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Effect of Jet Diameter on Surface Quenching at Different Spatial Locations

C. Agrawal, R. Kumar, A. Gupta, B. Chatterjee

***Abstract*—**An experimental investigation has been carried out to study the cooling of a hot horizontal Stainless Steel surface of 3mm thickness, which has 800±10°C initial temperature. A round water jet of 22 ± 1°C temperature was injected over the hot surface through straight tube type nozzles of 2.5-4.8mm diameter and 250mm length. The experiments were performed for the jet exit to target surface spacing of 4 times of jet diameter and jet Reynolds number of 5000 - 24000. The effect of change in jet Reynolds number on the surface quenching has been investigated form the stagnation point to 16mm spatial location.

***Keywords*—**Hot-Surface, Jet Impingement, Quenching, Stagnation Point.

I. Introduction

DESIGN and selection of effective cooling system is prerequisite of many industrial applications i.e. metal processing [1]-[3], electronics [4], [5], nuclear [6], [7]. The jet impingement cooling is preferred over the other cooling methods due to its high heat removal capability [3]. In the jet impingement cooling technique, for different applications, the fluids that are being used as coolants are air [8], [9] water [10]-[13], mist [14], [15], fluorocarbon (FC) [16], [17], Freon [18], [19] The choice of these coolants depends on the rate of heat removal desired from the hot surface. the surface quenching is also affected by several other parameters that are related to jet and surface properties, i.e. jet fluid temperature [7], jet direction, jet flow rate [10], [14], nozzle exit to test surface spacing [10], [11], surface properties [7], [13], surface initial temperature [6], [15].

In the present paper effect of jet diameter on the quenching of hot surface at different spatial location has been reported. A SS-316 surface of 3 mm thickness at 800˚C initial temperature is quenched with jet impingement cooling technique. The investigations were made with sub cooled water of 78˚C temperature with jet Reynolds number, Re = 5000. The jets of 2.5, 3.5 and 4.8mm diameter were used for the investigation. The surface temperature is obtained from the stagnation point to 16mm downstream spatial location.

II. Experimental Set-Up and Procedure

The schematic diagram of the experimental set-up is shown in Fig. 1. The cooling water was collected in a reservoir (9) which was supplied to the straight tube type nozzle (1) with the help of a pump (8). A control valve (7) was used to control the jet flow and a turbine flow meter (6) was installed to measure the flow rate. The nozzle was mounted on a vertical slide (4) and the test surface (5) was mounted on work table (2) concentric to the nozzle centre. The position of the test surface underneath to the nozzle was obtained with a transverse and lateral movement handle provided on the work table. Three nozzles of 250mm length were used to produce the round jet of 2.5mm, 3.5mm and 4.8mm diameter. The nozzle exit to test surface spacing is fixed at z/d = 4 by shifting vertical slide through a rack-pinion arrangement provided on the nozzle assembly. A Stainless Steel-316 surface of 130mm length 30mm wide and 3mm thickness was used as test surface.

C. Agrawal is with the Department of Mechanical Engineering, College of Technology and Engineering, Maharana Pratap University of Agriculture and Technology, Udaipur 313001, India (phone: 0294-2470510; fax: 0294-2471056; e-mail: chitranjanagr@gmail.com).

R. Kumar is with the Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Roorkee, Uttrakhand-267447, India (phone: +91-1332-285740(O); fax: +91-1332-285665, 273560; e-mail: ravikfme@iitr.ernet.in).

A. Gupta is with the Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Roorkee, Uttrakhand-267447, India (phone: +91-1332-285613(O); fax: +91-1332-285665; e-mail: akhilfme@iitr.ernet.in).

B. Chatterjeen is Scientist with Bhabha Atomic Research Centre, Mumbai-400085, India (e-mail: barun@barc.gov.in).

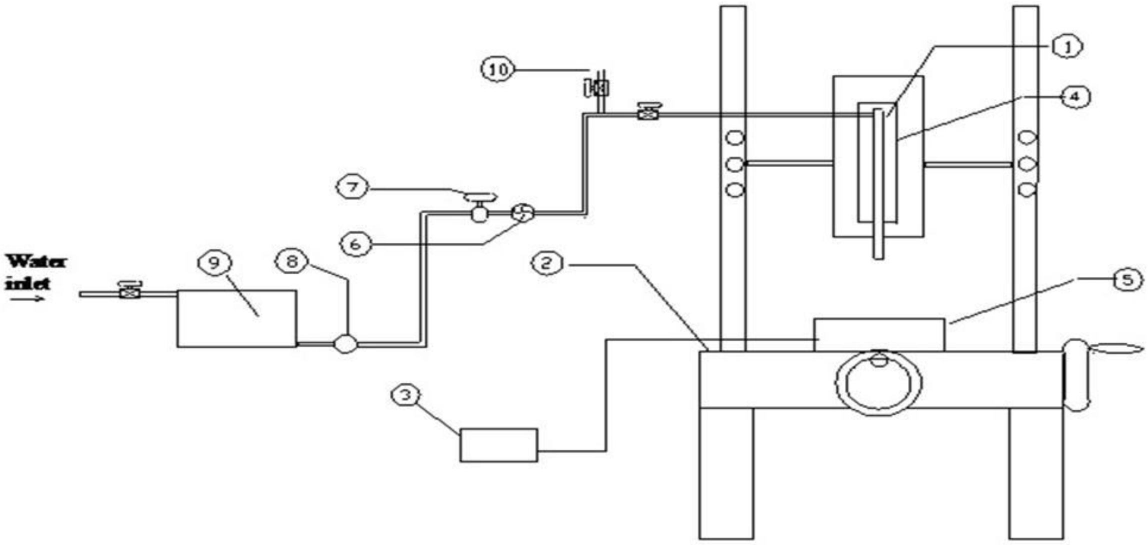

Fig. 1 Schematic of experimental set up 1. Nozzle assembly, 2. Work table, 3. Data-acquisition system, 4. Vertical slide, 5. Test-surface, 6. Turbine flow-meter, 7. Flow control valve, 8. Pump, 9. Water reservoir, 10. By pass line

To measure the surface temperature during the quenching three ungrounded, mineral insulated K-type thermocouples of 0.25mm sheath diameter were spot welded at the backside of test surface. These thermocouples were further connected to a Data Acquisition System (3) to record the transient surface temperature. The test surface was heated slowly up to 800 °C by using high current low voltage AC supply attached through two copper bus bars. The back side of the test surface was insulated by a layer of ceramic insulation and 50 mm thick Teflon sheet. A digital voltmeter was used to measure the voltage drop across the sides of test surface and current supplied was recorded with the help of an ammeter and a current transformer (CT) arrangement. The surface temperature during transient cooling was recorded at the rate of 100 samples per seconds by data acquisition system for different spatial locations, *r*. The flow of water to the nozzle was varied to maintain the jet Reynolds number at Re = 5000. The jet Reynolds number at the nozzle exit for a certain jet diameter, *d*, flow rate, *Q* and water properties can be obtained by (1).

$$\mathrm{Re} = \frac{dU}{\nu}, \text{ where } U = \frac{Q}{A_j} \qquad (1)$$

where A_j is the nozzle exit area, *Q*, is volume flow rate of water, *U*, is the jet velocity exiting the nozzle and *ν* is the kinematic viscosity of water.

The uncertainty in the measurement is shown in Table I. Since, the thermocouple diameter was 0.25mm, the uncertainties in the radial position of thermocouples were taken as 0.25mm. The operating ranges of experimental parameters are shown in the Table II.

TABLE I
UNCERTAINTY IN THE MEASUREMENTS

Parameter	Accuracy
Water flow rate	0.10 lpm
time	0.01seconds
nozzle diameter	0.10mm
test surface length and width	0.02mm
test surface thickness	0.01mm
temperature	1.5˚C @ 800˚C 0.5˚C @ 100˚C

TABLE II
OPERATING RANGE OF EXPERIMENTAL PARAMETERS

Experimental Parameter	Accuracy
Reynolds Number, Re	5000
Jet exit to surface spacing, z/d	4
Nozzle diameter, d	2.5mm, 3.5mm, 4.8mm
Thickness of test surface, w	3mm
Water temperature, T_j	22 ± 1ºC
Initial surface temperature, T_i	800ºC

III. RESULT AND DISCUSSION

The surface quenching curves are obtained with the recorded temperature data during transient cooling of the hot test surface for various downstream spatial locations. The quenching curves shown in Fig. 2 are for stagnation point, spatial location, r = 8mm, 16mm with jet of d = 2.5mm, 3.5 mm, 4.8mm diameter. It has been observed that with the increase in jet diameter, the rate of surface cooling rises for the entire measured spatial locations. Since, the time taken to attain a certain surface temperature, from its initial temperature of 800°C is lowest with the jet of 4.8 mm diameter as compare to other two jet diameter examined. This rise in cooling rate is significant for the extreme measured spatial location i.e. 16mm. It can also be observed with these curves that rise in cooling rate is significant with the increase in jet diameter from 2.5mm to 3.5mm, thereafter, the increase in jet diameter is not that much effective. The quenching curves for d = 3.5mm and 4.8mm are seems to very close, particularly at the stagnation point, r = 0mm. The rise in cooling rate or reduction in cooling time with 3.5mm and 4.8mm jet diameter as compared to 2.5m at the measured spatial location are shown in Table III.

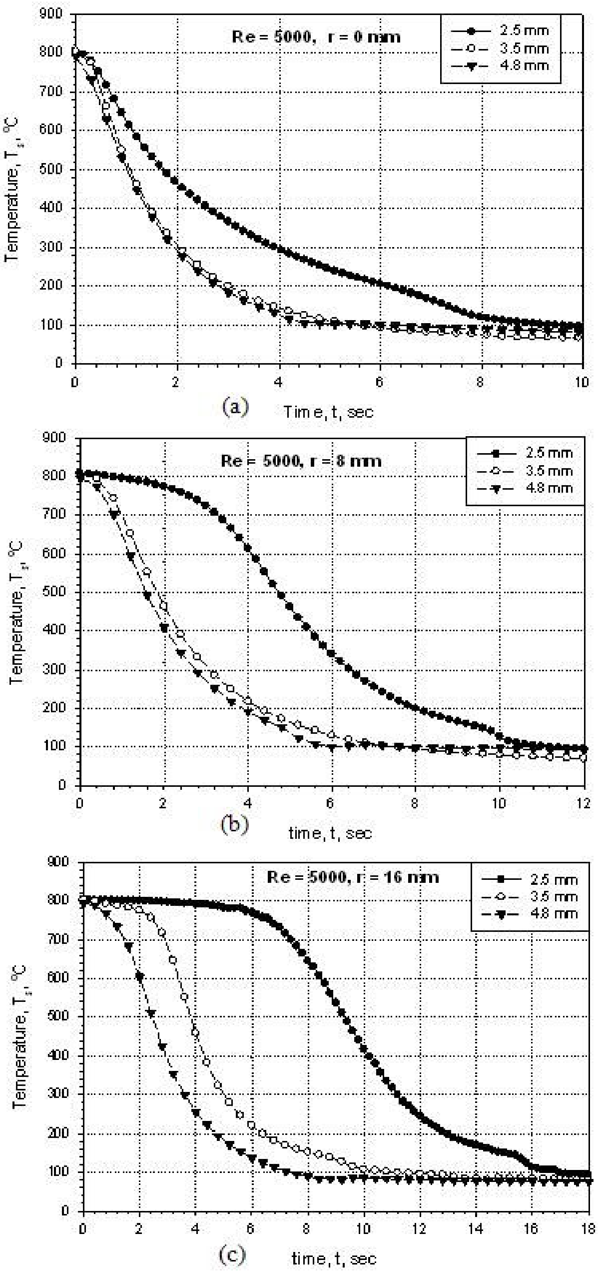

Fig. 2 Surface quenching curves for different jet diameter (a) r = 0mm, (b) r = 8mm, (c) r = 16mm

The quenching curve has been divided into three equal part of temperature drop, i.e. 800°C - 575°C, 575°C - 350°C, 350°C - 125°C. It has been observed that the cooling time reduces maximum by 64 percent with 3.5mm jet diameter which is 75 percent with 4.8mm. In-fact, the water flow rate raised by 40 percent with 3.5mm and 90 percent with 4.8mm as compared to 2.5mm jet diameter. This seems that the rise in jet diameter on the quenching is effective to a certain extent and thereafter, the rise in jet diameter or the rise in coolant flow rate has no effect on the cooling rate. The increase in coolant flow rate which is associated with the rise in jet diameter is responsible for higher surface cooling rate. With higher jet flow rate heat absorbing capacity is higher results in higher surface cooling rate. The rise in jet flow rate beyond a certain level may not that much effective due to lower thermal conductivity of stainless steel surface. Though, the higher flow rate has capacity to absorb more heat, however, the steel surface may not able to conduct the require amount to heat towards the cooling zone. It has been mentioned in earlier investigation that the rise in jet velocity increases the quenching rate [7], [10]-[13]. However, in present investigation this seems that it is not the increase in jet velocity that enhances the surface quenching rate. For a certain jet Reynolds number increase in jet diameter results in reduction in jet velocity (1). The earlier investigation that claimed the rise in jet velocity increase surface cooling is valid only for a single jet diameter. Since, for a constant jet diameter, jet flow rate is proportional to the jet velocity. Therefore, it is the rise in jet flow rate that enhance the surface quenching not the increase in jet velocity.

TABLE III
PERCENTAGE REDUCTION OF COOLING TIME FOR HIGHER JET DIAMETER

Temp. diff. (°C)	% Reduction of quenching time compare to d = 2.5mm					
	d= 3.5mm			d= 4.8mm		
	0mm	8mm	16mm	0mm	8mm	16mm
800-575	34	64	60	40	70	75
575-350	47	31	52	60	46	54
350-125	42	14	5.6	45	26	35

IV. CONCLUSION

The surface quenching of a hot stainless steel surface is experimentally investigated at the stagnation and different downstream spatial locations. For same temperature drop at jet Reynolds number of 24000 the surface cooling rate is approximately 30% higher as compare to at 5000 Re. The cooling rate is further higher for the mid range of surface temperature as compare to the higher and lower surface temperature range irrespective of the change in jet flow rate.

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