} C

The Fig.4.8 shows the variation of temperature of the hot surface with time. This case also follows the same trend line as in the case of 300 ^{o}C initial surface temperature.

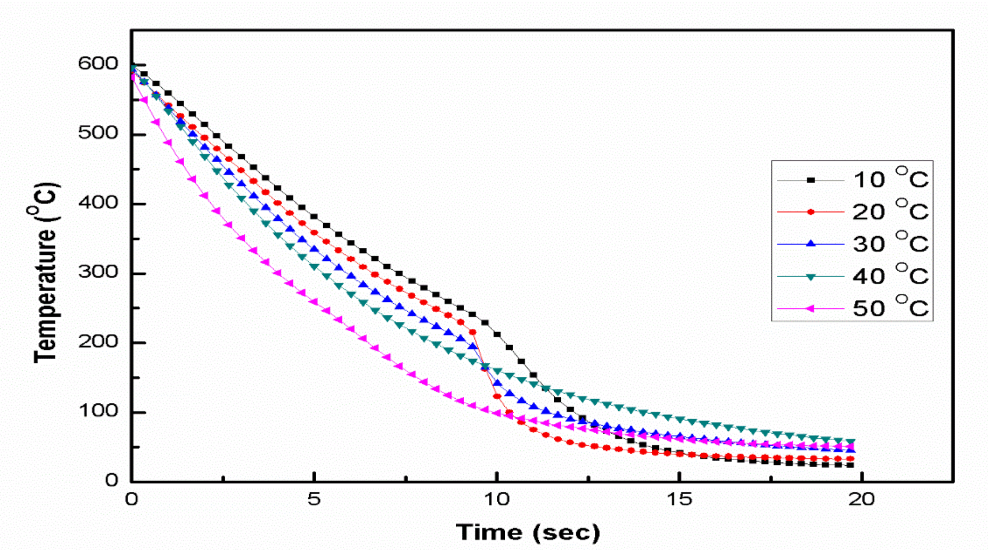


Fig.4.8 The Variation of Measured Temperature with Time at Different Water Temperature

Fig.4.9 shows the variation of surface heat flux with time. Initially, the heat flux increases up to 2.5 s. During this period transition boiling is observed. At t=2.5s,the heat flux reaches at maximum and thereafter the nucleate boiling starts due to which the heat flux starts decreasing. The maximum heat flux is observed corresponding to the water temperature of 50^{0}C.The amount of sensible heating period is less at high temperature of water and as a result critical heat flux is achieved soon.

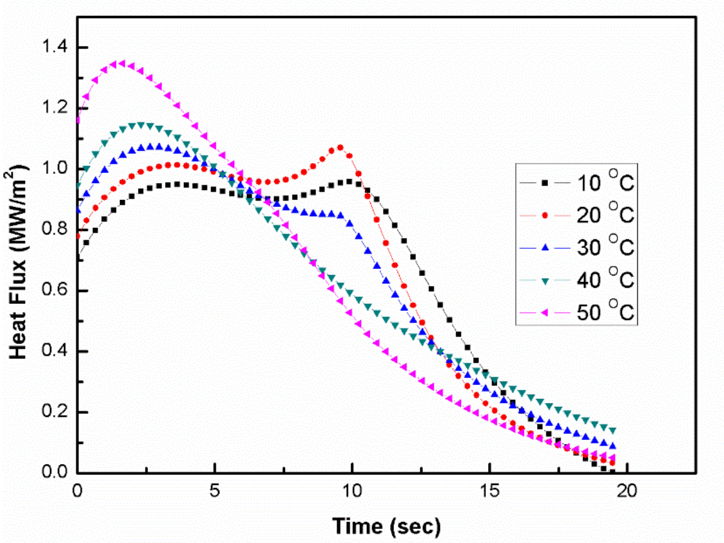


Fig.4.9The Variation of Heat Flux with Time at Different Water Temperature

Fig.4.10 depicts the change of surface heat flux with surface temperature at different water temperature. As the cooling starts, the surface heat flux increases and after reaching the critical point it starts decreasing .Beyond the critical heat flux, on further cooling due to transition boiling it decreases. The maximum critical heat flux is obtained at water temperature of 50 ^{0}C. At this temperature, the latent heat removal rate increases due to the decrement of sensible heating time for a particular residence time and as a result shows the maximum initial heat flux and maximum critical heat flux have also been observed.

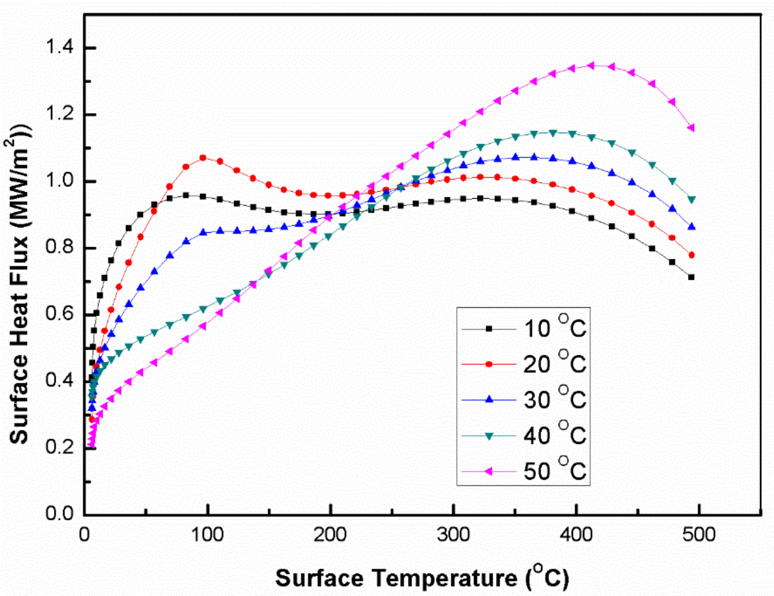


Fig.4.10 The Variation of Surface Heat Flux with Surface Temperatures at Different Water Temperature

4.2.2.1 Average Heat Flux and Cooling Rate

According to experimentations, the average heat flux has been estimated for the surface temperature drop of approxly 300 ^{o}C. Fig.4.11 depicts the variation of average heat flux with different water temperatures. It shows that by increasing water temperatures the average heat flux increases and reaches the maximum value at a water temperature of 50 ^{o}C. Above 50 ^{o}C water temperature, the current experimental set-up doesn't work and as a result maximum water temperature of 50 ^{o}C is taken in the current case

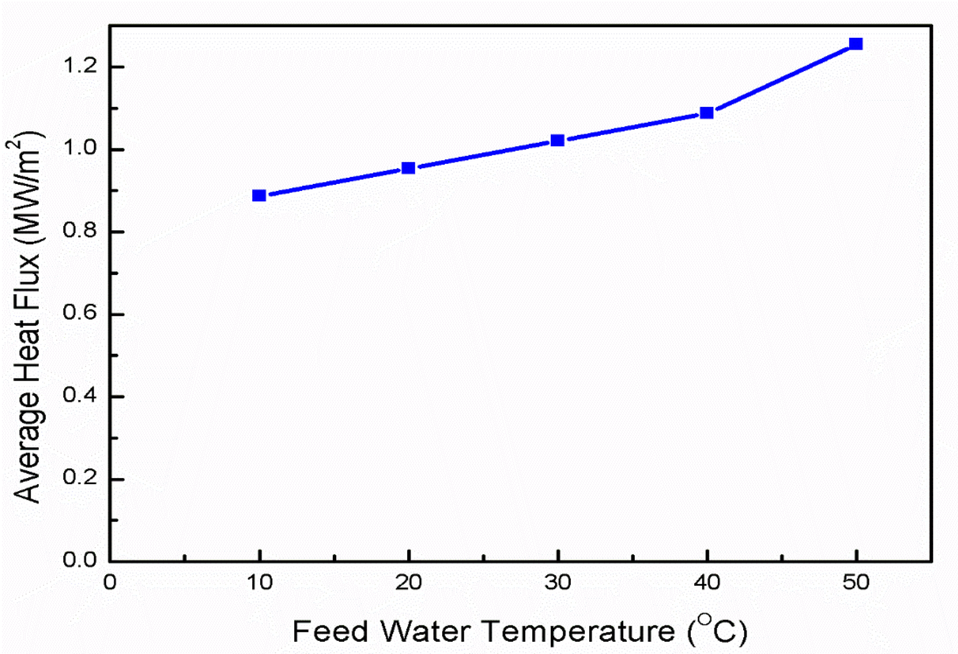


Fig.4.11 The Variation of Average Heat Flux with water Temperature

The variation of average cooling rates with different water temperatures are shown in Fig.4.12.The achieved cooling rate is almost 1.5 times of value obtained at water temperature of 50 ^{o} C.

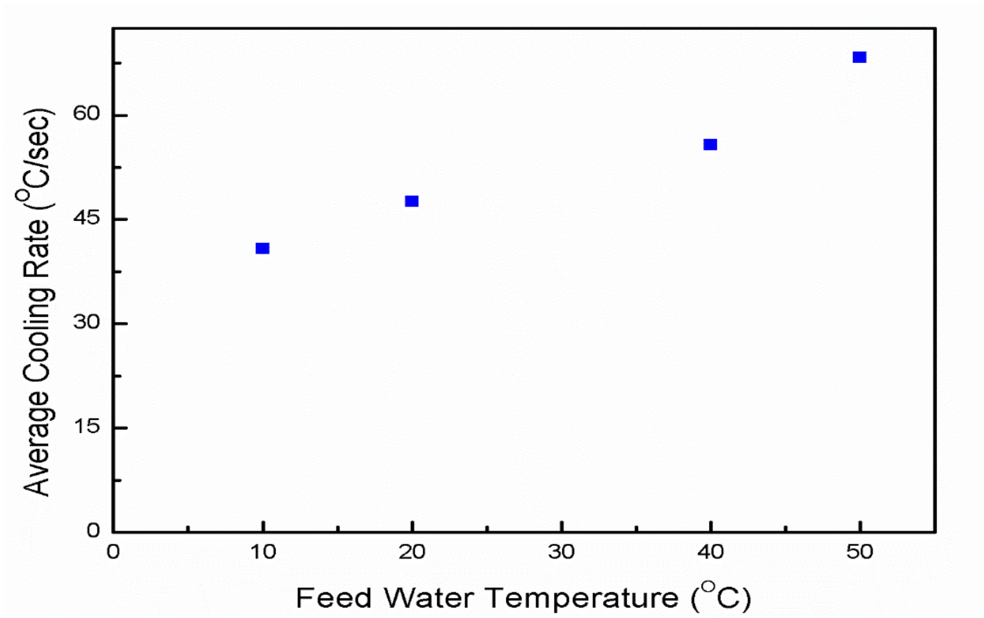


Fig.4.12 The Variation of Average Cooling Rate with Water Temperature

4.2.3 For Initial Surface Temperature of 900 °C

The variation of temperature with time is shown in Fig.4.13.The trend for coolant at 50 °C depicts fast decrease in temperature initially and then slows down. The same trend is followed by all other coolants also.

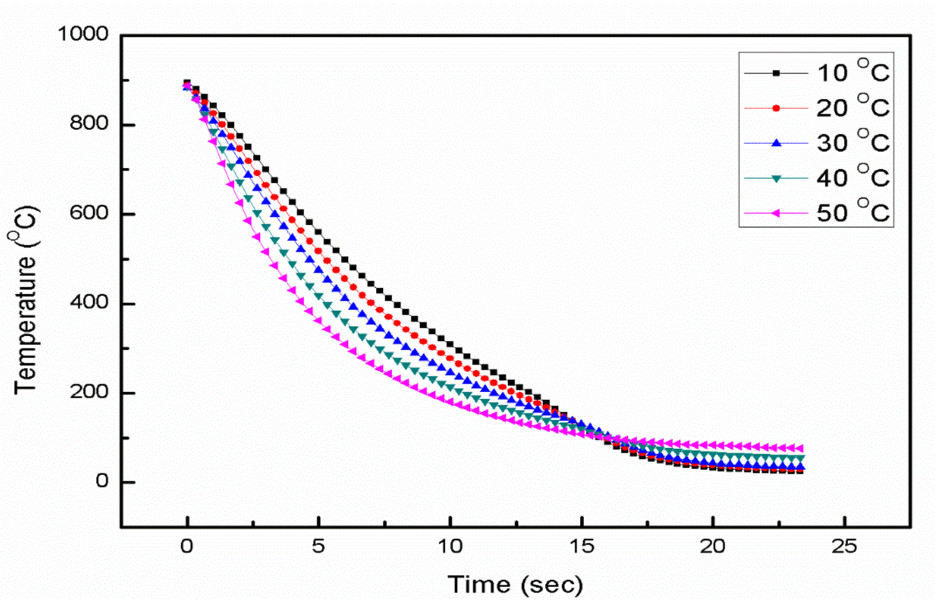


Fig.4.13 The Variation of Measured Temperature with Time at Different Water Temperature

The surface heat flux calculated from temperature which varies with time is shown in Fig.4.14. For coolant with 50 ^{0}C temperature, the surface heat flux first increases and reaches than the critical heat flux. Thereafter, it shows decreasing trend. The same trend is followed by the plot of coolants at lower temperatures too. The initial heat fluxes are different for different coolant temperatures. The highest critical heat flux is achieved by coolant at 50 ^{0}C. This is of because the amount of heat required to reach the boiling point is minimum in this case. Similar trend line the boiling curve also shows.

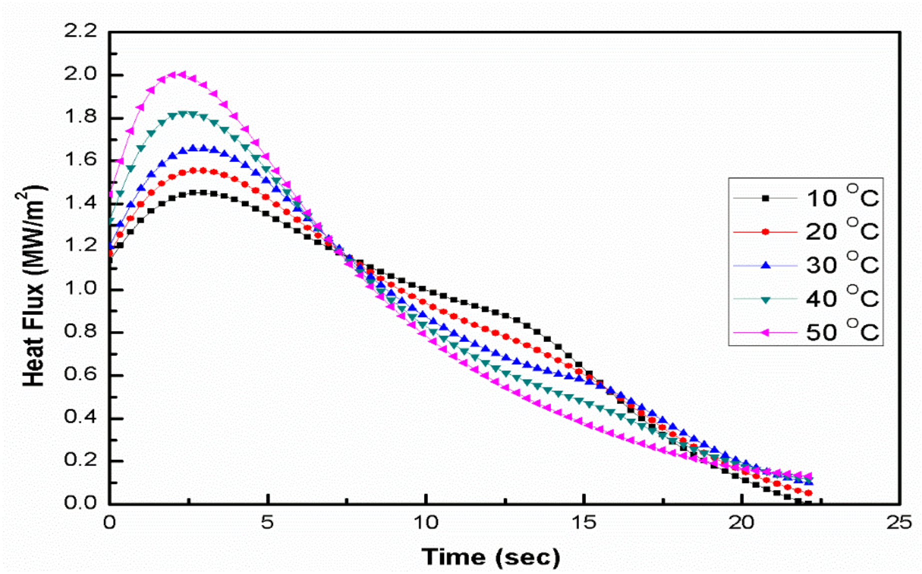


Fig4.14 The Variation of Heat Flux with Time at Different Water Temperature

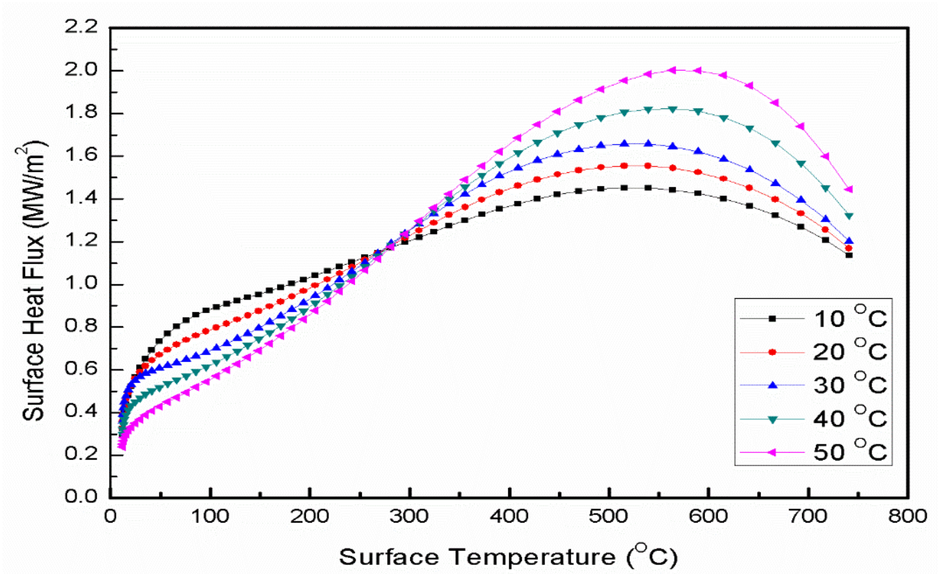


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Fig.4.15 The Variation of Surface Heat Flux with Time at Different Water Temperature

4.2.3.1Average Heat Flux and Cooling Rate

Fig.4.16 depicts the variation of average heat flux at different water temperatures. It shows that by increasing water temperatures the average heat flux increases and reaches the maximum value at a water temperature of 50 ^{o}C. A maximum value 1.84 MW/m^2 is observed at a water temperature of 50 ^{o}C .Similar trend line is also observed for the cooling rate case (Fig.4.17)

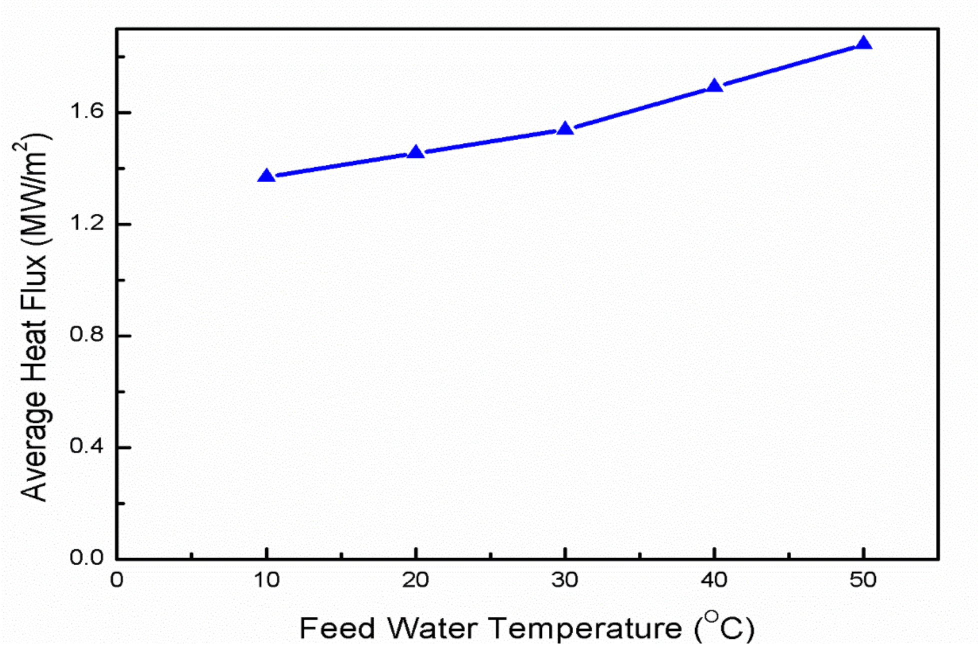

Fig.4.16 The Variation of Average Heat Flux with Water Temperature

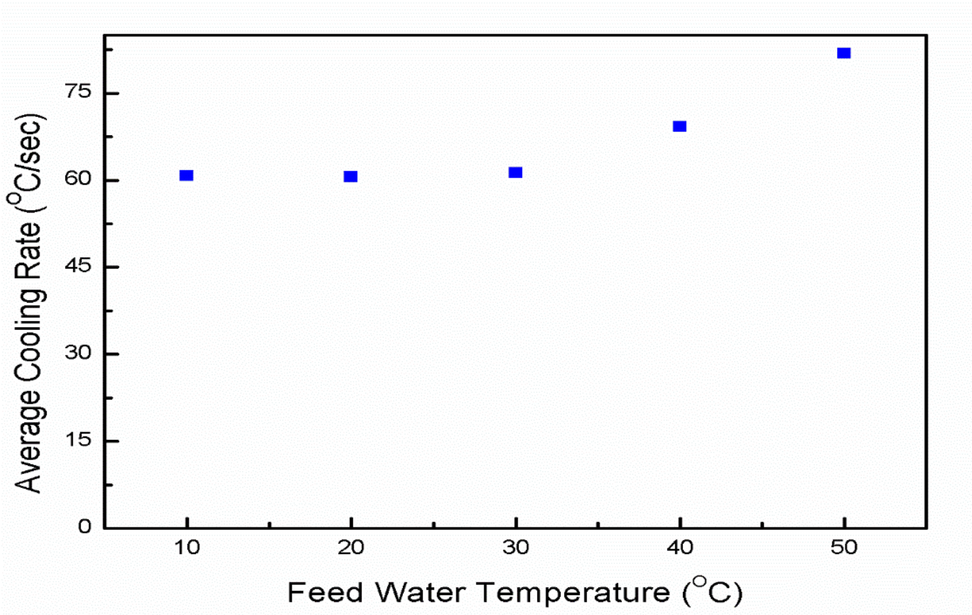

Fig.4.17 The Variation Average Cooling Rate with Water Temperature

4.3 Visual Observation

The cooling rate is directly proportional to the rate of increment of forced convection area . For the varification of cooling enhancement , at different cases , the forced convection cooling area is calculated by taking images at the different intervals of time.The obtained images with respect to time are shown in Fig.4.18.

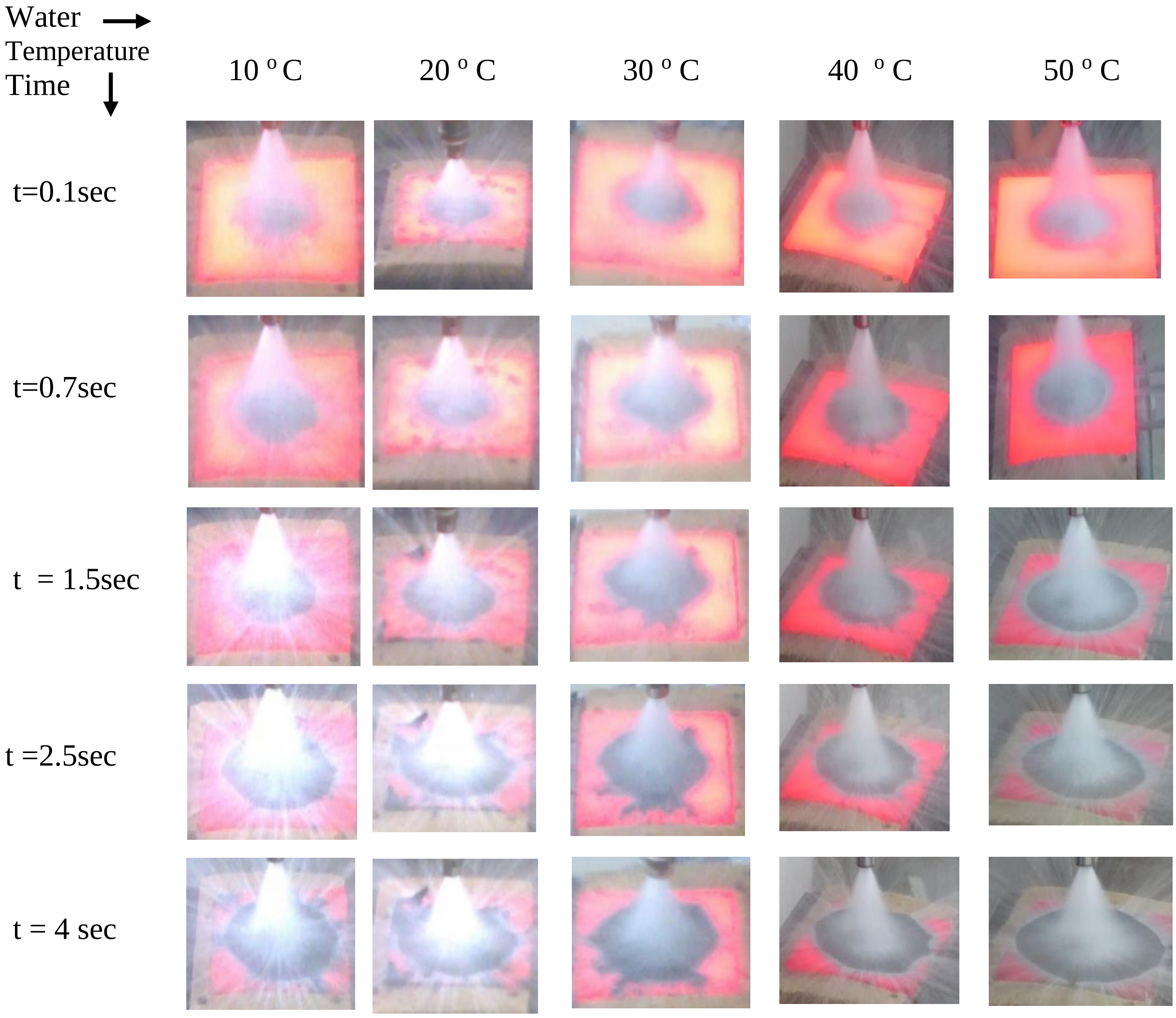

Fig.4.18 Visual Analysis of Experiments Conducted at Different Water Temperatures

From the images, the dark diameter, which corresponds to the forced convection cooling area at different time were calculated and the variation of dark diameter is shown in Fig.4.19.

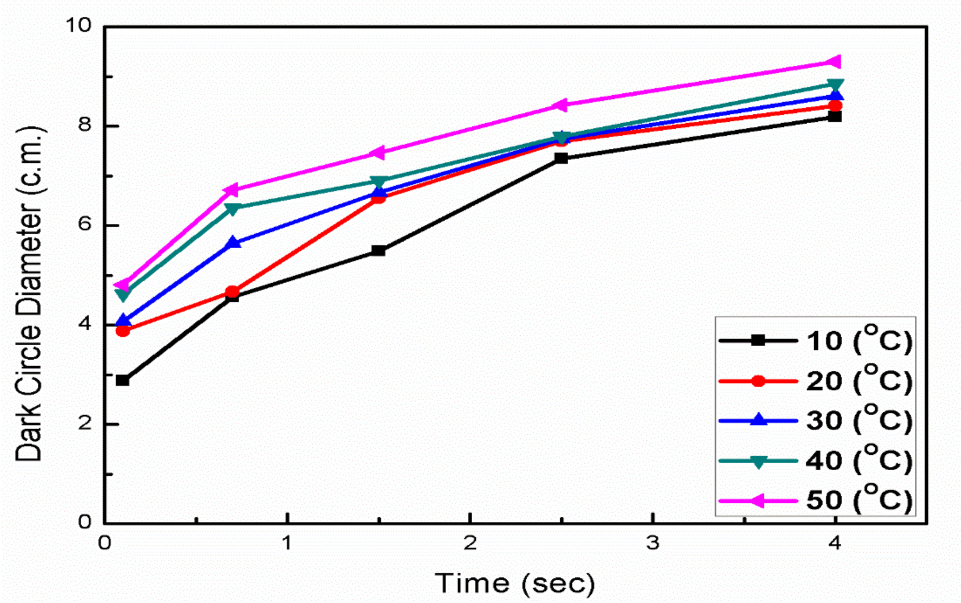

Fig.4.19 The Variation of Dark Circle Diameter with Time

4.5 Initial and Critical Heat Flux

From the above Figs (4.20 and 4.21), it can be clearly concluded that cooling at higher temperature produces higher initial heat flux and also critical heat flux. These are the two characteristics of any cooling system mainly quenching rate.

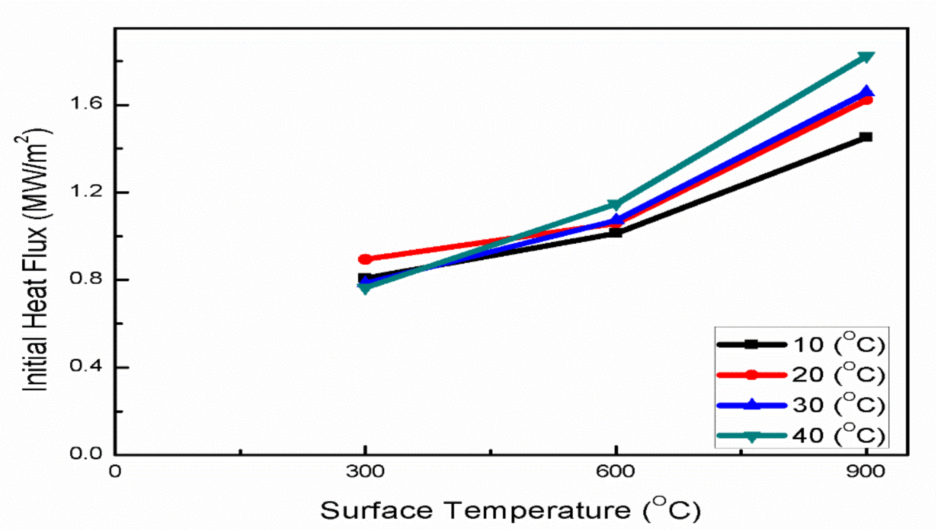

Fig.4.20 The Variation of Initial Heat Flux with surface Temperature at Different Water Temperatures

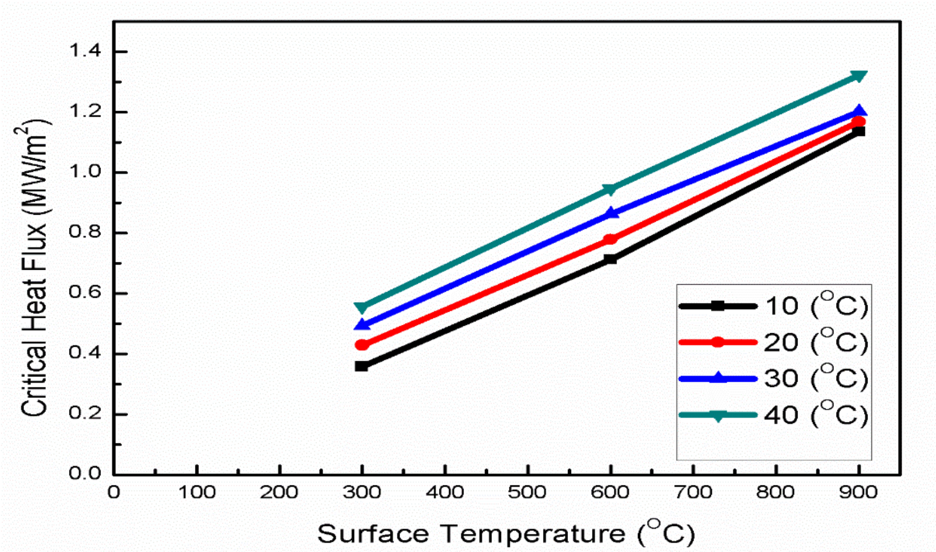

Fig.4.21 The Variation of Critical Heat Flux with Surface temperature at Different Water Temperatures

Chapter -5

Conclusions and Future Work

Conclusions

Experiments were conducted in spray cooling and single droplet cooling systems. The parameters varied include coolant temperature and substrate temperature. The followings are the conclusions

- The effects of sensible heat and initial test sample temperatures on heat transfer were studied. The droplet lifetime is found to be decreasing with increasing coolant temperature for any initial test sample temperature. A similar trend is observed in case of film boiling time also. This shows significant effect of sensible heat on heat transfer.
- In case of spray cooling, critical heat flux is found maximum in case of 20 ^{o}C for initial substrate temperature of 300 ^{o}C. But, for higher initial test sample temperatures, critical heat flux is observed maximum in case of highest coolant temperature. Moreover, the time to achieve critical heat flux is very less when the initial test sample temperature is higher as compared to lower ones. This shows that high heat removal occurs in beginning stage of cooling when initial test sample is high. Therefore, using high temperature coolants in case of high initial temperatures of test sample is favourable.

Future Work

The possible future work are

- Spray cooling can be conducted from both side of the plate
- All the experiment conducted can further be done by other cooling methodologies such as air atomized spray and jet cooling

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