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Studying of the Heat Transfer Characteristics of Circular Water Jets Impinging Hot Plate

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Abstract

Quenching is popularly used in the past decades in the steel industries to increase hardness like in southern India high material specifications called wootz is produced and it was bought all over the world also in the Islamic era they produced swards and shields with very high hardness and light weight. In our days quenching is widely studied to be the foundation of metallurgy science it depends on reducing the crystal grain size in the material. [1]

One of the most challenging techniques that devolved to positively respond to such steel industry needs is “liquid jet impingement heat transfer”, wherein one or more jets are enforced to impinge onto the hot surface by using different kinds of liquids like Water, Oil, Brine…. etc. While the main advantage of this cooling technique is providing higher heat transfer coefficients (˜20 kW/m² ·K) as compared to the conventional forced convection techniques.

Quenching process with multi jets sure will make more efficient cooling than the single jet as the specimen is surrounded with water jets in different places which will reduce the surface and core temperature and also the heat flux.

Key Words Cooling Technique, Flat Plate quenching, Heat Flux, Heat transfer, Impinging Jets, Multi Jets, Quenching heat transfer.

1. Introduction:

THIS research focused on all of the above-mentioned factors especially the number of jets and its obvious effect on the cooling process. Jet impingement technique provides effective method of heat removal comparing with conventional methods of heat removal. It has been used for thermal management of large variety of processes and applications. Jet of fluid is released normally to the surface to be cooled through circular impinged on surface with high velocity to remove the heat. The heat transfer coefficient is maximum in impingement region which is called wet front below the orifice and decreases away from this region. For extracting great amount of heat and providing better heat removal of hot surfaces, arrays of jets are used.

Accordingly, it is shown that further research work is still needed to highlight the physical insight about the liquid jet impingement research. Also, the effects of changing the jet parameters, including the jet velocity (v), degree of subcooling (ΔTsub), initial specimen temperature (Ti), and jet height from the specimen(H), need to be more analyzed. In the present work, jet impingement quenching of a stainless-steel specimen under a circular free water jets is experimentally and numerically studied. The effects of Vjet, ΔTsub, Ti, and H on the heat transfer characteristics along the block surface are investigated. In addition, some turbulent features are focused on to further attribute for the maximum heat flux at the impingement zone. In this sense, the parametric variance of jet velocity and the diameter, specimen initial temperature, and nozzle-to-specimen spacing are combined with porosity to monitor the performance. The addition of the porous screens is proposed to raise the favorable characteristics of impingement, which thus contributes to the passive control in parallel to the active control.

Impinging cooling is an effective method to make super cooling rate in many engineering applications such as steel industry, glass industry and electronics industries. Impinging jets are used to cool down the product after heating. Also, it is used in laser or plasma cutting industries and cooling of electronics equipment. in 1964 Watson studied theoretically the motion of the smooth jet of water falls vertically on the horizontal plate and spread out on its surface. In the same year 1964 Chaudhury investigated the heat transfer to Watson’s study in a parallel form. In 1981 Craik measured the liquid depth using a light absorption technology in which a laser shone through water holding a strong dye.

2. Experimental set-up and procedure: -

The experimental set-up shown in Figure 1 consists of three major components: the fluid flow system, the heated block section, and the data acquisition system (DAQ) (Point 19). The water flow loop consists of 1-m³ water tank (point 1) equipped with six heaters (point 2) of 6-kW capacity for each.

The heaters are connected to a 220-V AC power supply and six relays actuated via thermostats, which are inside the tank for controlling the water temperature. A centrifugal pump (point 4) is used to circulate the water from the tank to the acrylic tank (point 13) which is installed to have a bottom drilled with 3mm jets at several structure. A 1/2-in. turbine flow meter (point 7) is installed in the pump delivery line to measure the flow rate of the water so as to calculate the velocity of the jet issuing from the nozzle. A pressure gauge (point 6) is used to monitor the pump discharge pressure, and a needle valve (point 8) is utilized to regulate the flow rate for the jet velocity variation. A by-pass valve (point 5) is installed to provide good control to the flow rate through the main discharge line, while an air vent (point 14) is installed at the highest level to extract the entrained gases in the flow line. A K-type sheathed thermocouple (point 15), of 0.5-mm diameter, is inserted upstream of the water exit to measure the water jet temperature.

At the end of the flow loop, a 3/4-in. pipe is held

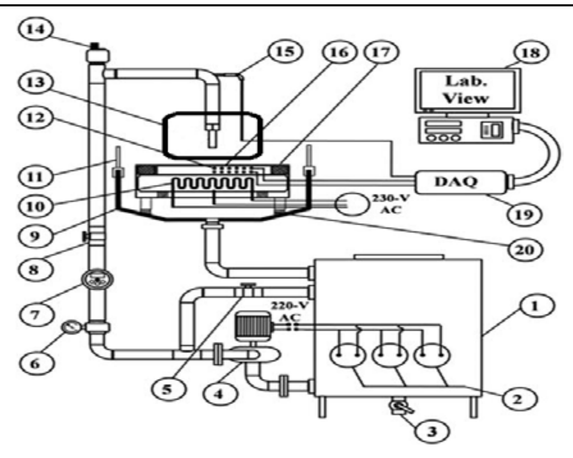


Fig.1 Experimental test rig layout (1: water tank, 2: Electrical heaters, 3: drain valve, 4: pump, 5: by-pass valve, 6: pressure gauge, 7: turbine flow-meter, 8: regulating valve, 9: water sink, 10: plate heater, 11: protective screen, 12: thermocouples, 13: Acrylic tank contains a nozzle, 14: air vent, 15: water thermocouple, 16: test block, 17: fire brick insulation, 18: computer,19: DAQ, 20: electric insulation).

vertically downward with an M17 nut welded at its end. A 16-cm long M17-threaded rod is centrally drilled by an electric-discharge machine to the specified nozzle diameter and is screwed through the nut to provide variable jet-block spacing. Once the jet impingement proceeds, the water sent out radially outward is collected in a sink (point 9), which returns the water by gravity to the tank; protective plastic sheets (point 11) are installed around the water sink to prevent hot water splashing outside the work area.

The test section consists of an electric squared plate heater (point 10), connected to a 230-V AC power supply whose rated capacity is 2 kW (to heat the test specimen [point 16] from its bottom face to prescribed temperatures).The test specimen is square shape and its length is 185mm and 25mmwidth, it was made from stainless steel (Table 1 shows the specimen chemical composition). Ten blind holes of 3mm diameter are drilled through the block parallel to the impingement surface (where five of them were drilled at 4 mm below the outer surface, and the other five holes were drilled at 10mm depth, the ten thermocouples are distributed 1.5cm between each one [2]. The specimen and the thermocouples are shown in figure 2.

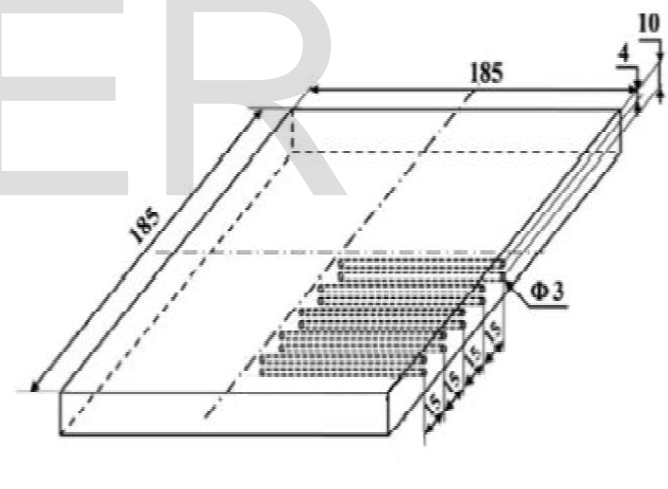


Fig. 2 Test Specimen

The chemical composition of the specimen is shown in table1

Element	Chemical Composition (%)
Cr	24-26
Ni	19-22
Mn	2
Si	0-1.5
C	.25
P	0-.045
S	0.03

Table 1. Specimen chemical composition

In the beginning, by using the regulating valve to control the amount of the water entering the acrylic tank. It starts to be filled with the cooling water and regulate the valve until achieving that all the water flow rate at the inlet "Q in" = all the water flow rate at the outlet (Jets at the bottom of the tank) after the head of the water in the tank became constant jet velocity can be calculated for every jet experiment. Also, Jet velocity can be changed by using regulating valve, flow meter and stopwatch.

Water temperature should be adjusted by using six impeded heaters to reach the testing temperature i.e. ΔT_{sub} = 20, 40 and 70°C, meanwhile the initial temperature of the specimen is raised to achieve the specimen testing temperature i.e. $T_{initial}$ = 350, 400 and 450°C, when The thermocouples temperature reading exceed the measuring temperature i.e. > $T_{initial}$,the specimen heater is turned off, and wait some moments until the specimen heat is transferred by natural convection from the surface of the specimen to the surrounding and by conduction between the inner and outer of the specimen, so the temperature of the whole specimen becomes equal, Then the DAQ. Monitor and when the reading reach the measuring temperature, the pump is turned on to deliver the coolant to the solenoid and the water valve is turned on to permit the water jet to flow to the specimen, The previous steps had been repeated for every testing condition in 8 and 16 jets at the bottom of the tank as shown in figure 3&4 by closing some jets and opening the required testing jets using screw nuts.

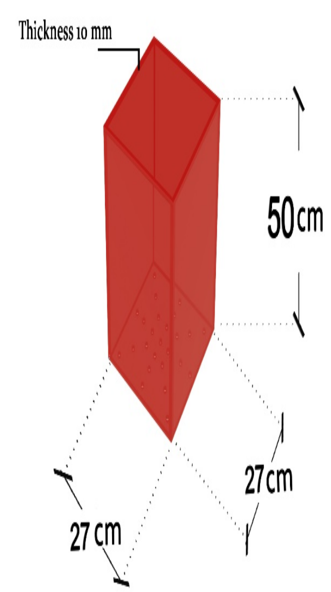


Fig.3 The Acrylic Tank

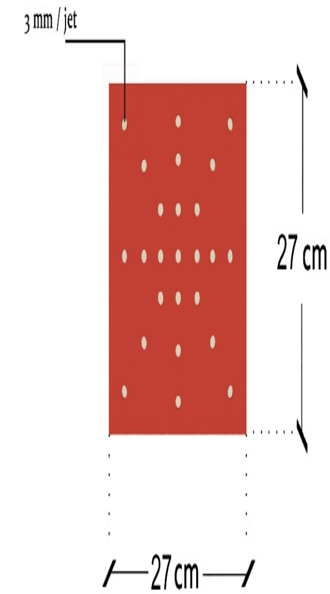


Fig.4 The bottom of the tank

This research has been done to analyze the effect of the single and multi-jets on the cooling curve and heat flux. At single jet impingement experiment, the water jet firstly remains slightly moving on the small region called stagnation region or wet front that happened for short time and then the diameter of this stagnation region start to increase with time. When the water is impinged on the block of temperature around the boiling temperature, drops spread over the solid surface in a thin layer, boil and quickly vanished. But if the block temperature is much higher the drops is no longer in contact with the solid but rise in the air above its own vapor.

In the multi jets (8 and 16 Jets) the water drops from the bottom of the tank so it creates many small regions on the specimen (stagnation point),but this regions don`t stay for a while because with the amount of water and the number of jets the water overcome the surface temperature in seconds and the cooling process transfer from the surface to the middle of the specimen. The time needed to make the quenching process is more less than that in the single jet. In the sixteen jets after 30 seconds it seems like the specimen has been submerged and the surface temperature and heat flux has been reduced in faster rate.

3. Results and Discussion

The thermocouples were located under the test surface, because it is impossible to get the temperatures directly from the surface at which the jet is impinged without greatly disturbing the flow and boiling fact.

The 2d-inverse-conduction code used can be used to get the surface temperature in different regions with inserting the parameters of the like Tinitial =400°C, ΔTsub = 70 °C, Vjet= 1.8m/s. the difference in cooling curve at different depths from stagnation point, increasing the depth away from surface decrease the effect of water jet impingement due to decreasing heat transfer coefficient also slight lag in cooling start with increasing depth. The specimen has been divided as shown in figure 5 and every region has its own temperature with three levels (Surface, Depth 4mm and depth 10mm)

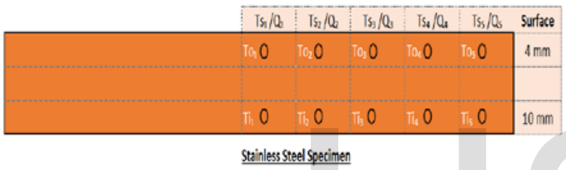


Fig.5 the specimen division of regions

Here is the comparison between the single, Eight and Sixteen jets at the same conditions in different regions on the specimen. Also, will show the effect of increasing the number of jets on heat flux and surface temperature.

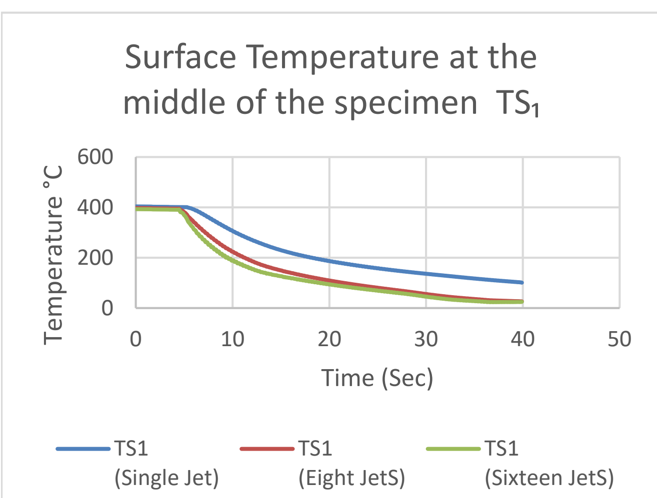


Fig.6 using 2d-inverse-conduction code to get surface temperature

The surface temperature and heat flux during quenching can be estimated from the measured temperatures in the specimen using two-dimensional inverse solution. It reveals how surface temperature changes with the movement of the wetting point.

The time needed in the eight jets and sixteen jets to make full cooling process is less than the cooling in the single jet. The curve of the temperature of the surface is the most slope will be obtained because of the amount of the water flow that will be affect the temperature of the surface.

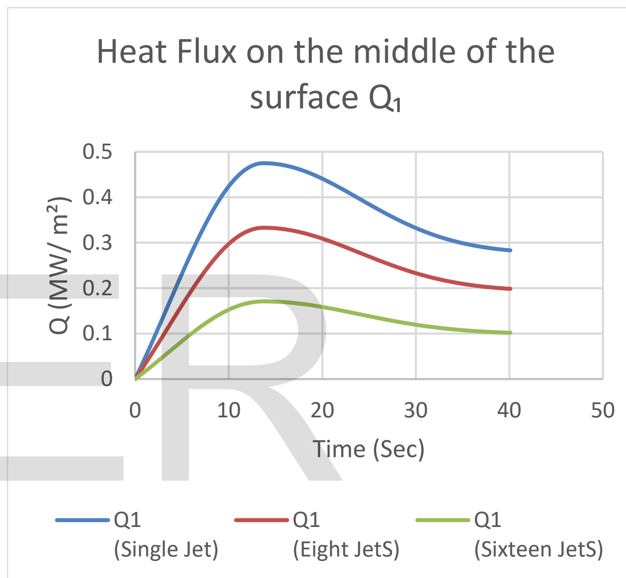
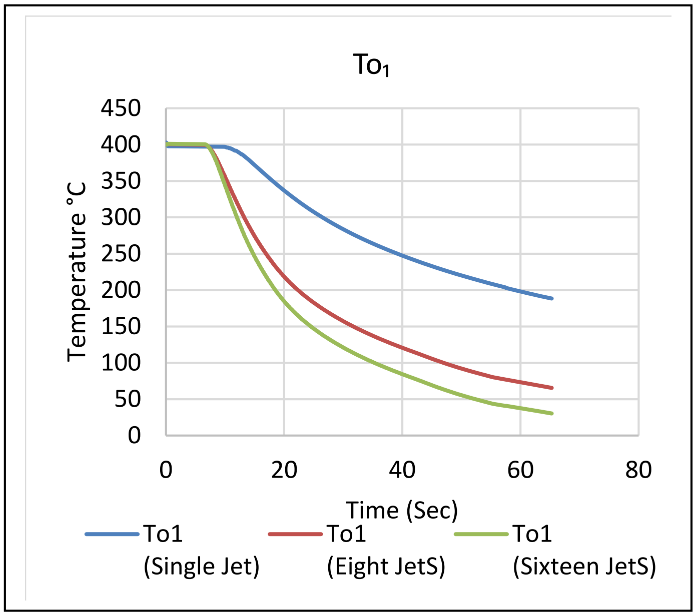
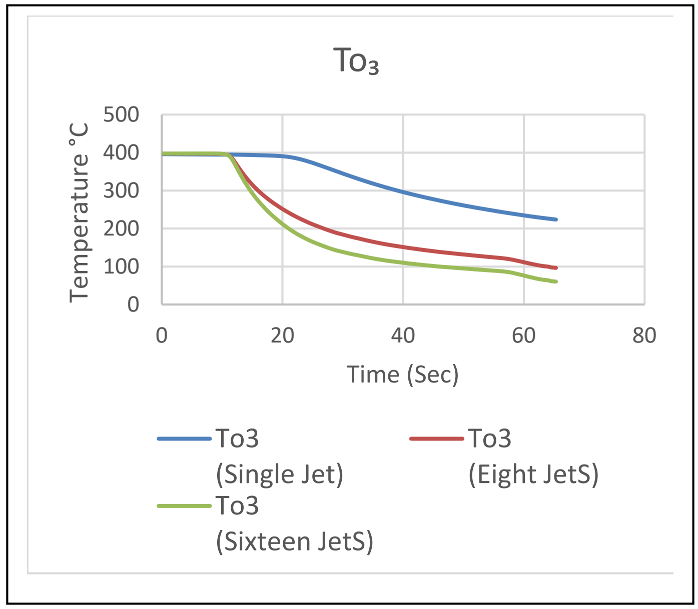
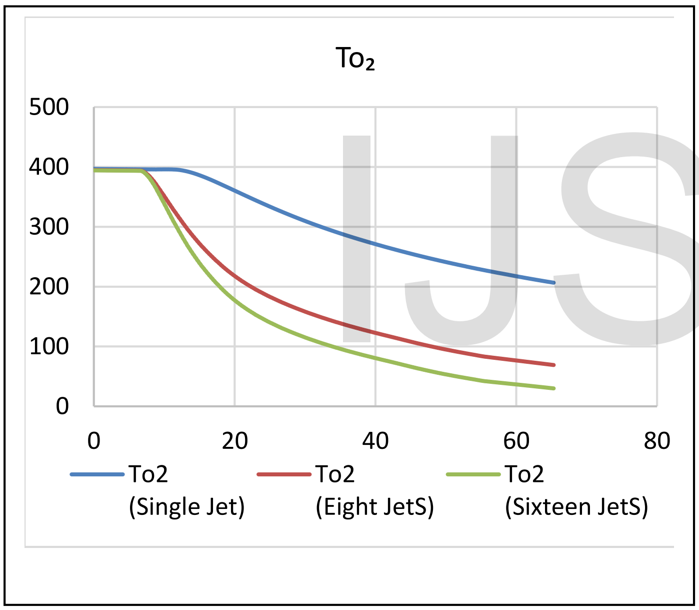


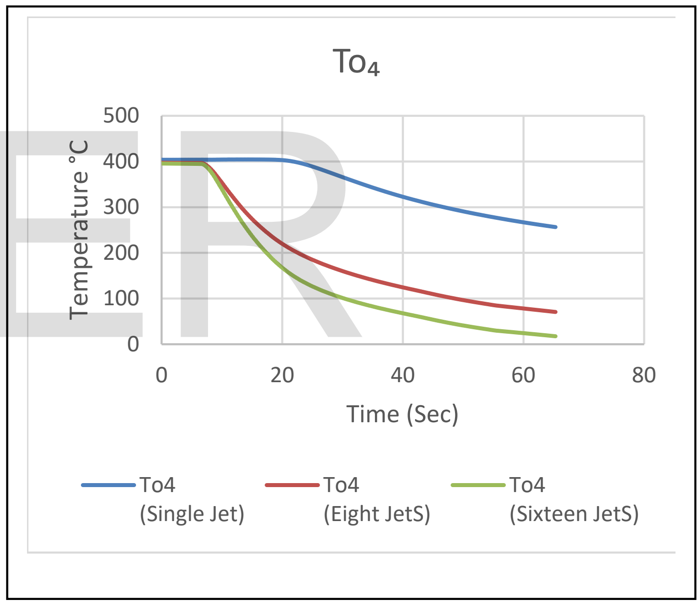
Fig.7 using 2d-inverse-conduction code to get heat flux curve on the surface

The heat flux in the case of sixteen jets was affected and the maximum value didn`t exceed 0.17 MW/m² that's mean that the flow could overcome the high temperature of the specimen that was 400°C in few times. The variance between the three readings is clearly explained by this curve.


To₁
Temperature °C
450
400
350
300
250
200
150
100
50
0
0
20
40
60
80
Time (Sec)
To1 (Single Jet)
To1 (Eight JetS)
To1 (Sixteen JetS)


To₃
Temperature °C
500
400
300
200
100
0
0
20
40
60
80
Time (Sec)
To3 (Single Jet)
To3 (Eight JetS)
To3 (Sixteen JetS)


To₂
500
400
300
200
100
0
0
20
40
60
80
To2 (Single Jet)
To2 (Eight JetS)
To2 (Sixteen JetS)


To₄
Temperature °C
500
400
300
200
100
0
0
20
40
60
80
Time (Sec)
To4 (Single Jet)
To4 (Eight JetS)
To4 (Sixteen JetS)

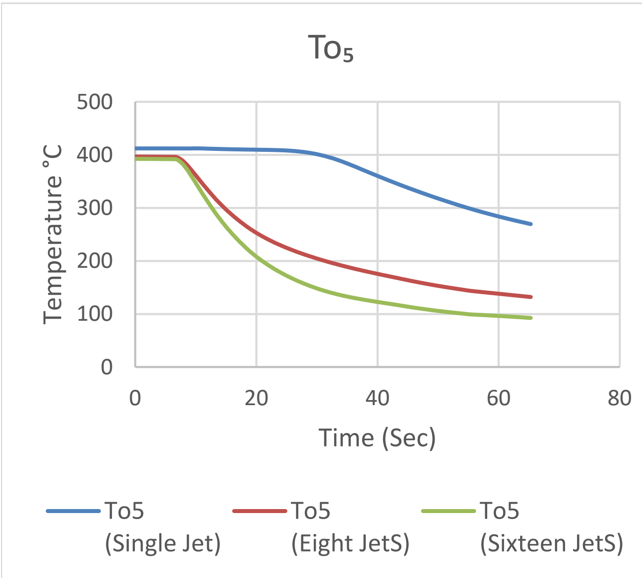
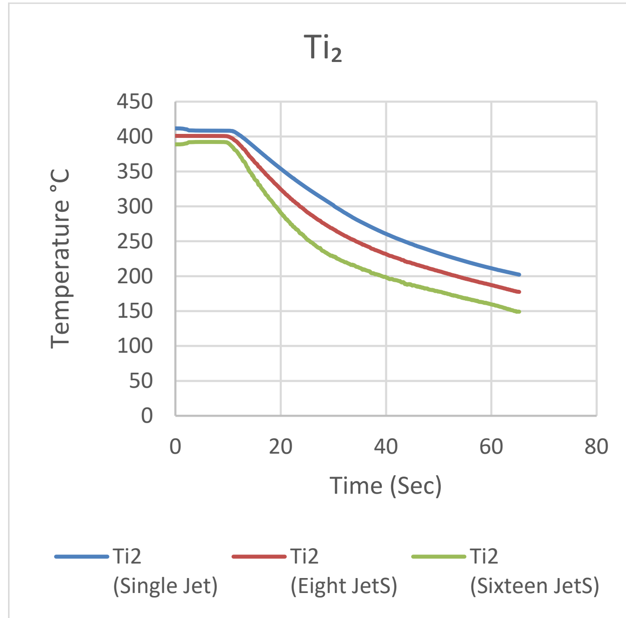
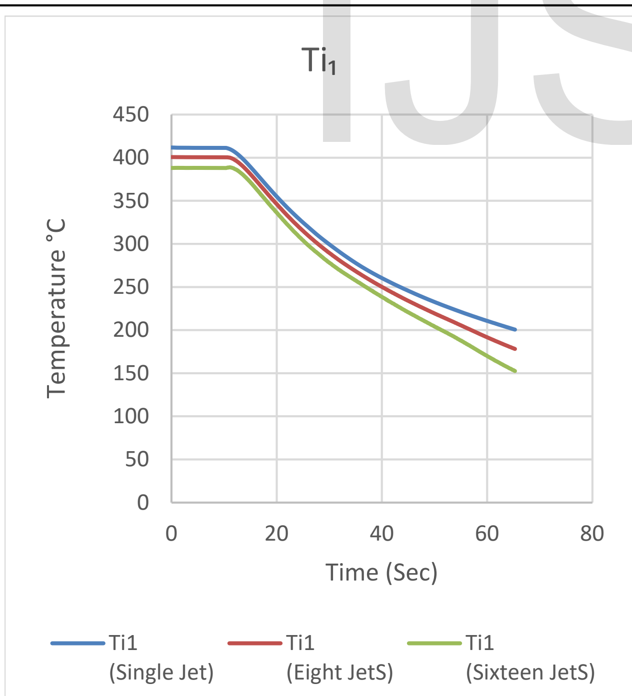
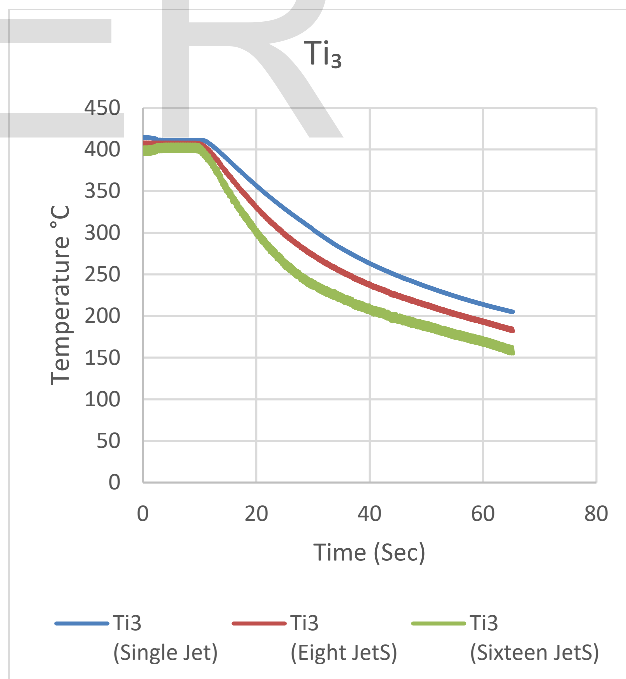


Fig.8 the different outer temperature cooling curve







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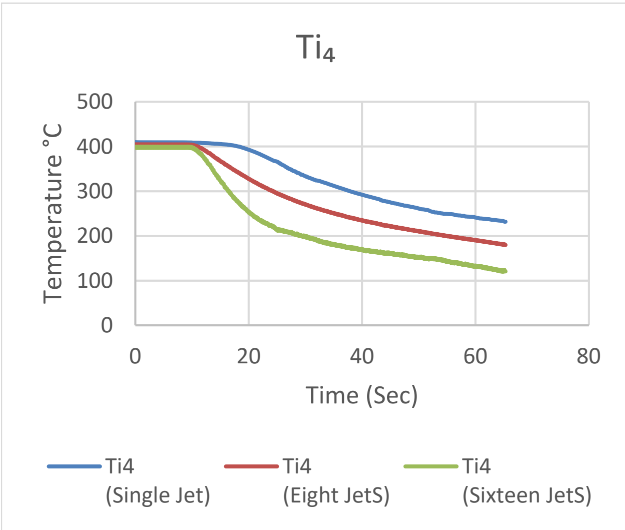

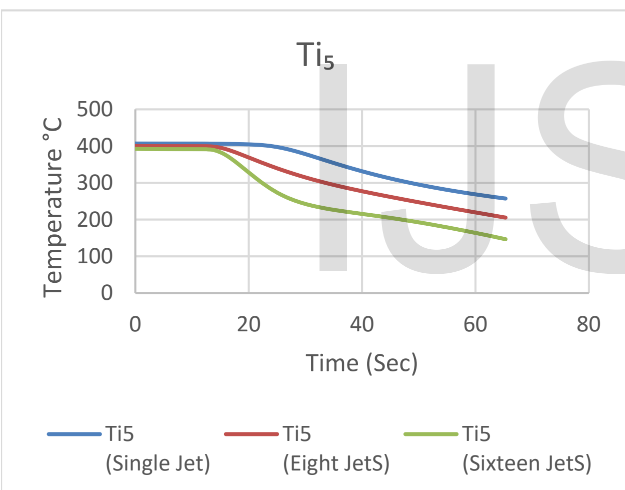

Fig.9 the different inner temperatures cooling curve

The inner temperatures curve has no obviously affected because the effect of its depth from the surface but in the edges, it began to be more obvious. The effect of the cooling process starting from the wet points on the surface after that it transferred to the bottom of the specimen and need time for doing that, so the points that located on the bottom cooled after more time.

4. Conclusions:

The heat-transfer characteristics of the water jet on stainless steel plate have been successfully determined by inverse code heat conduction method. The verification indicated that the test facility and the data filter method are suitable to evaluate the heat flux on a test plate. Quenching with multi jets is a faster method to make the specimen cooled faster and with less time. In the case of sixteen jets the specimen was like submerged with water and it takes less time to overcome the heat flux and the surface temperature. Also, there are some points that can be summarized below in this experiment:

1- Water jet impingement is one of the most important heat dissipating method for systems operating under thermally critical conditions.
2- The great effect of jet impingement placed in the center of the water jet and the heat flux difference decrease away from the center.
3- Increasing the number of jets has a clear and significant effect on the cooling process in the manufacturing and different electronics industries.
4- The resistance of the wet font in the case of single jet is more than the resistance in case of eight and sixteen jets.
5- There are a small lag between eight jets curve , sixteen jets curve and single jet curve in the beginning of the cooling curve because in the case of multi jets curve the water directly distributed in many areas not only in the middle of the specimen this leads to faster cooling curve than in the single jet curve so that the water reaches more areas on the specimen.
6- The thermocouples at 10mm depth have higher temperature in comparison to those ones at 4mm depth because of the inhomogeneity in temperature distribution of the specimen
7- Increasing the depth away from the surface decrease the cooling curve slope.
8- The time needed in the sixteen jets to make full cooling process is less than the cooling in the eight jets is less than the cooling in the single jet.

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ECI International Conference on Boiling Heat Transfer.
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6. Nomenclature:

$T_{initial}$	The specimen initial temperature (°C)
$Ts_1 \rightarrow Ts_5$	The surface temperature at different areas on the specimen (°C)
$Ti_1 \rightarrow Ti_5$	The inner temperatures at depth of 10mm (°C)
$To_1 \rightarrow To_5$	The outer temperatures at depth of 4 mm (°C)
Q	Heat Flux (MW/m²)
ΔT_{sub}	Degree of coolant sub-cooling (°C)
V_{jet}	Jet velocity (m/s)
N	Number of jets
t	Time (Sec)