Kinematics of steam film wetting while quenching cylindrical samples in thermal oils

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Abstract. The paper presents the determination of the velocity of the vapor front along the outer wall of a cylindrical specimen in the process of two-dimensional axisymmetric quenching of the samples in thermal oils. One thermal oil is Isorapid 277 HM heated to 40°C and the other thermal oil is Marquench 722 heated to 90°C. The experimental setup of the work consists of heating to a temperature of 850°C, then quenching three dimensionally different cylindrical probes. The dimensions of the probe were: ϕ25x100, ϕ50x150 and ϕ75x225 mm. All quenchings were done in strictly controlled conditions of the flow rate of the quenchant around the cylinder as well as maintaining the temperature of the quenchant within the maximum 40±2.5°C or 90±3°C, during the quenching of the samples. The velocity of movement of the steam front on the outer surface of the cylinder was determined from the time-measured values of temperatures at the marked points of each sample. The analysis of the steam front movement velocity along the cylinder wall starts from the moment the lower base of the probe touches the quenchant. During the process of immersing the test probe in the quenchant, in addition to measuring the temperatures in time, the time of lowering the probe to contact with the quenchant sample was also measured. The approximate average velocity of the vapor front was determined based on the indications of the lower and middle thermocouples located 1.5 mm below the outer surface of the cylinder wall. Based on the distance of one half the height of each probe and time, the velocity of the steam film movement or the kinematics of the steam film wetting was obtained. The obtained results were compared with the results of quenching in water and aqueous solutions of the same probes under the same strictly controlled conditions.

1. Introduction
Quenching process represents a fast cooling of a workpiece in quenchant in order to gain certain material properties. However, the quenching process also prevents undesired crystal grain size and other similar reaction. During quenching three different phases can be identified: vapor blanket (full film boiling), nucleate boiling and convective heat transfer. Most vaporized liquids which can be found in the quenching are water, oil and aqueous solutions [1]. The cooling conditions can be categorized by three groups factors (i) workpiece characteristics (composition, mass, geometry, surface roughness and condition) (ii) quenchant characteristics (density, viscosity, specific heat, thermal conductivity, boiling temperature) and (iii) quenching facility (bath temperature, agitation rate, flow direction). The cooling behavior of thermal oil during quenching can be identified similar like water which involves three stages of cooling namely mentioned previously. However, the cooling performance of thermal oil is much lower than water [2].
The estimation of the velocity of the steam front on the surface of the test sample was made on the basis of cooling curves formed by measuring the temperatures at the indicated points of the test probe according to [4] and [5]. The theoretical description of the problem is shown in Figure 1.

Figure 1 shows a cylinder of diameter D, height H, initial temperature 850 °C, which was vertically immersed at a velocity of $w_a = 0.025$ m/s in the bottom-up cooling fluid, which flows to the cylinder at a velocity of $w_1 = 0.336$ m/s. During immersion of the probe in the quenchant, four probe temperatures were measured continuously over time using built-in thermocouples. Based on the obtained values of temperatures in the probe, the velocity of movement of the vapor front on the surface of the probe was estimated. The experimental setup of the work consisted of quenching three dimensionally different cylindrical probes. The dimensions of the probes were: $\phi 25 \times 100$, $\phi 50 \times 150$ and $\phi 75 \times 225$ mm, and the material of the probes was AISI 304 steel. Quenching agents were two thermal oils. One thermal oil was Isorapid 277 HM and the other thermal oil was Marquench 722. A detailed description of the experimental setting of the problem as well as the experimental results were given in [3] and [6]. The task of the work was solved at the level of heat conduction through the cylinder wall. As the solving algorithm did not know the events in the fluid that surrounds the probe, it was not able to give a current picture of the movement of steam on the probe surface. Accordingly, the rate of wetting, i.e. the rate of disappearance of the vapor film was estimated on the basis of experimental results of temperature measurements at points 1, 2, then 5, 6 in the probe $\phi 25 \times 100$, then 5, 6 in the probe $\phi 50 \times 150$ and 9, 10 in the probe $\phi 75 \times 225$ mm, which were 1.5 mm below the outer surface of the probe.

2. Experimental determination of steam front velocity
The analysis of the velocity of the vapour film along the cylinder wall began from the moment the lower base of the probe touched the quenchant. At places 1, 2, 3, 4, then 5, 6, 7, 8 and 9, 10, 11, 12, in the mentioned tests, temperatures in time were measured in parallel, on the basis of which the average velocity of the steam front was estimated. In [3] and [4] in addition to the cooling curves, the results based on video recordings were used because pure water is transparent for video recordings. In this paper, the analysis of the velocity of the steam front was given only on the basis of the measured cooling curves because thermal oils were not transparent to video rays. The physical properties of both thermal oils were given in detail in [3]. The recommended quenching temperature of steel in Isorapid 277 HM oil was from 50
to 80 °C and max up to 130 °C in a protective atmosphere, while the recommended quenching temperature in Marquench 722 oil was from 60 to 130 °C and in a closed furnace up to 150 °C. In this paper Isorapid 277 HM was heated and maintained at 40 °C, while Marquench 722 was heated and maintained at 90 °C.

2.1. Determination of steam front velocity based on cooling curves

The velocity of the steam front was determined on the basis of showing the temperatures in the time of thermocouples at half the height of each probe, i.e.: 2 in the probe φ25x50 mm, 6 in the probe φ50x150 and 10 in the probe φ75x225 mm. Each thermocouple was located 1,5 mm below the outer surface of the corresponding probe. A vapour film was formed at the moment of contact of the probe base with the quenchant. This moment was determined by measuring the movement time of each probe from the center of the furnace to the water contact indicated on each cooling curve.

The second time or position of the vapor front was its breaking in the middle of each probe indicated by a sharp rise in the temperature gradient of cooling, read from the cooling curves. The approximate mean velocity of the vapour front over the surface of the probe was determined with two necessary assumptions: the speed of the steam front or the speed of the Leidenfrost front (disappearance of the steam film) was constant and the delay of the central thermocouple was also compensated by the delay of the lower thermocouple (1,5 and 9).

Figure 2 shows an enlarged view of the cooling curves at the location of thermocouple 2 in the probe φ25x100mm for both thermal oils. The contact of the lower base of the probe with the oil was in 16,5 seconds, corresponding to the moment of formation of the steam front or a sudden rise in temperature gradient at position 1, and the breaking of the steam front (Leidenfrost effect), in the middle of the probe height was indicated in Figure 2.
Figure 3. The steam front movement time on the way to half of the $\phi 50 \times 150$ probe height.

Figure 4. The steam front movement time on the way to half of the $\phi 75 \times 225$ probe height.

The difference between these two times defines the movement time of the steam front along the way of half the probe height. Cooling curves at the location of thermocouple 6 in the probe $\phi 50 \times 150$ mm for both thermal oils were given in Figure 3. Contact of the lower base of the probe with thermal oils was in 15.5 seconds, corresponding to the time of steam front formation or sudden rise in temperature gradient at location 5 and the breaking of the steam front was in the middle of the probe height, marked in the same Figure. The time temperature response of thermocouple 10 in the probe $\phi 75 \times 225$ mm for both thermal oils was given in Figure 4. The contact time of the lower base of the probe with the oils was 14 seconds corresponding to the time of vapour front formation or a sudden rise in temperature gradient at position 9, and the Leidenfrost effect was in the middle of the probe height, indicated in Figure 4.
Table 1. Mean velocity of the vapour front on the outer surfaces of individual probes quenched in Marquench 722 thermal oil preheated at 90 °C.

| Probe  | Time to probe contact with Marquench oil, \( t_1 \), s | Steam film breaking time, \( t_2 \), s | Temperature 2, 6 and 10, at the \( t_2 \), °C | The way of steam film, \( h \), mm | Steam velocity mm/s, \( \bar{w} \) |
|--------|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| \( \phi 25 \times 100 \) | 16.5 | 18.3 | 815 | 50 | 27.8 |
| \( \phi 50 \times 150 \) | 15.5 | 16.5 | 827 | 75 | 75 |
| \( \phi 75 \times 225 \) | 14 | 17.5 | 830 | 112.5 | 32.14 |

Table 2. Mean velocity of the vapour front on the outer surfaces of individual probes quenched in Isorapid 277 HM thermal oil at a temperature of 40 °C

| Probe  | Time to probe contact with Marquench oil, \( t_1 \), s | Steam film breaking time, \( t_2 \), s | Temperature 2, 6 and 10, at the \( t_2 \), °C | The way of steam film, \( h \), mm | Steam velocity mm/s, \( \bar{w} \) |
|--------|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| \( \phi 25 \times 100 \) | 16.5 | 18.3 | 815 | 50 | 27.8 |
| \( \phi 50 \times 150 \) | 15.5 | 16.5 | 827 | 75 | 75 |
| \( \phi 75 \times 225 \) | 14 | 17.5 | 830 | 112.5 | 32.14 |

According to the assumptions introduced in Table 1, the mean velocity of the steam front was calculated. The quenching results from Table 2 shown the same tendency as the quenching results from Table 1. The mean temperature read at the thermocouples 2, 6 and 10 was 826.7 °C.

3. Results comparison with previously published results

Previously published papers describing the velocity of the vapor front with the same test probes and under the same experimental conditions, but with different quenchants which were water at a temperature of 40 °C [4] and aqueous solutions at a temperature of 40 °C, [5]. Cooling rates in thermal oils Isorapid 277 HM and Marquench 722 are about 3.5 to 10 times higher than quenching rates in water, and 15 to 40 times higher than aqueous solutions. Range values mostly depend on the probe diameter, as shown in Figure 5. The conclusion for the given results would be that thermal oils belongs to different category, while water and aqueous solutions in another. The results shown that the obtained cooling rates in water and aqueous solutions are far less than the cooling rates in thermal oils, which is nonobvious since the heat capacities of water and aqueous solutions are twice as high as the heat capacities of thermal oils. The reason for this is the stability of the vapor film on the wall of the probe which acts as an insulator. Figure 5 shows the cooling curves at point 2 in the \( \phi 25 \times 100 \) probe.
Figure 5. Cooling curves at point 2 of the 25x100 probe for five different quenchants

A comparison of the corresponding cooling rates for five different extinguishing agents is shown in figure 6.

Figure 6. Cooling rates at point 2 of the 25x100 probe for five different extinguishing agents

The maximum values of the temperature gradients are related to the moment of vapor front decay or the period of the droplet evaporation phase. Figure 7 shown the comparative values of the mean velocities of the steam front depending on the diameter of the test probe. Quenching results in: pure water was reported in [4], 5% aquatenside BW in water and 25% aquatenside BW in water were reported in [5].
Figure 7. Velocity of the steam front on the surface of the probes

It can be seen from the figure that the velocities of the vapour front when quenching the probes in thermal oils were the highest and not comparable with water and aqueous solutions. The average temperature read at the site of thermocouples 2, 6 and 10 was 824 °C.

4. Conclusion

The mean temperatures at the thermocouple sites 2, 6 and 10 in the middle of the height of each probe at the time of the steam front breaking were approximately 824 °C, for quenching in Marquench 722 the temperature was 90 °C, while the mean temperatures at the same positions in Isorapid were 277 HM 826,7 °C. The results show a short duration of the vapour film during quenching in thermal oils, and thus the values of surface temperatures at the time of breaking of the vapour front remain high. The reason for this was the high resistance of thermal oils to evaporation. Previously published results of quenching in water and aqueous solutions [4] and [5] shown lower velocities of the vapour front, and the residence of the vapour film on the sample wall was longer with a reduced surface temperature at the time of vapour breaking. The final contribution of this paper is reflected in the comparison of the results obtained during quenching in five different steel quenchants.

References

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