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Boiling heat transfer of multiple impinging water jets on a hot rotary cylinder

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Abstract

Quenching technique is widely used in industrial applications as it enhances the mechanical properties of metals such as hardness and tensile strength. This technique consists of a heating process followed by fast cooling which results in different microstructures that enhance the metal behavior. Current competitive market in metal field requires the implementation of advanced and optimizing techniques by means of efficient and sustainable quenching techniques. Furthermore, cooling by multiple array of water jets offers wide range of cooling rate control and consequently the achievement of the desired properties.

Quenching cooling rate for a rotary cylinder by multiple impinging jets is investigated in this experimental study. A rotating steel cylinder is heated up to 700°C by an induction heater and cooled down in short time by an array of water impinging jets in order to study quenching process of the test specimen by the impinging jet technique. This fast cooling has been found to be a crucial parameter that enhances the characteristics of steel thoroughly. The magnitude of its influence has been previously studied in water pools cooling techniques. Consequently, a further understanding of quenching technique is aimed in this study by the variation of different parameters: the multiple jet's pattern (inline and staggered), jet-to-jet spacing (S/d=4 and 6), rotational speed (10-70rpm) and water subcooling temperature (55-85K) that have been studied in 10 experiments. Running of the experiments have been done with the help of different programs such as LabVIEW and NiMAX. Measurements of the temperature along the cylinder has been carried out by using some embedded thermocouples that have been connected to the DAQ.

Results from the study revealed faster cooling with rotation speed 30rpm since the contact between hot surface and impinged water jet is improved for lower speeds. However, rotation speed10rpm results experienced negative effects. In addition, jet-to-jet spacing $S/d = 4$ caused higher cooling rate than $S/d = 6$ since the impinged water from neighbor jets lead to higher interaction between water fronts and consequently a more uniform cooling. Furthermore, significant differences have been found in temperature drop between points located closer to the center of the cylinder and the ones beneath the cooling surface. Regarding the multiple array configuration of nozzles, staggered configuration revealed more uniform cooling over the surface due to the fact that placement of the jets led to a better distribution of the impinged water in the measurement line. The effect of higher subcooling temperature in agreement with previous studies results in which higher cooling rate and more drastic temperature drop.

The aim of this study is to make a better understanding of the multiple water impinging jets quenching technique in order to make further research in the area of enhancing the mechanical properties of steel by understanding effect of the quenching parameters and their characteristics in order to optimize the quenching technique for different applications.

Keywords

Quenching, unsteady heat transfer, multiple impinging jet, boiling, rotary cylinder, fast cooling.

Nomenclature

D	cylinder’s diameter (mm)
d	nozzle diameter (mm)
H	jet-to-surface spacing (mm)
n	number of jets in array (-)
q''	surface heat flux (MW/m^2)
r	radial axis (mm)
S	jet-to-jet spacing (mm)
T	temperature (^{o}C)
t	time (s)
Q	cooling flow rate (m^3/h)
x	longitudinal axis (mm)
ω	rotation speed (rpm)

Subscripts

j	water impinging jet
lf	Leidenfrost point
MHF	maximum heat flux
s	surface
w	water
sub	subcooling temperature
onb	onset temperature of nucleate boiling
stg	stagnation point

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1. Introduction

Quenching is a metal behaviour improving technique generally used in industrial processes which gives the opportunity to control wide variety of properties of steel such as hardness and tensile strength. This method is based on increasing the steel temperature above a critical value followed by a fast cooling. Different phases and constituents formed in the process lead to different microstructures as ferrite, martensite and cementite obtained from distinct cooling rates and chemical compositions of the steel.

Furthermore, quenching technique has mainly been studied for water bath (pool boiling), sprays and impinging jets cooling methods. The first one could be stated as the traditional method, leaving the latter ones as developing systems. Currently the most used technique is the pool boiling because of its simplicity even if the steel characteristics are not enhanced homogeneously along the sample. However, the lack of control regarding the cooling rate during the quenching process has led to the necessity of a deep research in another alternative in the quenching technique, cooling by multiple impinging jets. Consequently, this study tries to enhance the knowledge regarding the previously explained technique.

1.1. Background

Nowadays, steel has become one of the most fundamental materials in the industry and has even been considered an indicator showing the economic progress globally. The high importance of steel is based on the wide range of applications it provides and its material properties. It is used in different fields such as buildings infrastructure, transport (i.e., railways, roads and aerospace) and the food industry. Regarding its properties, steel is a strong, versatile and ductile material which is infinitely recyclable, over 60% globally [1].

Steel is an alloy of iron and some percentage of carbon that can vary from 0.2 to 2.14 % of its weight. The variation of the mass percentage of carbon in the alloy, the physical and the chemical process while it’s making up lead to a ductile iron as well as an enhancement of the properties such as hardness, quenching behaviour and high tensile strength [2].

1.1.1. Heat treatment

Heat treatment is an industrial process made in different metal alloys under abrupt temperature and pressure changes in order to enhance mechanical properties of the corresponding work piece. Among the different materials used in this technique the most common ones are iron-carbon alloys and glass, followed by wood and ceramics used in industrial applications.

Regarding the heat treating for steel there are three most common processes: annealing, tempering and quenching. These different processes are worth doing when the composition of steel is above the eutectoid composition (0.77% of carbon). This treatment enhances the properties of steel such as elasticity, hardness and resistance [3].

Regarding the mechanical properties of metals, they depend on the nature of the grains forming the microstructure of small crystals. Furthermore, these microstructures can be modified with the help of heat treatments such as cooling rates and diffusion. Among the mechanisms manipulating the properties of the alloys it should be remarked both martensite (intrinsic information of the crystals) and diffusion (leading to a homogeneous microstructure).

On the other hand, martensite transformation (diffusionless) it can be both for metals and some non-metals when fast cooling is presented. Due to the fact that cooling is done within seconds, there is the possibility that insoluble atoms do not have time to migrate out of the solution. These trapped atoms, do not let the crystal matrix transform into the lower temperature corresponding structure. In addition, shear stress is created within the microstructure. This transformation makes different effects depending on the material used, when done in steel it hardens the metal and when done in aluminium alloys creates a soften effect.

On the other hand, regarding the diffusion transformation atoms have time enough for migrating out of the solution causing this a homogeneous distribution in the microstructure. Diffusion is also known as precipitation process in which atoms piece together at boundaries of the grains that generate a structure at least two phases. For instance, in the case of steel when it is cooled down slowly layers of ferrite and cementite are formed known as soft pearlite [3].

Heat treatment methods

As it has already been mentioned the most common heat treatment methods are: annealing, tempering and quenching.

Annealing

Annealing process is made with the main aim of increasing ductility, reduce internal stresses and to give workability for machine-tool industry in cold working. This heat treatment consists of a first phase in which the material is heated up to a predetermined temperature which is generally upper the critical temperature in ferrous alloys. Secondly, this temperature is held for a certain time and finally is slowly cooled down by natural convection until room temperature is reached. Consequently, a refined microstructure is obtained, leading to the formation of pearlite so that recrystallization can occur and plastic deformation recovery is achieved [4].

Quenching

This common technique consists of a first phase of heating an iron-cast alloy above the recrystallization point followed by a later phase of fast cooling it in different fluids such as water, air and oil in order to obtain some specific material properties such as increasing hardening and the ductility which is a fundamental purpose in the steel industry. Regarding the air as a cooling fluid, it is normally used when it is compressed for a faster cooling. However, this rate is still too slow to change mechanical properties. In contrast, oil has a higher cooling rate which allows the mechanical properties to change within a shorter period of time. Nonetheless, oil is highly flammable and has a higher cost of maintenance, causing this a remarkable disadvantage. Among the three mentioned fluids, water is the one that provides the highest cooling rate, is an available concern, as well as economically affordable makes it the most used one. When water is used in the quenching heat treatment it can be used in both water bath tanks or with partial flush.

Generally, water is used as the cooling fluid since it reaches the maximum hardness of steel with risk of having cracks in the work piece. Therefore, when requirements of the alloy are not so strict, oil and air are used as cooling fluids since they give a lower cooling rate.

These properties are obtained by heating above the eutectoid point of iron-cast alloys at 727^{o}C, so that transformation from pearlite microstructure to harder microstructure known as martensite is achieved. Among the different methods for quenching the most popular one is based on a water bath of the heated work piece. Furthermore, there are some developed techniques which are still in research such as using water impinging jets [5].

Tempering

Tempering refers to the heating treatment on ferrous alloys which increases toughness, and reduces both hardness and brittleness of the processed body. Tempering is normally done in furnaces after quenching by heating the alloy to a temperature below the critical point. By running the process at a temperature lower than the critical point avoids the alloy from destroying the martensite, the hard microstructure obtained from previous quenching. Furthermore, once the desired temperature has been reached and held for a certain time the process of cooling down by means of natural convection with air starts.

There are different types of tempering depending on the temperature at which heating is done. Between 160 and 300^{o}C heating process at low temperatures, hard working tools are obtained with up to 60HRC hardening. Next, at medium temperature (between 300 and 500^{o}C) spring steels are obtained with a softer structure of up to 45HRC. Finally, at the highest temperatures (above 500^{o}C) both hot working tool steels as well as high speed steels are produced between 65 and 300HRC, [6].

1.1.2. Boiling regime curves

Boiling regime curve for water bath technique

Pool boiling curve show the relation between heat flux, q”, in the vertical axis with the temperature excess ΔT = T_W -T_{SAT} in the horizontal axis during the quenching process. Temperature excess refers to the difference between the wall temperature, T_W and the saturation temperature of the liquid T_{SAT}.

The aforementioned boiling curve is shown in the Fig 1. As it can be observed the graphic is shown in logarithmic scale in order to reach the wide ranges of the concerned parameters. The boiling curve given is under the conditions of 1 ATM for boiling water for a temperature-controlled environment in a bar.

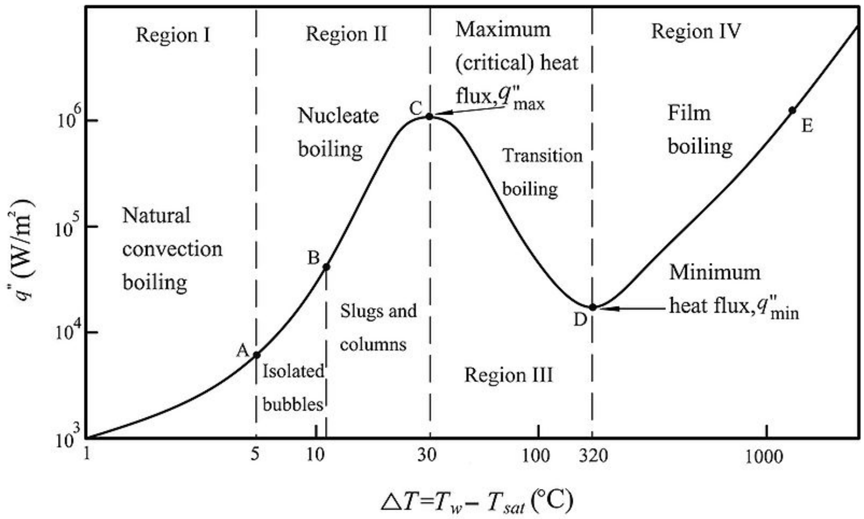


Figure 1. Pool boiling curve in a bar for saturated water [7].

In addition, the surface temperature values define three different boiling regions depending on the surface temperature magnitude:

- Natural/free convection
- Nucleate boiling
- Transition boiling
- Film boiling

Natural/free convection

Regarding the first region, the temperature excess is less than 5°C. No bubbles are formed in these conditions yet. As it can be observed in the Figure 1, heat transfer increases with the increase of the temperature excess. As no boiling occurs yet, all the heat transfer from the solid surface to the bulk liquid is done by means of natural convection [7].

Nucleate boiling

First of all, nucleate boiling refers to the region where ΔT is between 5 and 30ºC. In this second region, the formation of vapor bubbles start in different locations within the solid known as nucleation sites. These sites are microscopic cracks that result in a higher heat transfer as the interface between the liquid and the solid is enhanced due to the perfectly cracked smooth surface. Therefore, the liquid vaporizes in these sites first. Once bubbles are generated, they increase their size continuously as far as they reach the liquid free surface. When they leave the surface, the previously occupied space is later filled by liquid leading this to the increase of heat flux until maximum value q''_{max} is reached, also known as critical heat flux around 1 MW/m^2 at 30ºC of temperature excess approximately.

As it can be observed in Figure 1, two sub-regions are defined in nucleate boiling range. First, from A to B subregion, bubbles reach the free surface without interfering among them and convection heat transfer still remains. In contrast, for the other subregion (from B to C), as there is higher temperature excess more bubbles are formed, causing this the interaction among them [7].

Transition boiling

The increase of temperature excess results in the creation of unstable vapor films from the liquid as it takes too much heat from the heated solid. Consequently, the liquid present difficulty to get into the heated surface and eventually heat transfer shows a decreasing tendency.

The fact that unstable vapor film and partial nucleate boiling coexist leads to the nomenclature of “transition boiling”. Once the stable vapor film is obtained, the minimum heat flux q''_{min} value is reached at Leidenfrost temperature [7].

Film boiling

Last boiling regime is shown for temperature excess higher than Leidenfrost temperature. In these conditions, there is a complete separation between the stable vapor film and the liquid. In this region, heat transfer is both by convection in the vapor film and by direct radiation. Consequently, heat flux increases as excess temperature increases. Film boiling continues until the maximum temperature of the solid work piece is reached, before it melts [7].

Boiling curve of water impinging jets technique

The boiling curve related to the water impinging jet technique is shown in the Figure 2 which is completely different to the boiling curve of pool boiling method. As it can be observed the graphic is shown for three different regions depending on the surface temperature, T_s.

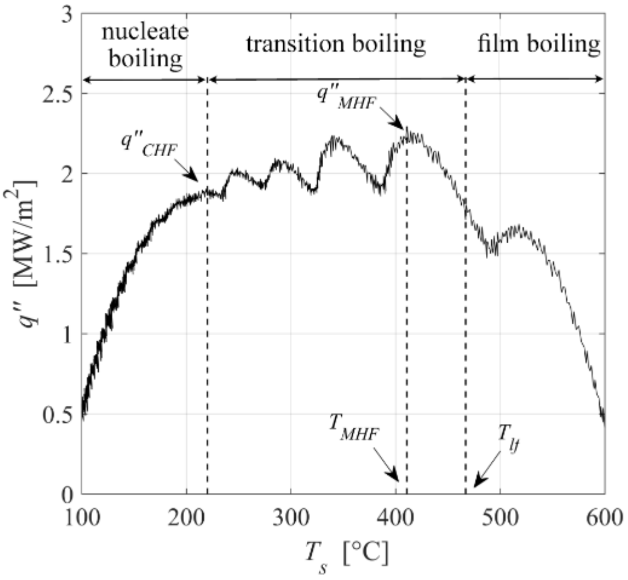


Figure 2. Boiling curve of subcooled water in the impinging jet technique [9].

As it can be observed in the Figure 2, transient quenching begins at a surface temperature of 600^{o}C in film boiling regime. As T_s continues dropping due to the cooling process, it reaches the Leidenfrost temperature,T_{LF} which marks the boundary limit between film and transition boiling located within the range 450 and 475^{o}C of the surface temperature [9].

Then, cooling continues within the transition boiling regime and the maximum heat flux value, q''_{MHF} is reached at the corresponding temperature T_{MHF}, lower than the Leidenfrost temperature. Transition boiling regime presents an unstable vapor film over the cooled surface as well as a decrease in the inefficiency of quenching by means of the vapor film.

Furthermore, temperatures lower than T_{MHF} (the one associated to the heat flux peak value) continue decreasing in the unstable regime until they eventually reach the critical heat flux value, q''_{CHF}. This peak defines the boundary limit between transition and nucleate boiling. As Ts continues decreasing in the quenching process in the nucleate boiling regime less bubbles are formed over the surface and consequently direct heat transfer is enhanced from the solid to the liquid while Ts is lower than $T_{ONB,}$ onset temperature of nucleate boiling, Eventually, for temperatures which are lower than $T_{ONB,}$ surface cools down by means of a single phase forced convection by water impinging jet [8].

1.1.3. Phase diagram (iron-carbon alloy)

In the Figure 3 the different structures of iron-carbon alloys are observed for the different temperatures and carbon percentage by weight. Eutectic and eutectoid points are presented as well in this figure.

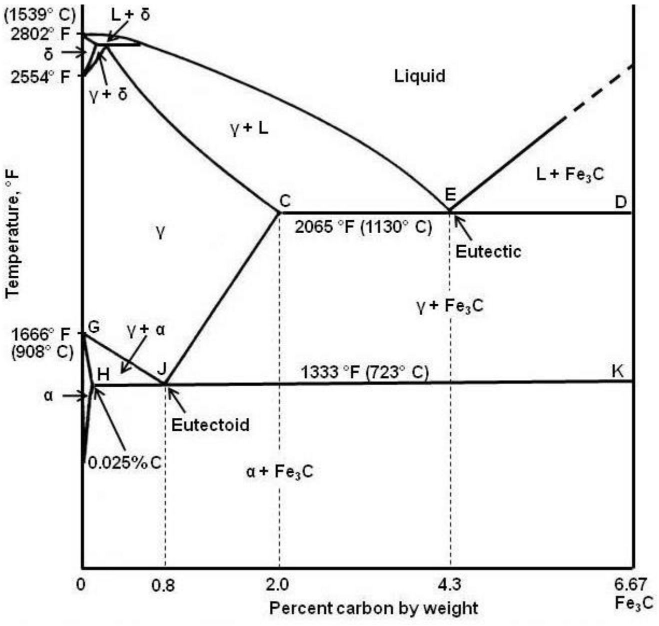


Figure 3. Phase diagram for iron-carbon alloys [2].

Eutectoid alloys

These alloys consist of a single melting point which is under the melting point of any of the substances forming the alloy. Regarding the cooling of an eutectoid alloy, the materials forming the alloy crystallize in different phases leading this to the creation of a single microstructure.

For instance, eutectoid steel corresponds to 0.77% of carbon in the weight percent of the alloy. In this configuration, slow cooling reaches to a state where iron and carbon separate into ferrite and cementite phases forming pearlite, a microstructure of layered nature [3].

Hypoeutectoid alloys

These alloys consist of two different melting points which are lower than any of the melting points of any substance in the structure. This kind of alloys has both a solid and a liquid part. Among the constituents forming the system, the first one solidifying is the one with the smaller melting point.

Furthermore, the hypoeutectoid alloys are the ones with a lower than 0.77% of carbon in the alloy's weight percentage. When temperature is decreased in hypoeutectoid alloys small ferrite is formed in austenite transformation which continues growing until the eutectoid concentration is obtained in the rest of the steel. Finally, the microstructure solidifies creating a crystal structure of pearlite which enhances ductility property [3].

Hypereutectoid alloys

In this kind of alloys there are also different melting points and is the substance with higher melting point the one that will solidify. In addition, the cooling of this alloys from high transformation temperatures leads to the solidification of excess solutes which continues until all the concentration reaches the eutectoid point [3].

1.1.4. Quenching cooling rate

In order to discuss relation between cooling time and the temperature drop in the material, continuous cooling transformation diagram (CCT) steel alloys are explained. This diagram shows the relation between the logarithmic of time and the temperature of a steel alloy for a certain composition.

Among the objectives of this diagram, it should be remarked that it is useful for determining the percentage of austenite microstructure at different temperatures as well as giving the possibility to identify the type of microstructure and their composition with the aim of reaching desired properties in the alloy. Furthermore, both spray jet and water impinging jet cooling result in different mechanical properties which can be obtained by thermal management adjustments such as modifications in the cooling rate [10]. In addition, different parameters such as the hardness of the transformed body and the specification of the time needed to accomplish the desired transformation are shown in the diagram.

However, there might be some factors that affect the CCT diagram such as:

- Percentage of carbon in weight in the steel alloy
- Grain size
- Level of heterogeneous austenite

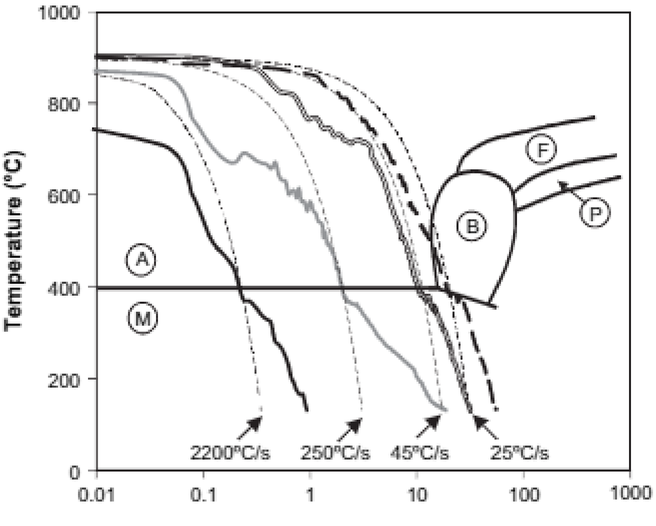


Figure 4. CCT diagram for BORON steel USIBOR 1500P [11].

Figure 4 shows the CCT curves for BORON steel (USIBOR 1500P) where it can be seen the different microstructures areas:

- A: austenite

- M: martensite
- B: bainite
- F: ferrite
- P: pearlite

The figure presents four different cooling rates: 2200, 250, 45 and 25ºC/s. When direct transformation occurs from austenite to martensite microstructure, the maximum hardness is obtained. Nevertheless, as it can be observed in the diagram, 25ºC/s cooling rate is close to the critical value since not only martensitic microstructure, but also unwanted bainite microstructure takes place.

As the carbon in boron is less than 0.6%, the further analysis of the magnified section of micrographs shows austenite grain boundaries as well as packets of parallel lath crystals which are characteristic in martensite [11].

In order to confirm the enhanced mechanical properties for austenite-martensite direct transformation, micrographs of the 2200ºC/s revealed a fined randomly oriented structure along microstructure. As a result of this increase in the dislocations, strength and hardness properties enhance.

In conclusion, when martensite full transformation is obtained the final alloy has a higher strength which is what current industry looks for. However, when lower cooling rates than the critical line (25ºC/s) are used, undesired configurations such as bainite, pearlite and ferrite are formed. These unwanted transformations lead to undesired internal stresses.

1.2. Literature review

Previous researches have studied the quenching techniques from different points of view and in different fields in order to give a better understanding of this method, as well as being able to forecast the cooling time in an element to obtain new or better mechanical properties. Previous investigations used basic arrangements with a higher temperature than the Leidenfrost one (the phenomena that describes the vapor formation near a liquid when it is contact with a surface whose temperature is higher than the boiling temperature). For instance, unique jet impinging a moving plate [12].

In addition, theoretical studies focused on simple situations as starting points such as a symmetric jet impinging a fixed cold surface and a planar jet impinging a moving plate (cold or hot). Consequently, the necessity of a different situation was raised regarding the field of research [12].

It should be remarked the development in advanced techniques. The experiment was based on a hot rotary cylinder heated up to 600ºC and impinged by a planar jet. Signal treatment and special instrumentations were used and arranged in order to acquire the data corresponding to the surface temperature as well as the extracted heat flux [12].

This study focused on some ideas which the researchers considered a matter of study, such as the behavior of the ultra-fast temperature drop with the analysis of different parameters as water jet velocity, surface-to-jet speed ratio and the subcooling temperature. As a result of the high heating temperature above the Leidenfrost one, all the regimes from film to nucleate boiling are put to examination.

As a result of this experimental study, it was proven that cooling rates vary with the rotational speed of the surface and it was accomplished a wider understanding of the boiling regimes and the surface speed relation to the water flow field over the moving surface. This experiment concluded that cooling rates also depend on the surfaces that are being cooled down whether they are in a static or dynamic state, resulting in a great difference between the ones that move and the ones that have a fixed position. Due to the fact that the moving surface induced a collapse of the heat flux, it was found that the largest difference was located in the surroundings of the flux region.

Further research carried out experiments in a rotary cylinder that was previously heated up to 500-600°C and quenched next by an impinging planar jet located in a parallel position to the symmetry axis. It consisted of a stainless-steel piece that was subcooled after heating it to comprehend the two-phase flow developed during the quenching [13].

Temperature of the wall which varies with the time was measured with embedded thermocouples. However, as heat fluxes meant a more challenging measurement, they were calculated with inverse solution method. The results from the experiment confirmed the existence of the relation between the quenching cooling rates with the water jet's speed and its corresponding temperature, as well as with the speed ratio from the surface to the jet. In addition, it must me remarked that this experiment was held in boiling conditions since its aim was to understand boiling heat transfer by water impinging jet cooling.

The research concluded the existence of three different regions over the impingement surface: an outside dry region, a moistened free-surface of the impinged liquid (normally water) located in the center and a circular wet front area in the surroundings of the central region. Furthermore, results from the experiment noticed the deflection of the subcooled fluid around the circular wet front area, followed by the breaking into droplets due to the high surface tension and shear forces.

Further investigation regarding the quenching technique in cylinders has been done. Regarding other studies [14], more parameters were taken into account for a wider range such as the subcooled liquid flow rate which was varied from 0.36 to 0.6m^3/h and from 60 to 80°C which had previously been fixed in aforementioned research. The impinging jets used in this experiment had 15mm of diameter and the water impinged in a horizontal direction to a hot hollow cylinder. Furthermore, the rotational speed of the surface was varied from 0 to 60rpm in 15rpm increasing steps, and heated up to 560°C. In contrast to previous researches, the surface wall temperature was not measured with thermocouples but with the help of inverse solution. In addition, the heat flux measurement technique was maintained in regard to previous investigations, with inverse solution also.

The analysis of the experiments led to the conclusion of the existing significant heterogeneous cooling. Consequently, a heterogeneous wetting front formation occurred. From the study it was also concluded that there is a strong relation between the surface speed (rotation) and the surface boiling heat transfer during cooling.

The experiment revealed that the heat transfer decreased for moving surfaces as it was the case in this research in which the cylinder's temperature was analyzed at different rotational speeds. Due to the fact that the jets were stator and the cylinder was rotating, it could be observed from the measurements the cyclical tendency of the surface temperature showing a similar behavior to nucleate region regime curves.

In addition to the aforementioned investigations, more recently research has been done in the area of quenching process on a rotating hollow cylinder by one row of impinging jets [15].
In contrast to previous researches, different modifications were held in this investigation such as smaller jet diameter leading this to higher water jet velocity for the same flow rate. In addition, subcooled water varied from 55 to 85˚C and jet's pattern was analyzed regarding the separation between one another which was varied from 2 to 8 times the size of the diameter. It must be remarked that this study included the variation of the impinging jet's impact angle from 0 to 135°.

Data interpretation revealed that more homogenous cooling rates were obtained for less distance between different jets as wet regions for each of the impinging nozzle spacing was closer to the jets installed besides. Furthermore, the analysis of the results showed different characteristics when the water was impinged from and horizontal direction. In addition, lower cooling rates were obtained for surface temperatures higher than the Leidenfrost temperature and higher ones when the temperatures where below it, since higher heat transfer took place. The investigation also confirmed the higher effects on cooling rate in transition and film regimes and neglectable in nucleate boiling regime.

Research study of quenching process by water impinging jets has been continued recently. Jahedi and Moshfegh [16] reported further investigations in rotation speed (from 10 to 70rpm), the spacing between jets (from 4 to 10*d*) as well as the distance between the jets and the surface (from 1.5 to 7*d*).

It was concluded that higher average heat transfer was obtained by increasing flow rate and subcooling temperature and lower initial wall superheat temperature corresponding to onset of transition boiling regime. Further results concluded that much better cooling rates were achieved with: lower ω (30rpm), which guarantees longer interaction time between the moving surface and the water coming from the jets, lower jet-to-jet spacing (2 - 4*d*) and impinging impact angle of 90°, so that the effect of gravity force on water impingement flow becomes weaker which leads to better contact between liquid and solid surface [16].

This research meant a big advance in the area of the improvement of the quenching technique as a wide range of parameters were analyzed as well as because it introduced the method of using multiple jets. However, further research is needed to be done to confirm the patterns of quenching technique in the steel to enhance its properties which are enormously needed in current industry. Consequently, more parameters such as the shape of the steel, jet configurations, impinged water temperature and jets impinging velocity should be studied. In addition, previous research has been done in hollow cylinders leading this to the necessity of a further investigation in solid cylinder which will be carried out in this study.

1.3. Aims and approach

The research study aims to enhance further knowledge in the area of quenching technique by means of an array of impinging jets in a steel rotary cylinder experimentally that consider different parameters which are followed by a sensitive analysis. This aim is achieved by carrying out experimental study of various parameters in this study and analyzing the output data from Matlab inverse solution code that predicts surface temperatures and heat flux distribution along the steel cylinder.

In addition, as the quenching technique used in this investigation is still in development phase, another aim this project considers is to study its efficiency in order to get controlled cooling rates as homogeneous heat flux distribution is expected, while traditional pool boiling technique shows heterogeneous properties along the test specimen.

Furthermore, this project enlightens knowledge concerning advantages and disadvantages of quenching using multiple arrays of impinging jets in rotary test specimen in order to achieve the desired cooling rate.

2. Method

2.1. Experimental test setup

An experimental test rig [15] has been used in order to run the experiments as it can be observed in the Fig. 5. As it can be seen both heating and cooling operations occur in test chamber 7. The process starts by recirculating the water from the upper tank (5) in a closed circuit, when solenoid or magnetic valve (4) is closed so water does not go to the impinging setup (8). This recirculation process allows to check water levels in both tanks and is useful for adjusting the flowrate by means of the control box for the blue pump which is responsible for pumping water in the recirculation process and will later be the one in charge for the impinged flow rate used as cooling water to the heated steel cylinder when solenoid valve is open.

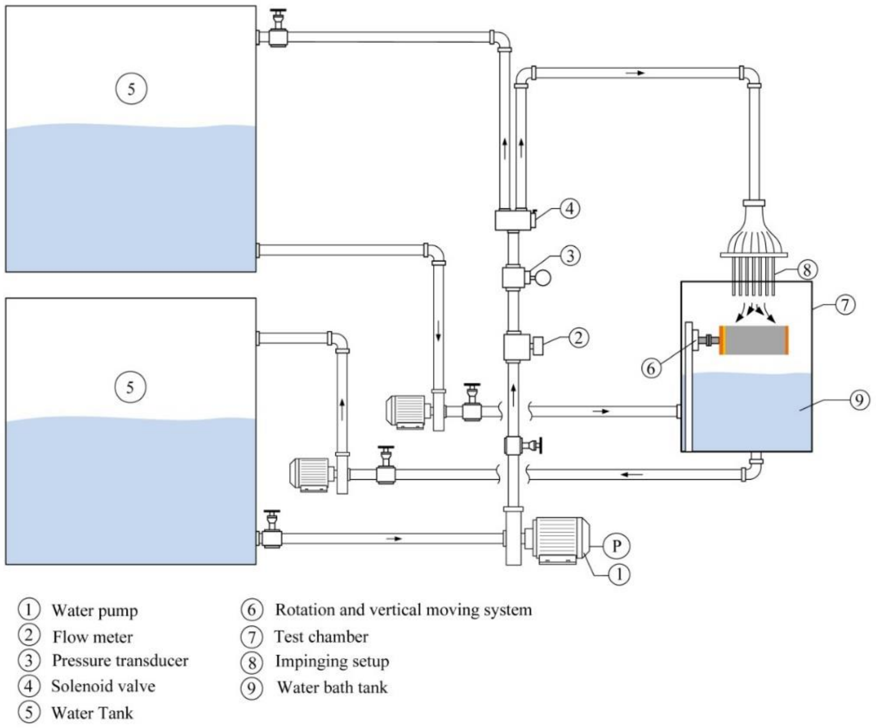


Figure 5. Experimental set-up of the test rig.

In parallel to this recirculation process, as this project holds different cooling water temperatures, two water heaters are responsible for adjusting the temperature of water by a different external recirculation process in which they take the fluid from the upper tank and recirculate it back to the same vessel. This heating/cooling operation continues until the temperature after the blue pump (which is obtained with a thermocouple and shown in LabVIEW program) is around 0.3^{o}C from the desired cooling temperature, as it will still have a short-time temperature changing tendency from the heaters and therefore, quenching process is done at the experimental plan's value.

That is to say, there are two recirculation processes occurring at the same time: one is in charge of getting water levels in the tanks correctly and allows checking the flowrate of the fluid that will next be used for impinging the heated work piece, while the other one is responsible of adjusting water temperature to the plan’s corresponding value. Both recirculation processes meet in the upper tank where water from both processes is mixed.

Furthermore, water used for cooling the steel cylinder pumps from the upper tank when solenoid valve is open. The lower tank is mainly used to pump water (1) to the tank above in order to guarantee an appropriate level of liquid for cooling. This water level is a fundamental factor so that there is enough pressure (checked with the pressure transducer from Fig. 4) and therefore the pumping (done with the blue pump) from the upper tank to the impinging set-up (8) is done properly.

Also, in parallel to the two aforementioned recirculation processes, heating process is done by means of the induction heater inside the test chamber.

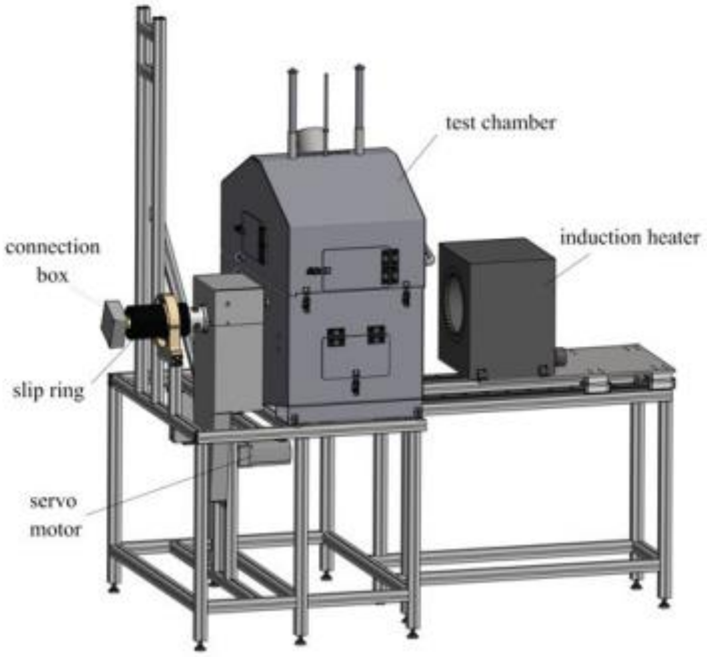


Figure 6. 3D illustration of test chamber.

As it can be observed in the figure above, the induction heater follows a guided rails structure which continues inside the test chamber and encloses the steel cylinder. In order that the heater can follow the guided rails and surround the work piece, the upper hatch must firstly be opened. Once this is done and the heater is moved all way until it encloses the steel cylinder, Festo program is run from the computer where low rotational speed of the cylinder is achieved (around 10rpm during the heating process). Next, ventilation for the test rig is turned on manually and the heating process of the cylinder starts with the help of LabVIEW program which is also controlled from the computer after switching the heater on from the electrical box. This heating operation is done manually by changing the current in the induction heater and therefore the temperature in the cylinder increases. Temperature in the rotational piece is measured as an average temperature of the different embedded thermocouples in the cylinder and shown also in LabVIEW program. Heating process begins by typing 10A value as the intensity of the induction heater in the program. In parallel to this, average temperature of the cylinder is checked and intensity is increased by 1A every 50-100ºC of temperature rise, until the desired temperature is reached (which is normally 10-15ºC above the quenching temperature, so that enough time for closing the hatch is guaranteed before the water starts impinging). In addition, 50ºC before achieving the desired temperature, rotational speed is adjusted from Festo for the corresponding experimental plan.

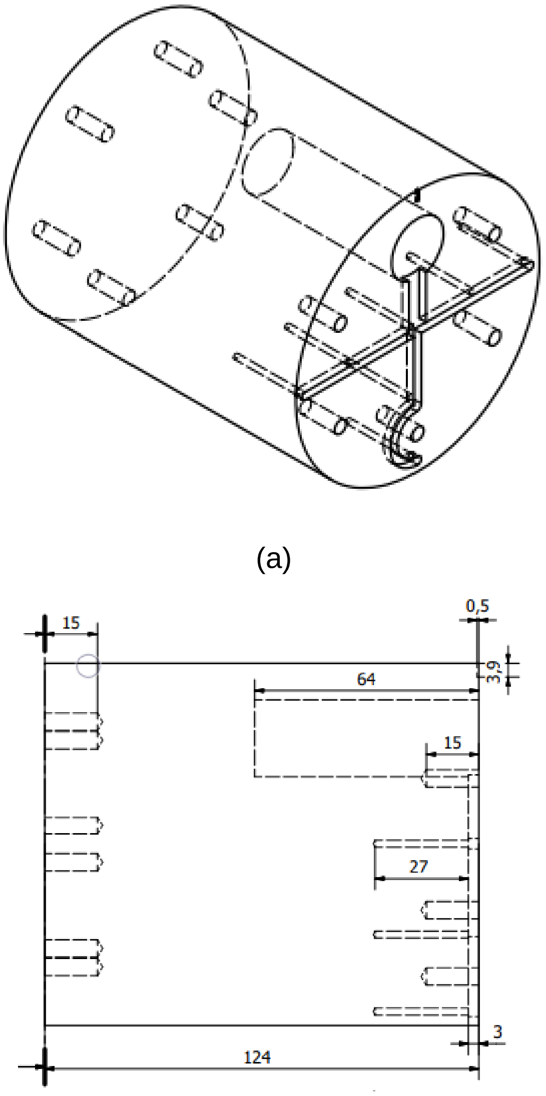
Once the wanted temperature is obtained, the heater is removed and the hatch is manually closed. Then, operation button is pressed and LabVIEW program will automatically monitor the quenching process by opening the solenoid valve for the impinging jets and finally cooling the rotatory cylinder. Temperature drop will be measured with the help of the embedded thermocouples as well as with DAQ which will give an output file of temperature measurements every 0.02s for each of the thermocouples. From the output file different plots will be analyzed showing how the temperatures vary during cooling for each of the thermocouples at each of the experiments.

After the experiment is finished, solenoid valve is automatically closed while Festo and LabVIEW programs are stopped manually from the computer. Later, the heater is switched off, and the recirculation process gets ends by switching the blue pump off. Ventilation is still active for a while until the cylinder reaches lower temperature values, closer to room temperature.

2.2. Thermocouple installation

The stainless steel cylinder used for these experiments consist of a total length of 124mm and a 104mm diameter. Figure 7a shows the different holes for attaching the insulation gaskets and the copper flange as well as the hole for the pin installation.

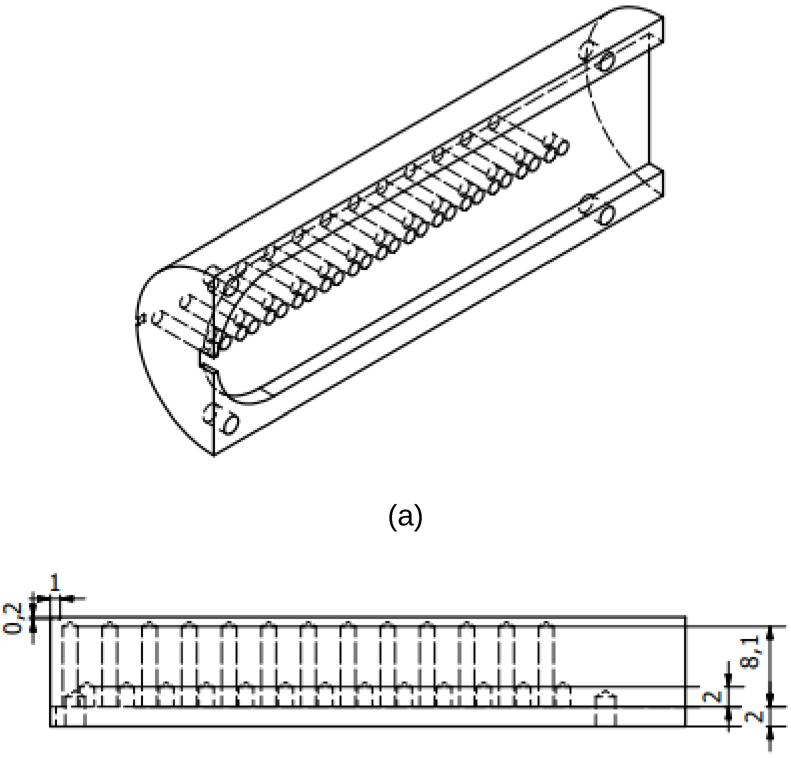
First of all, 26 thermocouples are installed inside a pin which will be pressed inside the cylinder in order to know the temperature along the test specimen during the heating and cooling process (Fig. 7b). Furthermore, one more thermocouple has been installed in the center of the bar and fixed with cement paste. All thermocouples used on this experiment are grounded N-type sensor.



(a)

(b)

Figure 7: (a) Schematic sketch of the steel cylinder with the different holes for the installation of the bar and for the pin; (b) 2D sketch of the steel cylinder



(a)

(b)

Figure 8: Schematic sketch of the pin where 26 thermocouples are installed: (a) in 3D; (b) in 2D with the corresponding dimensions.

As it can be observed in the Fig. 8, these 26 thermocouples will be distributed in 2 different depths, $R1$ and $R2$. Line $R1$ corresponds to a total 33mm from the center of the steel cylinder (in radial axis) while line $R2$ corresponds to 39,1mm radius. On each line 13 thermocouples have been embedded in measurement line with the corresponding length of 48mm.

All the thermocouples were connected to the data logger and checked their connections with NiMAX program.

Between the ending of the shaft inside the test chamber and the bar, a copper flange and an insulation gasket are placed in order to prevent unwanted cooling from the side of the bar, see Fig. 9. Similarly, also a gasket and copper flange are installed in the bottom face of the bar for same purpose. In this manner, the test specimen can be considered as a cut piece from the middle of a long bar produced in the practice where only outer surface of the bar is cooled directly by water jets during quenching process.

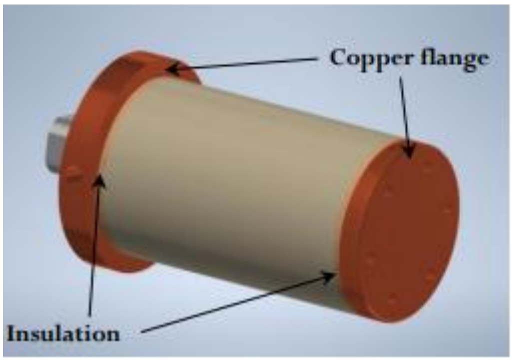
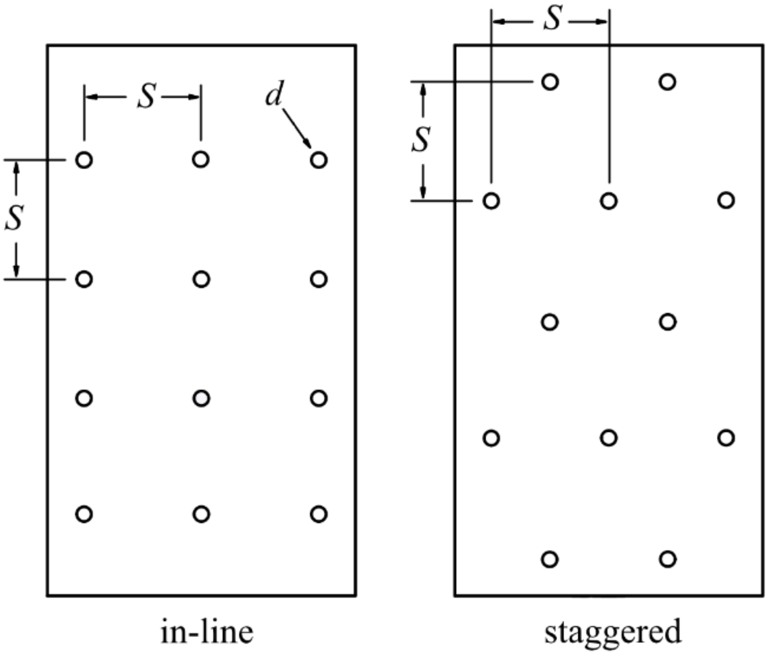


Figure 9. Copper flange and insulation assembling to the steel bar.

2.3. Configuration of multiple array of water jets

As aforementioned, this study holds different jet-to-jet spacing values as well as two jet patterns: staggered and inline configurations as shown in Fig. 10.

As it can be observed, inline pattern follows a uniform distribution for the jets in which the jet-to-jet spacing is the same in both vertical and horizontal directions of the test ring (*S*). In contrast, staggered pattern holds the same distance between the jets in the horizontal direction (*S*), but a diagonal distribution in the vertical direction ($\sqrt{2}S$), where horizontal lines are still at *S* spacing.



(a) (b)

Figure 10. Jet pattern configurations used in the experiments: (a) in-line; (b) staggered configuration.

2.4. Design of parametric study

In order to run the experiments different parameters have been taken into account as well as their corresponding range as it can be observed in the Table 1. Among these parameters, in order to develop a further understanding in the quenching technique by multiple impinging jets, jet-to-jet spacing, subcooling temperature, rotation speed and jet pattern are analyzed in the parametric study.

In order to analyze the parametric study, “experiment 1” has been set as the reference experiment and at each of the next experiments a single parameter has been modified in order to have a better understanding of its effect.

Table 1. Designed range of parameters.

	Parameter	Unit	Range
Jet’s diameter	d	mm	8
Subcooling	ΔT_{sub}	K	55, 65, 75, 85
Initial temperature	T_i	°C	700
Jet-to-jet spacing	S/d	-	4, 6
Jet-to-surface spacing	H/d	-	2
Rotational velocity	ω	rpm	10, 30, 50, 70
Number of jets	N	-	12
Jet pattern	-	-	Staggered, inline
Jet flow rate	Q_J	l/min	13.9

2.5. Experimental plan

Table 2 shows the experimental plan which was followed in this study in 10 experiments. Experiment 1 is the reference experiment to which the variation of various parameters are studied by comparing other experiment with this experiment. As it can be observed, jet diameter, quenching temperature, number of jets, water flow rate and H/d are constant in this study. However, subcooling, rotation speed, jet-to-jet spacing and configuration of multiple array of jets are parameters to be studied. Cells in gray from table 1 show different variables in contrast to the reference experiment.

Table 2. Designed experimental study.

Test	***d***	***Tw*** **(˚C)**	***Ti*** **(˚C)**	***ω*** **(rpm)**	***S/d***	**Jet pattern**	***N***	**Q_T (m3/h)**	***H/d***
Exp. 1	8	25	700	30	6	inline	12	10	2
Exp. 2	8	25	700	10	6	Inline	12	10	2
Exp. 3	8	25	700	50	6	Inline	12	10	2
Exp. 4	8	25	700	70	6	Inline	12	10	2
Exp. 5	8	25	700	30	4	Inline	12	10	2
Exp. 6	8	15	700	30	6	Inline	12	10	2
Exp. 7	8	35	700	30	6	Inline	12	10	2
Exp. 8	8	45	700	30	6	Inline	12	10	2
Exp. 9	8	25	700	30	6	staggered	12	10	2
Exp. 10	8	15	700	30	6	staggered	12	10	2

Nevertheless, experimental proceeding may experience different uncertainties in both measured data as well as in setting parametric values from Table 2. For instance, errors may come from sources such as setting the voltage in the pump in order to obtain the corresponding flow rate to each experiment, setting the current in the induction heater or regulating the temperature of the subcooling water. As a result, the maximum uncertainty regarding the thermocouple sensor within the range of 100 and 700oC was of ±1.9%. In addition, water heater used to regulating the subcooling temperature ($\Delta Tsub$) to the desired temperature with maximum ±7.6% of uncertainty (95% confidence) while cooling flow rate (Q) was at the level of ±1.4%. Eventually, in operation of induction heater to adjust the initial temperature of quenching, maximum operational error of ±1.17% was obtained.

3. Results and discussion

In this section the parametric study carried out by running the different experiments will be analyzed with the help of Matlab. Once temperatures in line R_1 and R_2 have been recorded by LabView program they have been used as an input data in Matlab in order to calculate and analyze cooling rate for each of the experiments. As aforementioned, experiment 1 is used as a reference starting point to which next experiments data will be compared with.

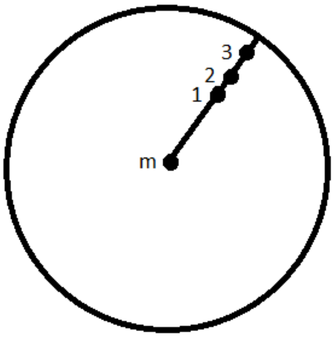


Figure 11. Position of the radial position of various points used in data analysis in radial axis.

Figure 11 shows the distribution of the points that have been studied in this investigation regarding the parametric study. Point “m” refers to the center of the steel cylinder which the temperature has been measured by one thermocouple embedded in that position. The temperature in lines R_1 and R_2 have also been directly measured with the thermocouples and their corresponding distance to the center are 33 and 39.1mm respectively. Finally, R_3 refers to the thermocouple located 4mm beneath the surface at radial distance of 48mm from the center of the cylinder.

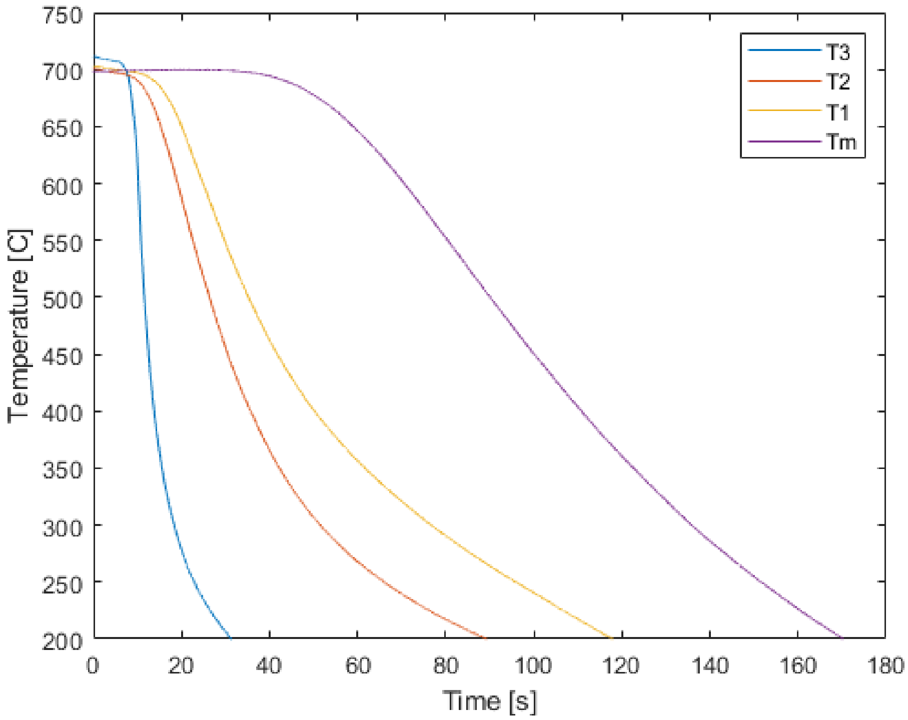


Figure 12. Temperature drop distribution in various radial distances in solid cylinder in experiment 1.

Figure 12 shows the plot of temperature measured in four radial positions (Fig. 11) taken into consideration in this study for the reference experiment, “Exp.1”. It can be observed the delay in cooling of cylinder center (T_m) since it is far away from the surface where boiling phenomena occurs in contact of impinging water jets and the hot surface. In addition, T_1 and T_2 present a similar trend of temperature drop due to the fact that spacing between these two radial points is 6 mm. However, T_2 is located closer to the surface and consequently, it experiences the cooling heat flux earlier than T_1 and slightly higher cooling rate. Eventually, T_3 is the only point with sharp temperature drop among all of them as it is 4mm beneath the cooling surface and consequently experiences the highest level of cooling heat flux. This occurs due to the fact that the solid surface experiences evaporation of water (boiling phenomena) as well as convection heat transfer which result in a larger magnitude of heat flux. Nevertheless, in the solid material in radial axis toward the center of the cylinder, energy (heat) is transferred only by conduction mechanism which is limited due to the thermal conductivity of material and the diameter of the cylinder which results in damping the cooling heat transfer in radial distances toward the center of the cylinder.

Figure 13 illustrates the stagnation point location in the measurement line which is located 28.3mm from edge of the pin installed in the cylinder. The reader should be aware about the importance of line R_2, since it is closer to the surface of the cylinder whose recorded temperature knowledge is important in analysis of characteristics of the impinging jets cooling technique. Among the 13 thermocouples embedded in line R_2, stagnation point of the impinging jet is the one to be studied as its characteristics is related into local effect of jet's impingement.

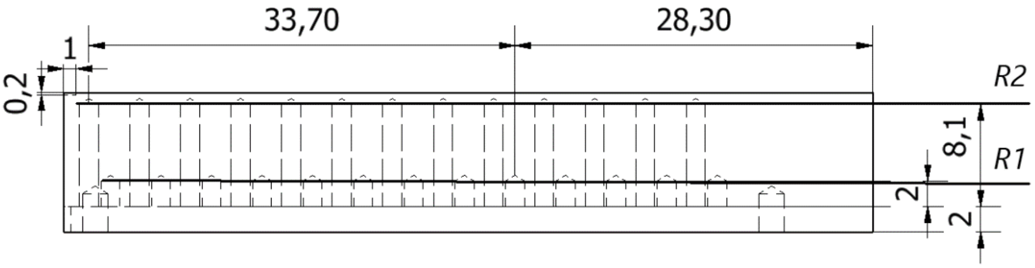


Figure 13. Schematic sketch of the stagnation point position in line R_1 and R_2 in the pin.

Rotational speed

Regarding the effect of surface movement which is represented by rotational speed in this study, first four experiments have been carried out to study range of rotational speeds ω = 10, 30, 50 and 70rpm. As aforementioned, line R_2 is of several importance as it is closer to the surface of the cylinder. Figure 14 presents the temperature variation of T_{R2} for the measurement point x_{stg} ,where the water jet is impinging. In study of quenching rotary hollow cylinder [17], quenching at lower rotational speed led to the heat recovery of the cylinder in each revolution during passage through the dry zone where there was no direct cooling on the surface, leading this to a cyclical tendency of non-uniform temperature drop during cooling process. While this effect decreases as ω increases, the potential of proper contact between the moving surface and the impinged water flow decreases. However, in quenching of rotary solid cylinder in this study (Fig. 14), no cyclic variation was observed in recorded measurements which may be due to both the thickness of the studied cylinder as well as the larger distance between R_2 line and the cooling surface in this study which lead to damping the heat flux by conduction heat transfer toward the center of the cylinder. Furthermore, it can be observed rotation at 30rpm revealed the fastest cooling followed by 10, 50 and 70rpm. As a result, it can be concluded higher rotational speed leads to a propagation in time during cooling process as contact between cooling liquid and hot surface is weakened.

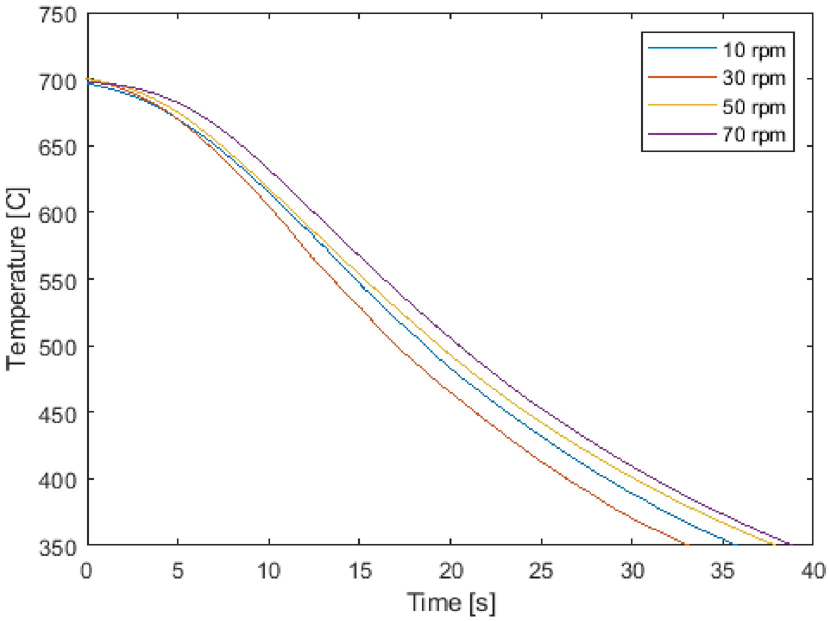


Figure 14. Measured temperature drop for different rotational velocities in line R_2.

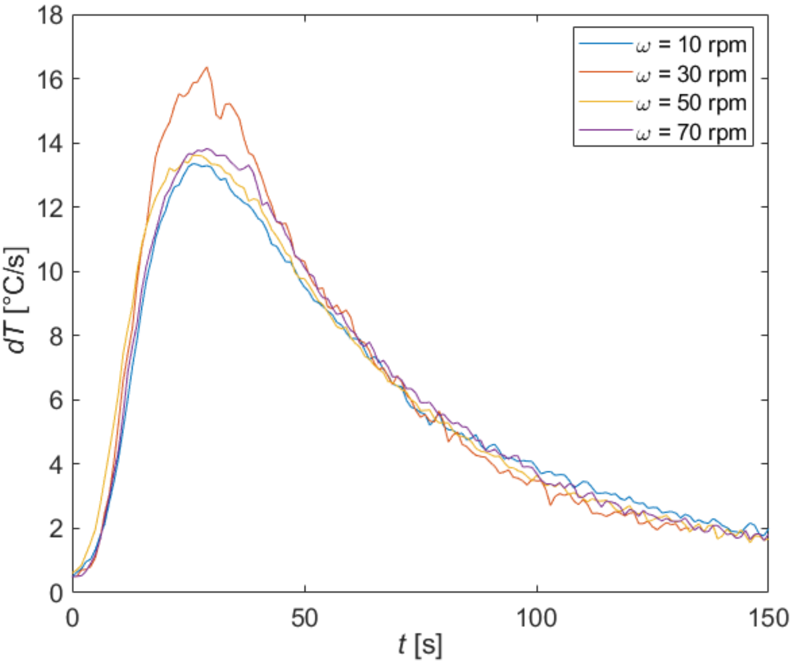


Figure 15. Quenching cooling rate variation at different rotational speeds in x_{stg}.

Figure 15 shows the cooling rate for the different experiments regarding the rotational speed analysis. This plot shows the effect of impingement of the jet flow in the onset of quenching with drastic increase of cooling rate which continues up to maximum value corresponding to the surface maximum heat flux (*MHF*) in the boiling curve (see Fig. 2). After the maximum heat flux is reached, drastic reduction is experienced which may be due to the fact that surface temperature is reduced and nucleate boiling regime is obtained on the surface. It should be remarked both the importance of disturbing the contact between liquid and solid on the surface and the total time for the surface to be covered by impinging jets per minute. Low speed results in less disturbance while high speed leads to higher disturbance as well as higher cover from impinging jets per constant time frame (minute). The results reveal a higher cooling rate for ω = 30rpm, which may be due to a higher potential of contact between the impinged water and the hot surface as well as having time enough to cover the surface by impinged water, leading to an overall balance for aforementioned phenomena. However, quenching at 10rpm leads to weaker cooling which may be due to worse cover of the hot surface by impinged water, even if disturbances are low enough.

Jet-to-jet spacing

Among the parametric study involved in this project, jet-to-jet spacing has been analyzed by running experiments at *S/d*=4 and 6. Figure 16 shows the temperature drop for the stagnation points corresponding to each of the jet-to-jet spacing experiments. Measurements reveal a faster cooling in the stagnation point for *S/d*=4 experiment. This shows that spacing 4*d* provides better condition for the surface cooling around the stagnation region of jets that creates positive effect on the local cooling rate at stagnation point of each impinging jet.

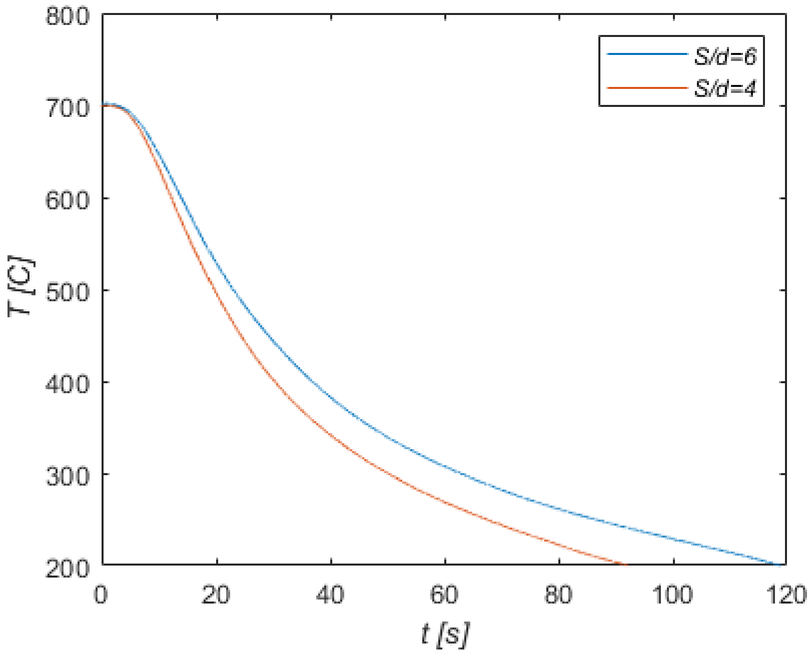


Figure 16. Temperature drop at x_{stg} for *S/d*=4 and 6.

As it can be observed in Fig. 17, in agreement with result of temperature drop in Fig. 16, cooling rate for smaller spacing between the jets resulted in a higher cooling rate. At the beginning of the cooling process, stagnation point experiences similar tendency of cooling rate increase, but the peak value at *S/d* = 6 is smaller than the increment of cooling rate at *S/d* = 4. This occurs mainly due to the fact that less spacing increases the interaction between water front lines from jet’s neighbors which lead to a higher cooling rate over the surface which is beneficial for stagnation region of jet to be cooled down at higher rate.

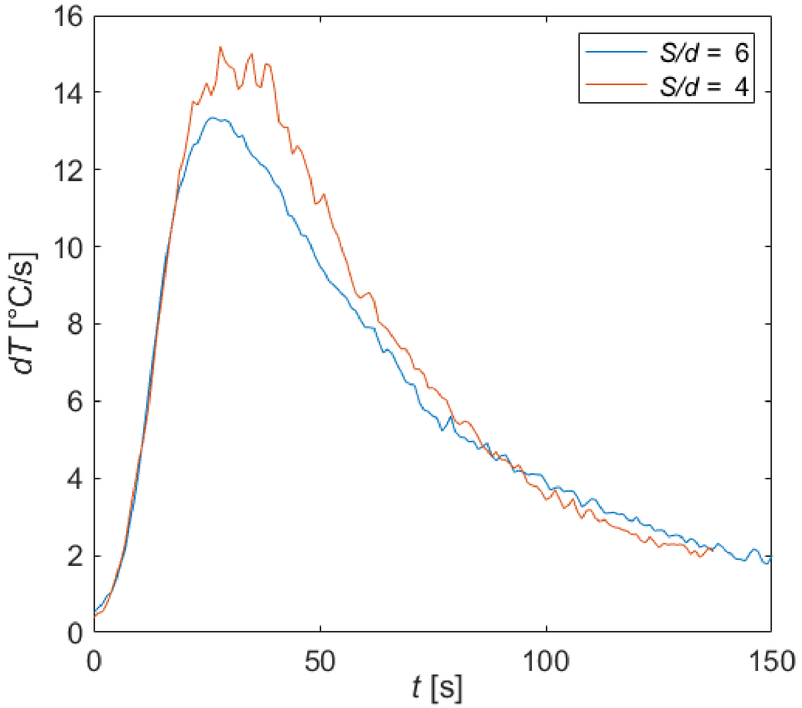
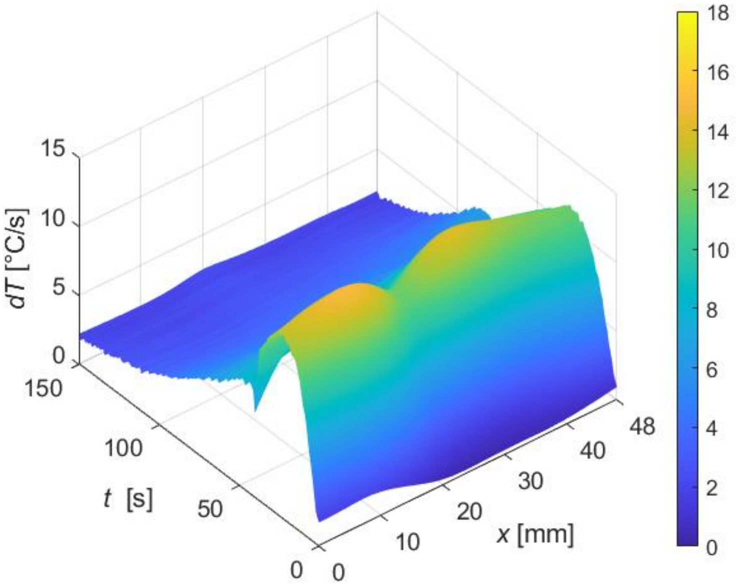
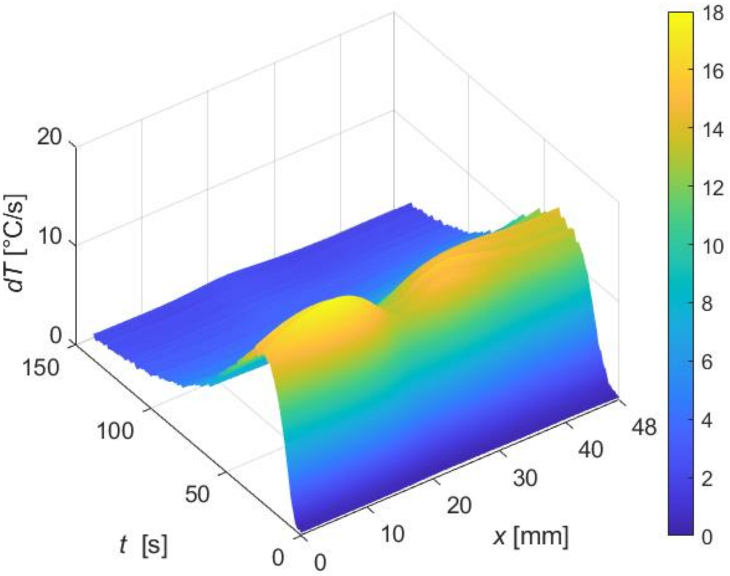


Figure 17. Cooling rate curve for different je-to-jet spacing experiments in x_{stg}.



(a)



(b)

Figure 18.Cooling rate for different jet-to-jet spacing: (a) *S/d*=*6*; (b) *S/d*=4.

Figure 18 shows the contour plot of cooling rate along the measurement line R_2 during the quenching process. Figure 18(b) presents higher cooling rate at x_{stg} with smaller spacing between the jets. This confirms previous study [9] conclusions regarding the characteristic of this parameter, where it results in more uniform cooling over the surface with smaller spacing since the adjacent wetting front flows from neighbor jets interact with each other resulting in a better cooling over the surface which is achieved by the increasing heat flux in film and transition regimes. This can be proven by analyzing at $x =$20mm where larger spacing revealed a higher cooling drop that leads to a less uniform cooling. As a result, it can be confirmed that higher value of *S/d* decreases the influence of neighbors jets' wetting front flow, so that they act more similar into the single impinging jet resulting in a less uniform cooling over the surface.

Multiple array configuration

In the study of multiple array of nozzles, the configuration of jets in the array is an important parameter. In this study, the jets' pattern of in-line and staggered configuration are considered to be studied. In order to compare the behavior of the configuration of nozzles, Fig. 19 presents the temperature drop in the stagnation point corresponding to line R_2. Similar drastic increase of cooling rate is obtained in onset of cooling in film and transition boiling regimes. However, it can be observed how staggered pattern increases slightly the cooling rate after the *MHF*. It may be concluded that better uniformity of cooling over the total quenching surface may lead to slightly better local cooling at the stagnation point. However, additional study has to be taken to analyze this conclusion.

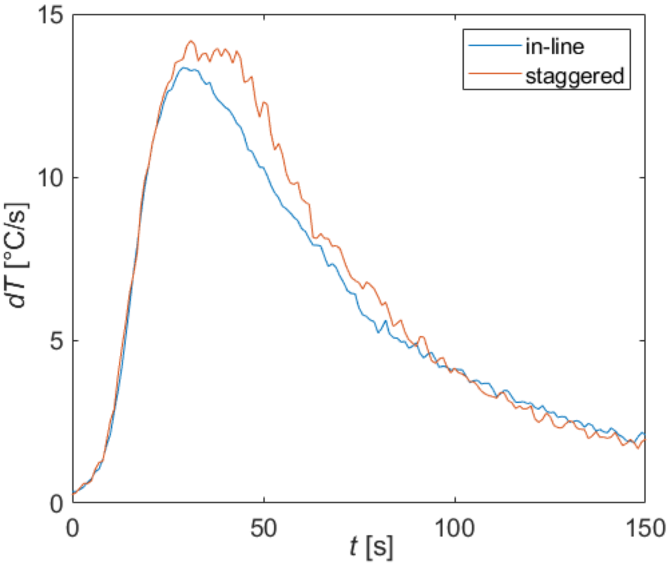
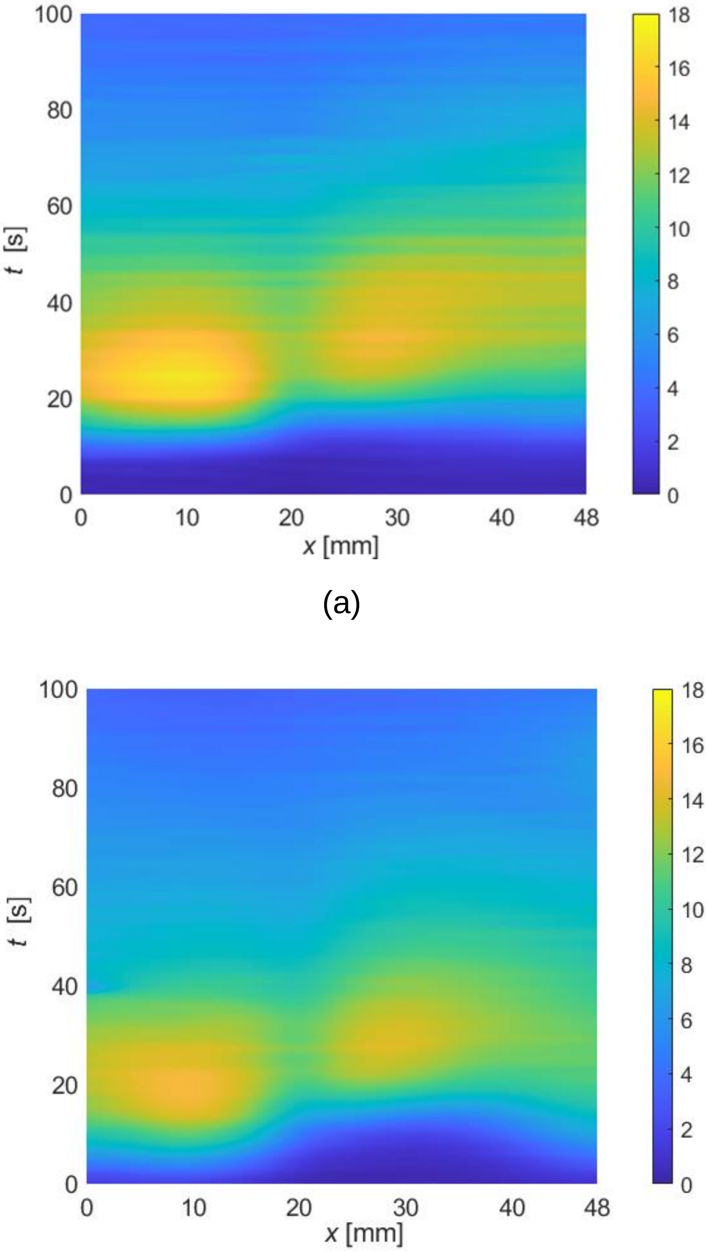


Figure 19. Cooling rate for different jet patterns in the stagnation point in *R2* line.

In order to develop a better understanding, Fig. 20 shows how in staggered configuration cooling is far more uniform along the measurement line since the distribution of the highest cooling rate (around 18 °C/s) is far more uniform than for in-line configuration. This result is due to the fact that staggered pattern provides a better placement of the jets which lead to more jets covering the measurement line. However, in inline pattern, the stagnation point is at x = 33mm and with 6*d* spacing, which means that neighbour jet is placed out of the measurement line. In addition, the increase of cooling rate in x = 0-15mm is due to the effect of upwash flow caused by the interaction of neighbour jets' impinged water.



(a)

(b)

Figure 20. Cooling rate distribution in different jet patterns: (a) staggered; (b) in-line.

Figure 21 shows the plot of the cooling rate at stagnation point in both T_{R2} and T_{R3} against the temperature for both jets configurations. As it can be seen, the significant difference between cooling rate in R_2 and R_3 which is around 7 times larger at radial position R_3. This is clearly due to the fact that position $R3$ is located 4 mm beneath the cooling surface while R_2 has 12.9mm distance from surface. As it has already been mentioned, heat flux toward the center of the cylinder is due to conduction energy transfer while in the surface boiling of water flow as well forced convection by impinging jets lead to much higher surface heat transfer. This is the reason that the magnitude of heat flux in line R_3 is much higher than in R_2 which is closer to the center of the cylinder where only conduction heat transfer occurs.

In addition, it can be observed that staggered configuration keeps high value in cooling rate for longer period of time during quenching in both depths R_2 and R_3 which may be due to the interaction of closer jets next to the stagnation point that contribute to the distribution of impinged water along the hot surface with small interferences. In contrast, in-line configuration shows a weaker cooling.

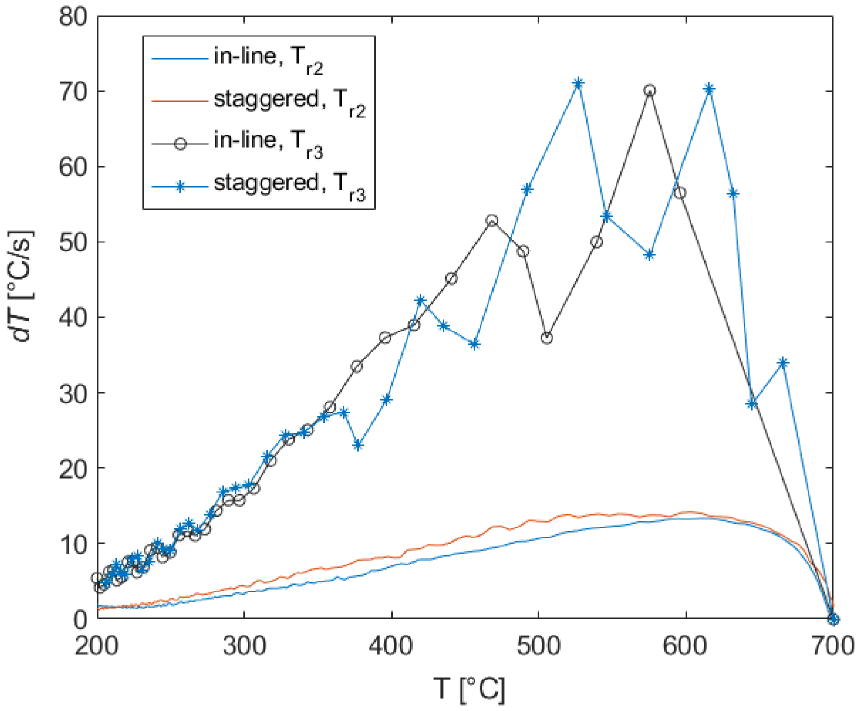


Figure 21. Cooling rate at R_2 and R_3 against temperature at x_{stg}.

Subcooling temperature

This study aims to develop further knowledge in quenching by water impinging jets technique by analyzing subcooling temperature parameter in four experiments for $\Delta Tsub_{=}$ 55, 65, 75 and 85K for in-line configuration and two experiments for staggered pattern $\Delta Tsub_{=}$ 75 and 85K.

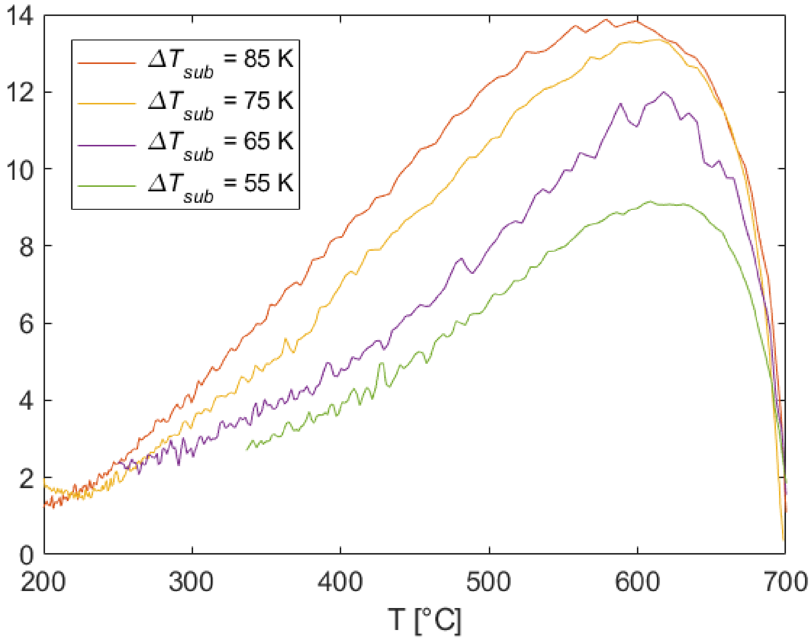


Figure 22. Cooling rate at stagnation point in R_2 line for in-line configuration.

Figure 22 shows cooling rate at stagnation point (see Fig. 13) in line R_2, for the different subcooling temperatures regarding in-line configuration. It can be observed that higher subcooling leads to faster cooling. For instance, higher subcooling ΔT_{sub} = 85K reaches maximum cooling rate of 14^{o}C/s which is much higher than ΔT_{sub} = 55K where the peak value reaches to 9^{o}C/s. This behavior agrees with previous studies [12] which confirmed higher cooling rate for higher subcooling temperature. Figure 23 proves the aforementioned conclusion, in which same tendency is repeated in lineR_3, which is beneath the cooling surface. However, cooling rate in this line is around seven times larger than for line R_2. For instance, ΔT_{sub} = 55K resulted maximum cooling rate of 48^{o}C/s while highest subcooling (ΔT_{sub} = 85K) lead to much higher maximum cooling rate of 75^{o}C/s. In addition, it should be remarked how subcooling of 55K shows that water flow cannot provide a shoulder of flux (increase of cooling rate in the film and transition region due to impingement of water flow to the surface) like other subcooling values.

To sum up, it can be proven that cooling rate at higher subcooling temperatures leads to higher cooling rates whose values are enhanced in the surrounding of the hot surface and result in significant difference compared to lower subcooling temperatures.

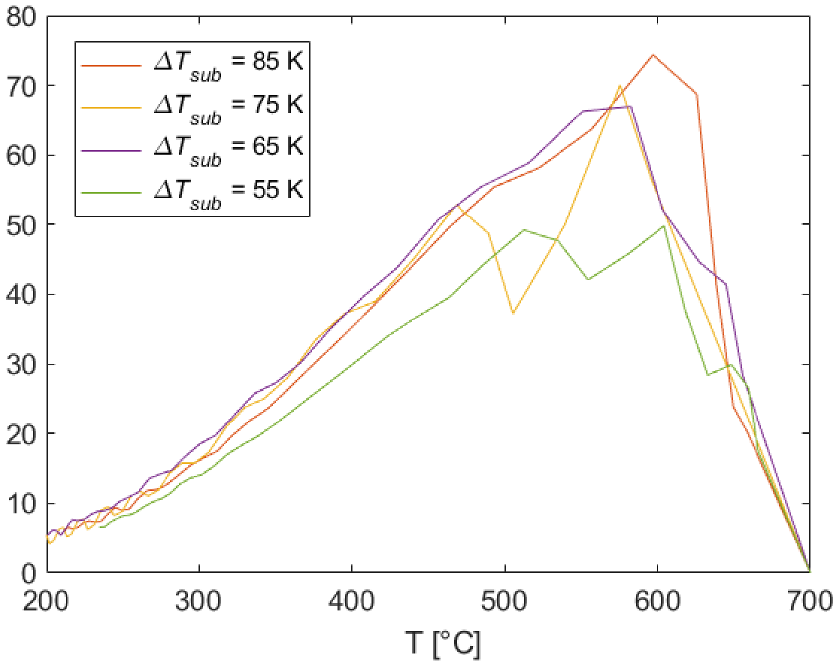
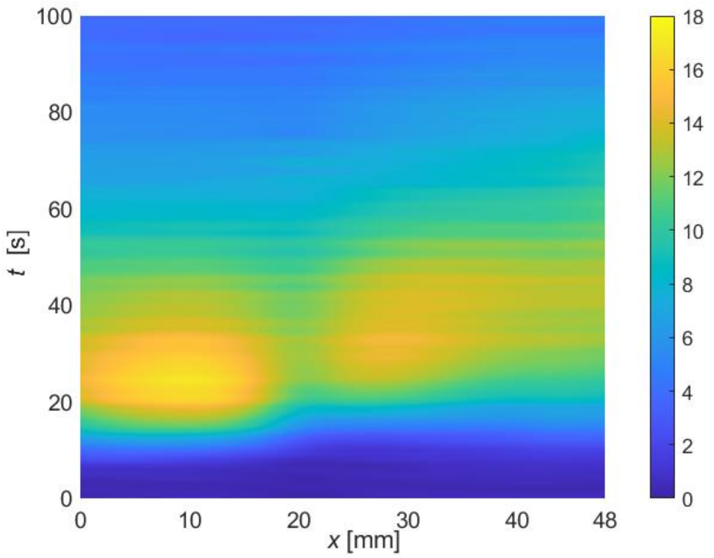


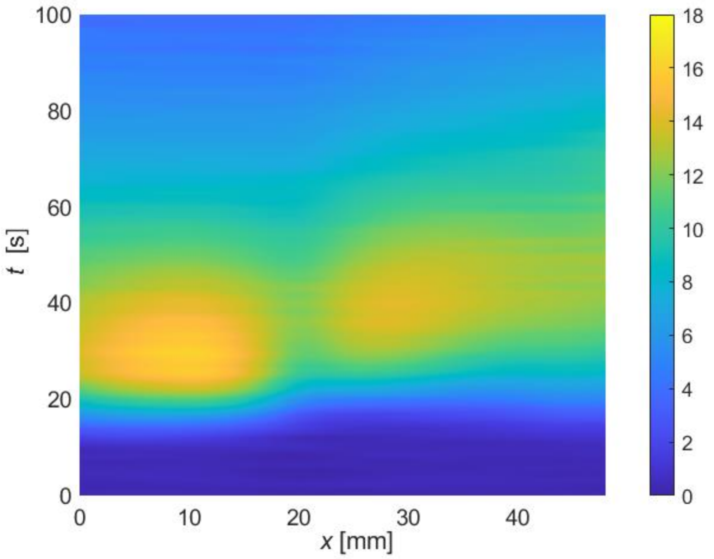
Figure 23. Cooling rate at stagnation point in R_3 line for in-line configuration.

Fig. 24 shows cooling rate in measurement line for staggered pattern. It can be seen how at $\Delta T_{sub} =$ 85K, cooling rate along the measurement line is higher and consequently surface is cooled faster. This can be confirmed by analyzing the stagnation region which obtains higher cooling rate with higher subcooling temperature in Fig. 24 (b).As aforementioned, the stagnation point is at $x =$ 33mm. In addition, the increase of cooling rate in x = 0-15mm is due to the effect of upwash flow caused by the interaction of neighbour jets' impinged water that lead to better cooling for higher subcooling temperature. In Fig. 24, it can be observed how the peak value is maintained within longer time frame for higher subcooling temperature.

As a result, this results confirm the behavior from previous studies for both in-line and staggered jet pattern.



(a)



(b)

Figure 24. Cooling rate in measurement line in staggered pattern: (a) $\Delta T_{sub} = 75K$; (b) $\Delta T_{sub} = 85K$.

4. Conclusion

This study aims to develop a better understanding in the area of quenching technique my multiple impinging jets. In order to enhance the knowledge in this field, experimental parametric study has been done on four important parameters of the impinging jet technique and the rotational quenching system.

4.1. Study results

After having analyzed the results in these parameters the following conclusions have been made:

- Quenching at low rotational speed (10 and 30rpm) reveals a faster cooling than 50 and 70rpm in the in-line configuration at the stagnation point. This could probably be since the contact between the hot surface and the impinged liquid is improved for lower speeds. Furthermore, cooling rate for 30rpm, resulted in a higher peak value as well as drastic cooling rate drop after reaching this value. However, 10rpm results experienced negative effects.This is why further analysis should be done for these rotation speeds in order to obtain the optimized range at which material properties are improved to their optimal value.

- Regarding the jet-to-jet spacing parametric analysis, *S/d*=6 caused slower cooling in the stagnation point as well as a less uniform cooling over the surface. In contrast, *S/d*=4 revealed a more uniform cooling, which is clearly due to the fact that jets are closer one from each other and interaction between them is enhanced. As a result, it can be confirmed smaller spacing leads to better cooling over the surface.

- The difference in magnitudes regarding heat flux in lines R_2 and R_3 is due to the fact that surface boiling and forced convection increases the surface heat flux, whose effect is significantly enhanced in radial positions near the surface. However, for the positions in radial distances closer to the center of cylinder, heat transfer by conduction occurs not only in radial direction, but in angular axis as well, which damps the effect of high surface heat flux.

- Jet pattern results revealed more uniform cooling for staggered configuration due to the fact that water fronts from neighbor jets led to less interactions because of a better jet distribution. However, in-line pattern revealed a less uniform cooling which is mainly the result from the distribution of the jets that result in higher interferences between water fronts of different jets and consequently a weaker cooling.

- Result of study higher subcooling temperatures was in agreement with previous research study results corresponding to a higher cooling rate and faster temperature drop that may result in enhanced mechanical properties in steel. Furthermore, significant differences have been found in the surroundings of the impinged surface (R_3 line) regarding the cooling rate for different subcooling temperatures as both boiling water and conduction heat transfer take place. In contrast, cooling rate analysis in line R_2 revealed less difference for different subcooled temperatures as conduction occurs in both radial and angular axis which decreases the effect of high surface heat flux.

4.2. Outlook

This study aims to develop a better understanding in the quenching of rotary cylinder by multiple array of water impinging jets. All the experiments in this investigation have been carried out with high accuracy. However, this research was an experimental study which may lead to imbalances for both human and technology factors. Furthermore, results obtained in these experiments agreed with previous works with water impinging jets technique. As a result, this research could be considered an opportunity to enlighten the knowledge in this area and carry out different applications in the steel industry.

4.3. Perspectives

Better understanding of quenching by water impinging jets is a key factor in current competitive steel industry market both for having enhanced mechanical properties as well as finding the most efficient way to achieve it from an economical point of view. In addition, the achievement of the most optimizing technique by determination of key parameters in quenching by multiple array of water impinging jets results in a wider understanding of steel material behavior leading this to a higher reliability in the material in different applications.

5. Ethical consideration

This research does not affect any ethical issue since it is irrelevant. Therefore, no ethical considerations are worth mentioning.

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