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Effect of Surface Roughness on Horizontal Cylinder Cooling

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Abstract. : Several experimental researches have been studied the effect of impinging jet on horizontal cylinder cooling whether the impinging jet is fixed or rotating. Very few studies have been investigated the effect of surface roughness in the quenching process. The current study focused on making a comparison of the cooling characteristics between smooth and roughened horizontal stainless-steel cylinders. The cooling characteristics have been studied taking into consideration different parameters as specimen initial temperature from 250 to 450°C, coolant temperature from 40 to 80°C, number of impinging jets from 1 to 3, effect of coolant velocity from 2.5 to 6 m/s and surface roughness which has been used two different types of surface roughness The first type fabricated by using laser cutting machine used to roughening the specimen. The second type fabricated by making narrow groove channels in the specimen with width 2 mm and 30 apart from each other.

Keywords: Quenching, impinging jets, surface roughness.

Nomenclature

$T_{surface}$	Specimen initial temperature	°C
ΔT_{sub}	Degree of coolant sub-cooling	°C
V_{jet}	water velocity at jet exit	m/s
No. of jets	Number of jets	------
Inner TC	Inner thermocouple	------
Outer TC	Outer thermocouple	------
ϴ	Angle from vertical jet	degree
t	Time	sec

1. INTRODUCTION

It would be unfair to state that one material is more important than another one, such as copper which has a great use in electronic industries. However, steel is considered one of the most important materials that human has used in history because of its amazing flexibility in metalworking and heat treatment to produce a large variety of mechanical and physical properties [1].

Quenching can be defined as a rapid cooling process of the specimen in water, oil or air to get certain material properties. Moreover, quenching is considered one of the main heat treatment process done to the steel, which has a great effect on its hardening. Across the history, quenching was widely used. In Europe, in the first millennium, some technologies were made to harden the swords and weapons. However, the advances in heat treatment techniques were done in the Arab-world, India, China and Japan [2].

Surface roughness can be considered as the measurement of the small-scale variation in the height of a physical surface. This is in contrast to large-scale variations which may be either part of the geometry of the surface or unwanted waviness [3]. Therefore, with increasing the surface roughness of a desired solid object which is under quenching process that gives more connection area between the solid object and the cooling fluid. Subsequently, it gets a better cooling rate which is proved in papers [7-8].

In 2012 El-Nasr et al. [4] reported on heat transfer characteristics of horizontal cylinder cooling under single impinging water jet, experimental and numerical studies have been conducted of a hot stainless-steel cylinder with an initial temperature of 300 to 400°C by a sub-cooled fluid from 20 to 60°C. Moreover, parameters investigated as water velocity, jet diameter and jet height. It was proved that as specimen initial temperature increases, the transition from film to nucleate occurs at a higher temperature, greater time laps and gives higher extracted heat fluxes.

In 2016 H. Wang et al. [5] investigated experimentally the effect of surface modification on heat transfer enhancement of ammonia spray cooling. Liquid ammonia has been used for cooling through two impinging jets. Three types of surfaces are used in this study, the first group used is treated by electrochemistry at different levels, the second group used is treated by coating with micro-copper particles and the last group used is treated by microporous coating with micro-channels. It is found that last group of surfaces which is treated by microporous coating giving the best results in heat removal capacity.

Finally, the main contribution of the current study is to investigate the effect of surface roughness on heat transfer. A comparison has been conducted to show the cooling characteristics between smooth surface and rough surface of the specimen, two different types of rough surfaces have been studied.

2. Experimental Setup and Procedures

The test rig used for this study was the same used by El-Nasr et al. [4]. The test rig consists of water tank (1), six water heater (2) used to increase the temperature of the water to the desired temperature, pump (3), isolated pipes (4), flow meter (5), regulating valve (6) used to control the speed of water at the exit of impinging jets, control valve (7), water sink tank (8), impinging jets (9), electric solenoid valve (10), air vent valve (11), tested stainless steel specimen (12), specimen holder (13), specimen internal heater (14), thermocouples (15), connecting signal wires (16), data acquisition system (17), computer (18) details are shown in figure 1.

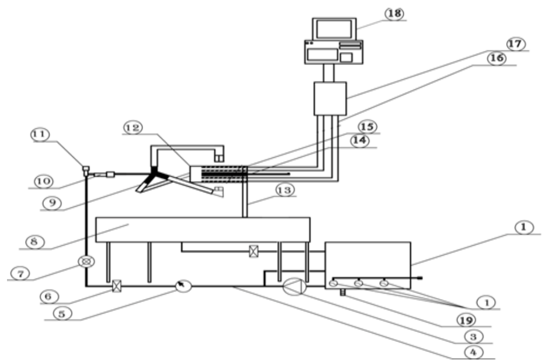

Fig. 1: Layout of experimental test rig.

The temperature distribution is measured using twelve thermo couples, k type, with sheath diameter of 1 mm, sheath length of 92 mm, thermo couples are distributed 30° apart from each other from angle 0° to 180° at angles (0°, 30°, 60°, 90°, 120°, 150°, 180°), outer thermo couple at depth of 3 mm, inner thermocouple at depth 10 mm, all the data from thermocouples during cooling have been transferred to data acquisition system, computer with programmable software which controls the operation of the data acquisition system device and is used for processing, visualizing, and storing measure data. The specimen and its distributed thermocouples are shown in fig 2.

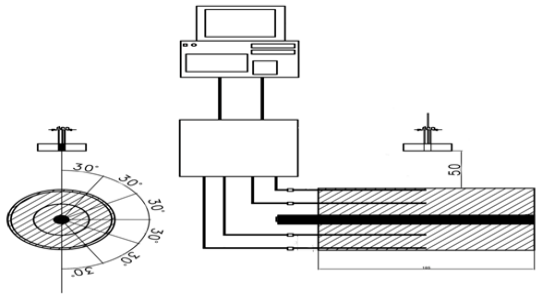

Fig 2: Thermocouples distributed in the test specimen

The specimen is made of stainless steel 134 of a chemical composition shown in Table 1.

Table 1. Specimen chemical composition

Element	Chemical Composition (%)
C	0.07
Si	1
Mn	2
P	0.045
S	0.03
Cr	17-19.5
N	0.11
Ni	8-10.5

A comparison has been conducted to show the cooling characteristics between smooth surface and rough surface of the specimen, two different types of rough surfaces have been studied. The first type fabricated by using laser cutting machine used to roughening the specimen, properties of the laser beam shown in table 2, shape of the first type of roughened surface shown in figure 3. The second type fabricated by making narrow groove channels in the specimen with width 2 mm and 30 apart from each other, shape of the second type of roughened surface shown in figure 4.

Table 2. Properties of the laser beam

Marking times	20
Mark speed (mm/s)	50
Jump speed (mm/s)	100
Laser on delay	100
Laser off delay	400
Jump delay	500
Turn delay	5
Switch frequency (kHz)	5
Release time	8
Current (A)	10

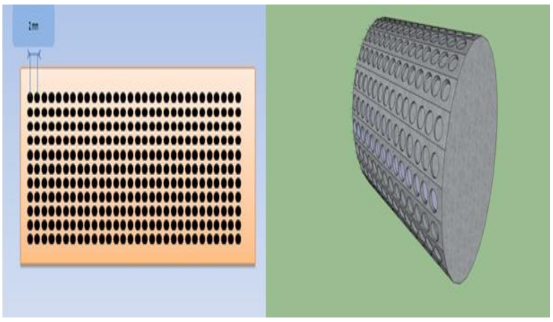

Fig 3: Shape of first type of rough surface

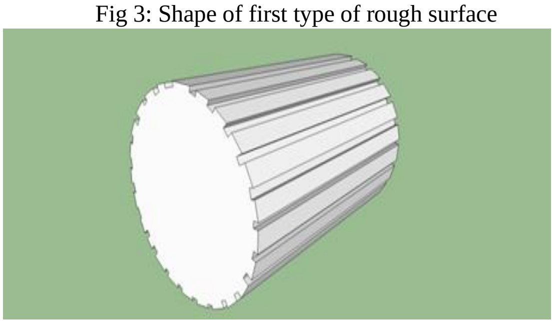

Fig 4: Shape of second type of rough surface

Table 3 represents the matrix of experiments parameters that were conducted on the test rig.

Table 3. Experimental matrix of the tested parameters

Cylinder initial temperature	**Degree of coolant sub-cooling**	**Number of jets**	**water velocity at jet exit**	**Surface roughness**
$T_{surface}$, °C	ΔTsub, °C	No. of jets	V_{jet} M/s	Smooth
250	20	1	2.5	First type
350	40	2	4	
450	60	3	6	Second type

3. Results and Discussion:

3.1 Effect of Specimen Initial Temperature ($T_{surface}$) and Comparison to Effect of Surface Roughness:

Specimen initial temperature can be expected to have a great influence effect on the cooling rate, moreover, it is important to have a comparison between the cooling rate of smooth surface and roughened surface of the specimen in the same conditions.

Figure 6 shows that with increasing the initial temperature of the specimen there is a dramatic delay on cooling rate. El-Nasr et al [4] have the same conclusion in them studies. However, figure 4 shows that of the outer point of the specimen at angle 0° the delay of cooling rate cannot be noticed as the coolant jet is just above this angle.

Additionally, it is clear that the inner points of the specimen due to the thermal conductivity of the specimen material has a slower cooling rate than the outer points as fig. 6, 8, and 10 shows.

Figure 5, 6, 7, 8, 9 and 10 shows the dramatic and noticeable effect of surface roughness as it has a great effect on increasing the cooling rate of the specimen, which i refer it to increasing of contact area between the coolant and the specimen so the heat transfer enchased consequently and it is obvious that second type of roughened surface gives better cooling rate than the first type. H. Wang et al. [5] have the same conclusion.

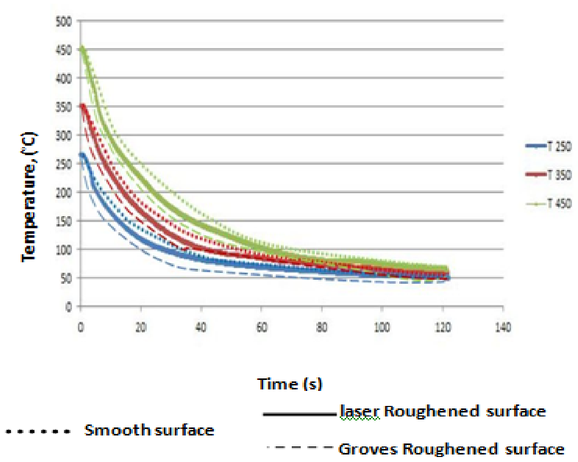

Fig. 5, Effect of $T_{surface}$, comparison between $T_{surface}$ = 450, 350, and 250 °C, effect of surface roughness, ΔT_{sub} = 60 °C, V_{jet}= 2.5 m/s, Nj =1, Outer TC, ϴ=0°.

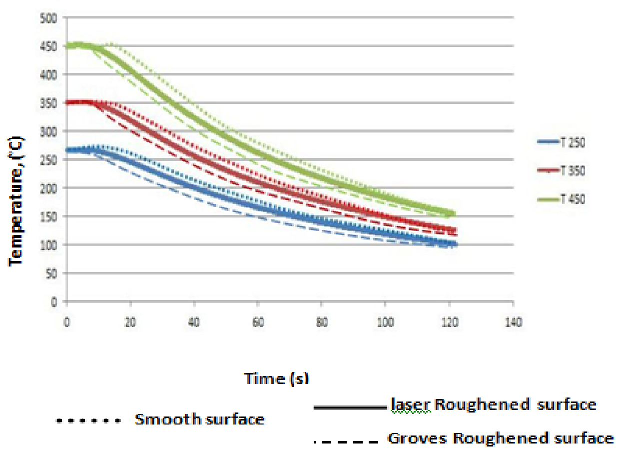

Fig. 6, Effect of $T_{surface}$, comparison between $T_{surface}$ = 450, 350, and 250 °C, effect of surface roughness, ΔT_{sub} = 60 °C, V_{jet}= 2.5 m/s, Nj =1, Inner TC, ϴ=0°.

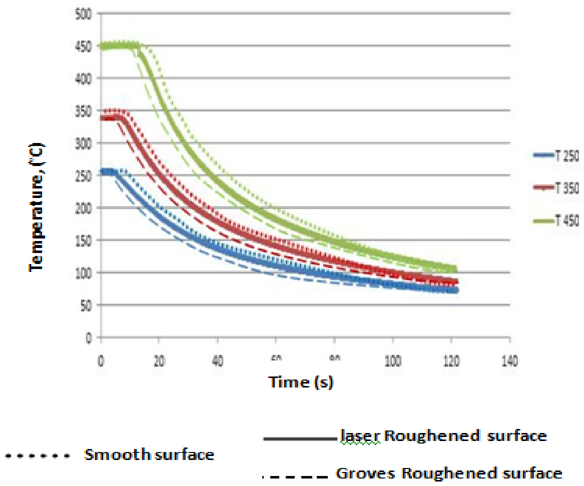

Fig. 7, Effect of $T_{surface}$, comparison between $T_{surface}$ = 450, 350, and 250 °C, effect of surface roughness, ΔT_{sub} = 60 °C, V_{jet}= 2.5 m/s, Nj =1, Outer TC, ϴ=90°.

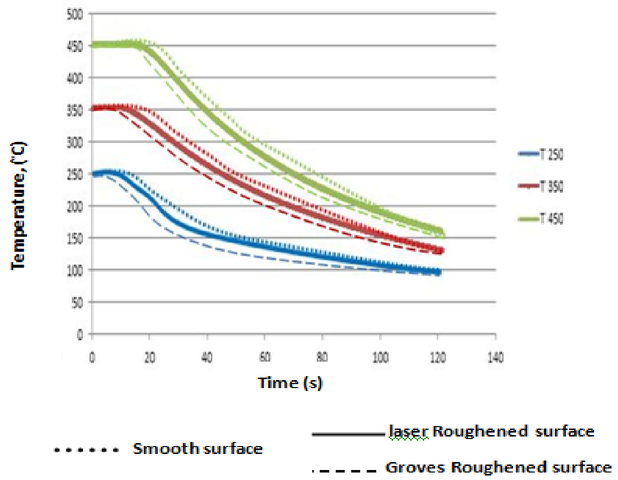

Fig. 8, Effect of $T_{surface}$, comparison between $T_{surface}$ = 450, 350, and 250 °C, effect of surface roughness, ΔT_{sub} = 60 °C, V_{jet}= 2.5 m/s, Nj =1, Inner TC, ϴ=90°.

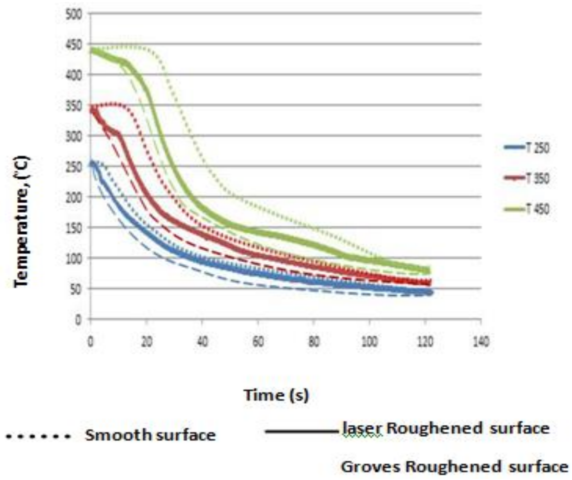

Fig. 9, Effect of $T_{surface}$, comparison between $T_{surface}$ = 450, 350, and 250 °C, effect of surface roughness, ΔT_{sub} = 60 °C, V_{jet}= 2.5 m/s, N_j =1, Outer TC, ϴ=180°.

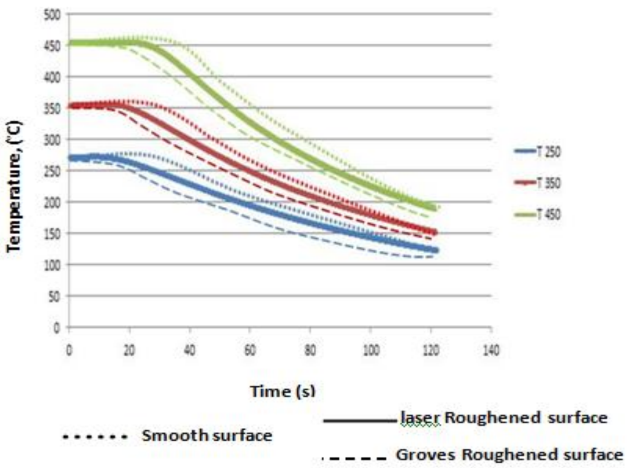

Fig. 10, Effect of $T_{surface}$, comparison between $T_{surface}$ = 450, 350, and 250 °C, effect of surface roughness, ΔTsub = 60 °C, V_{jet}= 2.5 m/s, N_j =1, Inner TC, ϴ=180°.

3.2 Effect of increasing no. of jets (single/double/triple) jet and Comparison to Effect of Surface Roughness:

No. of impinging jets can be expressed as one of the most important factors affecting the homogeneity of cooling of the specimen, the more we increase no. of jets the more we get more homogenous cooling of the specimen.

Figure 11 and 12 shows that at angle 0° there no significant difference in cooling rate between using 1, 2, or 3 impinging jets, which I refer it to the position of the impinging jet is always above the specimen at angle 0°. However, stile with increasing no. of jets there is a very little improvement of cooling.

Figure 13, 14, 15 and 16 shows that the more we increase no. of impinging jets the more we increase the cooling rate of the specimen. El-Nasr et al have the same conclusion in them studies [4].

Surface roughness influence can clearly be noticed in comparison to smooth surface, as the roughened surface has better cooling rate than smooth one as we approved before.

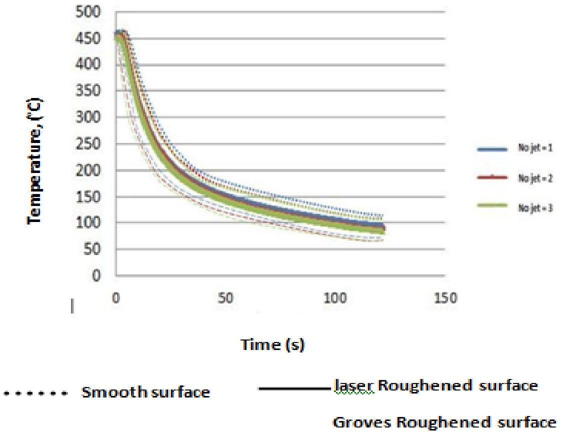

Fig. 11, Effect of number of jets, comparison between No. of jets = 1, 2 and 3, effect of surface roughness, ΔT_{sub} = 60 °C, V_{jet}= 2.5 m/s, $T_{surface}$ = 450 °C, Outer TC, ϴ=0°.

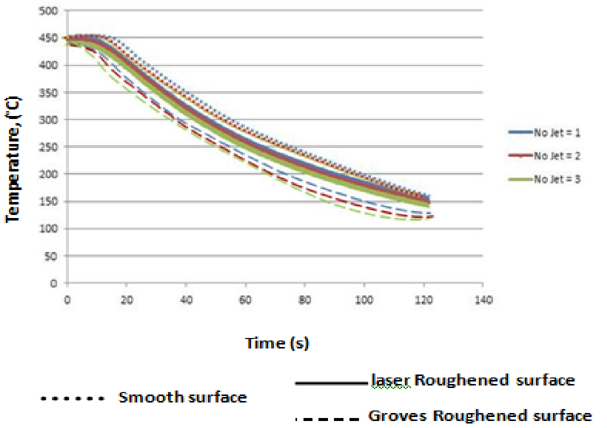

Fig. 12, Effect of number of jets, comparison between No. of jets = 1, 2 and 3, effect of surface roughness, ΔT_{sub} = 60 °C, V_{jet}= 2.5 m/s, $T_{surface}$ = 450 °C, Inner TC, ϴ=0°.

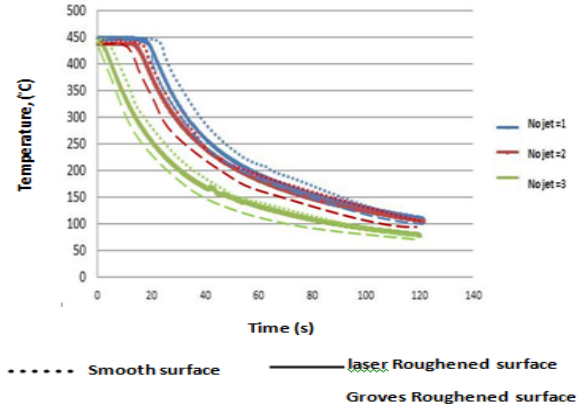

Fig. 13, Effect of number of jets, comparison between No. of jets = 1, 2 and 3, effect of surface roughness, ΔT_{sub} = 60 °C, V_{jet}= 2.5 m/s, $T_{surface}$ = 450 °C, Outer TC, ϴ=90°.

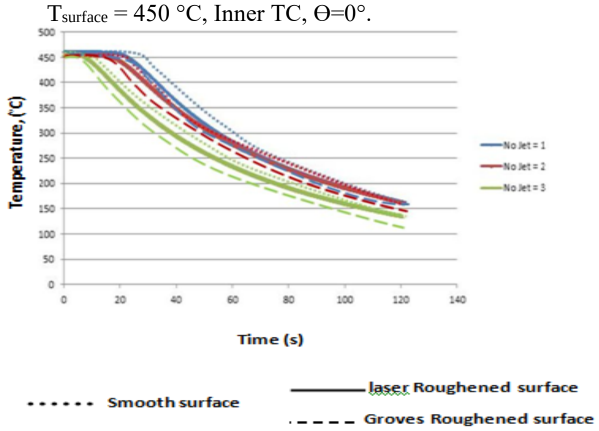

Fig. 14, Effect of number of jets, comparison between No. of jets = 1, 2 and 3, effect of surface roughness, ΔT_{sub} = 60 °C, V_{jet}= 2.5 m/s, $T_{surface}$ = 450 °C, Inner TC, ϴ=90°.

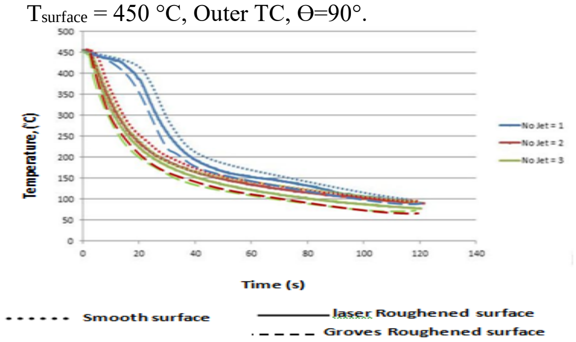

Fig. 15, Effect of number of jets, comparison between No. of jets = 1, 2 and 3, effect of surface roughness, ΔT_{sub} = 60 °C, V_{jet}= 2.5 m/s, $T_{surface}$ = 450 °C, outer TC, ϴ=180°.

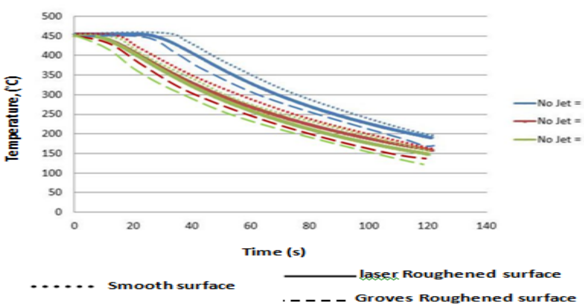

Fig. 16, Effect of number of jets, comparison between No. of jets = 1, 2 and 3, effect of surface roughness, ΔT_{sub} = 60 °C, V_{jet}= 2.5 m/s, $T_{surface}$ = 450 °C, Inner TC, ϴ=180°.

3.3 Effect of water sub-cooling temperature (ΔT_{sub}):

Temperature of the sub-cooling (Water) can easily be controlled in different practical usage, therefore it comes the importance of studying the influence of water sub-cooling temperature in cooling characteristics.

Figure 16 and 17 show three different trends of cooling with each (ΔT_{sub}). It is clear that with increasing sub-cooling temperature, water temperature degree is lower so the cooling rate increases consequently. And I refer that to the difference in temperature between specimen and sub-cooling increases which gives more opportunity for water to absorb more heat from the specimen surface before it evaporates.

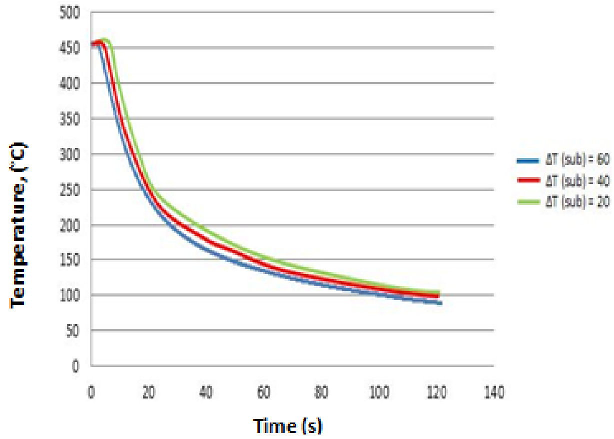

Fig. 17, Effect of water sub-cooling, comparison between (ΔT_{sub}) = 60, 40 and 20 °C, $T_{surface}$ = 450 °C, N_j =3, V_{jet}= 2.5 m/s, Outer TC, ϴ=0°.

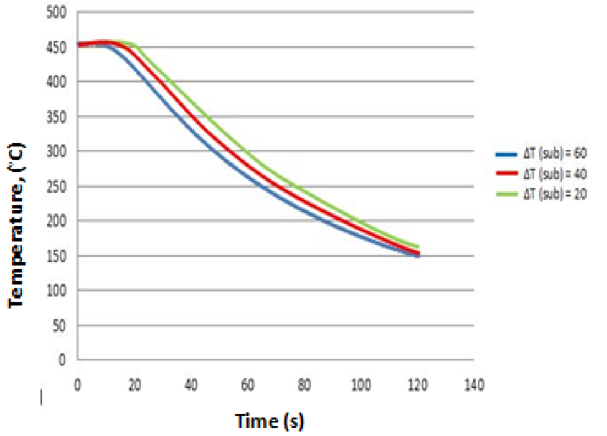

Fig. 18, Effect of water sub-cooling, comparison between (ΔT_{sub}) = 60, 40 and 20 °C, $T_{surface}$ = 450 °C, N_j =3, V_{jet}= 2.5 m/s, Inner TC, ϴ=0°.

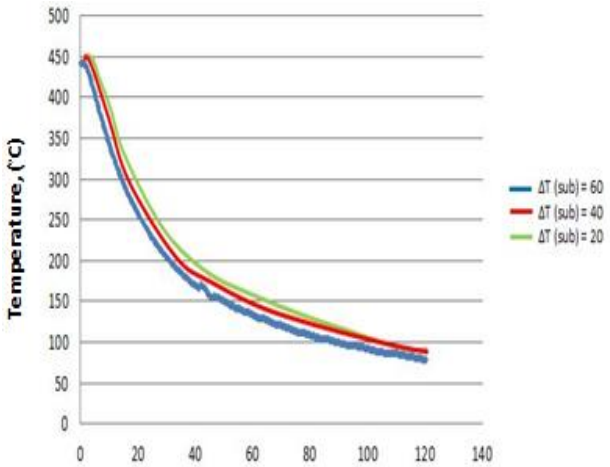

Fig. 19, Effect of water sub-cooling, comparison between (ΔT_{sub}) = 60, 40 and 20 °C, $T_{surface}$ = 450 °C, N_j =3, V_{jet}= 2.5 m/s, Outer TC, ϴ=90°.

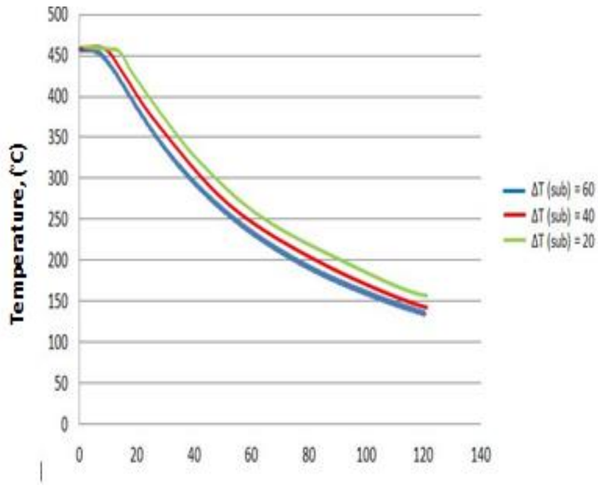

Fig. 20, Effect of water sub-cooling, comparison between (ΔT_{sub}) = 60, 40 and 20 °C, $T_{surface}$ = 450 °C, N_j =3, V_{jet}= 2.5 m/s, Inner TC, ϴ=90°.

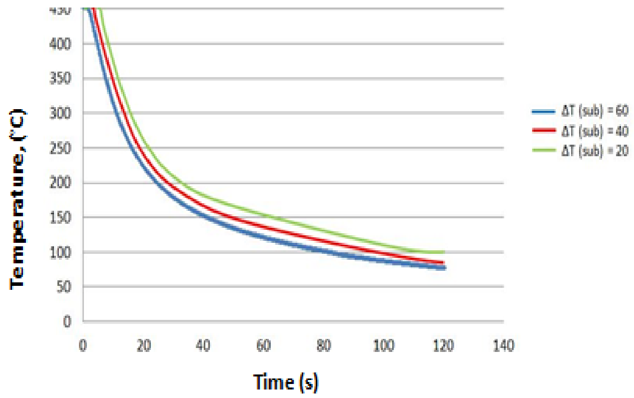

Fig. 21, Effect of water sub-cooling, comparison between (ΔT_{sub}) = 60, 40 and 20 °C, $T_{surface}$ = 450 °C, N_j =3, V_{jet}= 2.5 m/s, Outer TC, ϴ=180°.

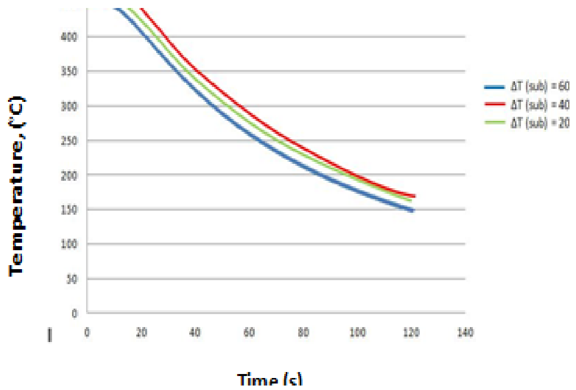

Fig. 22, Effect of water sub-cooling, comparison between (ΔT_{sub}) = 60, 40 and 20 °C, $T_{surface}$ = 450 °C, N_j =3, V_{jet}= 2.5 m/s, Inner TC, ϴ=180°.

3.4 Effect of water velocity at jet exit (Vj):

The last effect will be investigated is water velocity at jet exit, as it is also can be easily controlled in practical usage as temperature of the sub-cooling , Velocities of 2.5, 4, 6 m/s will be discussed.

Figure 22 and 23 shows the effect of increasing water velocity. The cooling rate increased when the velocity water increases. I refer that with increasing water velocity it gives more quantity of new water to absorb heat from specimen at its initial temperature which enhance cooling rate.

This phenomenon is similar to the effect of increasing temperature of water sub-cooling. Mozumder et al.[6] pointed that water velocity at jet exit and sub-cooling temperature have integrated role in cooling rate

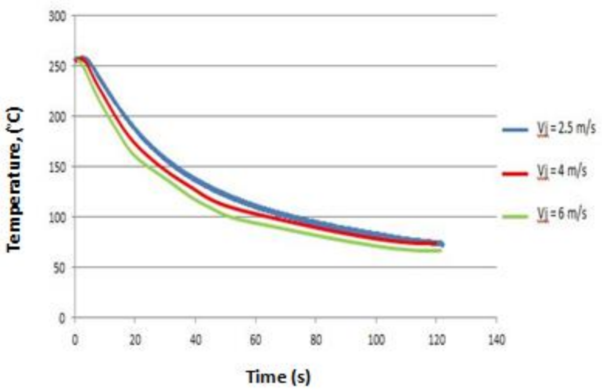

Fig. 23, Effect of water velocity at jet exit, comparison between (Vj) = 2.5, 4 and 6 m/s, $T_{surface}$ = 250 °C, N_j =1, ΔT_{sub} = 60, V_{jet} = 2.5 m/s, Outer TC, ϴ=90°.

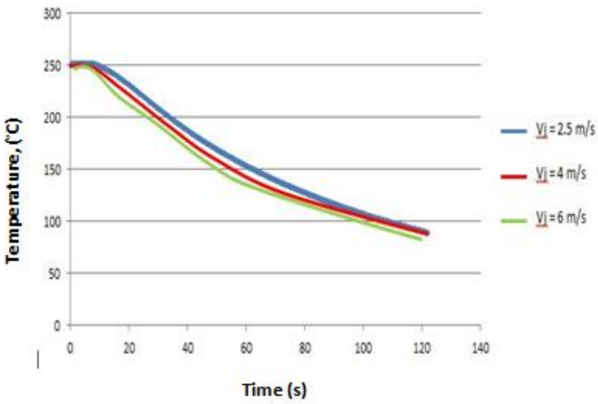

Fig. 24, Effect of water velocity at jet exit, comparison between (Vj) = 2.5, 4 and 6 m/s, $T_{surface}$ = 250 °C, N_j =1, ΔT_{sub} = 60, V_{jet} = 2.5 m/s, Inner TC, ϴ=90°.

4. Conclusion

Different parameters affecting the cooling characteristics of horizontal cylinder as Specimen Initial Temperature, no. of impinging jets, sub-cooling temperature and water velocity at jet exit. Moreover, extra investigation has been carried out to have a clear picture of the effect of surface roughness. The intrinsic achievements at present from this investigation are summarized

1) As more the initial temperature of specimen increased as more there was a delay in cooling curve.
2) At angle ϴ=0° the delay in cooling curve was not significant according to the cooling jet is just above this angle.
3) The inner points of the specimen had less cooling rate than the outer points.
4) at angle θ = 0 ° triple jets achieve slight better cooling at near surface impinging point than single or double impinging jet. However, the effect was still not significant. Moreover, the effect nearly vanished at points deep from surface.
5) The cooling effect of the triple jets appeared on angles 90° to 180° and showed that it achieved better cooling than single or double impinging jets.
6) It is clear that with increasing sub-cooling temperature, water temperature degree was lower so the cooling rate increased consequently.
7) Water velocity at jet exit and sub-cooling temperature had integrated role in cooling rate for the specimen.
8) Surface roughness has a dramatic effect on cooling characteristics, as it was clear that rough surfaces have better cooling rate than smooth surfaces due to increasing the contact area between specimen and coolant specially the second type of rough surface used in this study (groove channels).

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