Controlling Cooling rate of Carbon Steel during quenching process

DESCRIPTION

As an engineer you are supposed to design a quenching process for Medium carbon steel so as to obtain required cementite microstructure. This is accomplished by dropping the product in a bath of water during the process the temperature of bath maintained be controlled between 20°C to 25°C.

The following are the fixed parameters:

- Length of Steel product=400mm
- Width= 50 mm
- Height=25 mm
- Initial Cooling rate (required) = 8°/sec
- Initial Temperature of Steel =900°C

The properties of steel can be used for 450° degrees and the process must be designed as lumped mass system.

OUTPUT

Assuming that the obtained piece is a lumped mass, then we can say that the temperature in the piece is uniform, thus the temperature only depends on time T(t).

The heat transfer equation for a lumped system is:

$$\dot{Q} = hA(T_\infty - T)$$

It can also be:

$$\dot{Q} = mC_p dT$$

So we can say that:

$$hA(T_\infty - T) = mC_p dT \rightarrow hA(T_\infty - T) = mC_p d(T - T_\infty)$$

$$\rightarrow -\frac{hA}{mC_p} = \frac{d(T - T_\infty)}{(T - T_\infty)}$$

Integrated from the t=0 to t:

$$\frac{T(t) - T_\infty}{T_i - T_\infty} = e^{-\frac{hA}{mC_p}t}$$

$$T(t) = T_\infty + (T_i - T_\infty)e^{-\frac{hA}{mC_p}t}$$ (Steel Temperature Function)

$$\frac{dT}{dt} = -\frac{hA}{mC_p}(T_i - T_\infty)e^{-\frac{hA}{mC_p}t}$$ (Cooling Rate Function)

	Temperature°C	20	100	200	300	400	500	600	700	800	900
Steel	thermal conductivity W/(m · °C)	53.3	50.7	47.3	41.4	39.2	37.0	34.8	32.6	30.4	28.2
	Specific heat capacity J/kg · °C	431	471	522	573	624	675	760	1008	799	650
Concrete	thermal conductivity W/(m · °C)	1.36	1.35	1.34	1.32	1.22	1.10	0.97	0.85	0.72	60
	Specific heat capacity J/kg · °C	913	963	1022	10755	1122	1164	1200	1231	1256	1275

Figure 1: Values of specific heat for steel in fuction of temperature

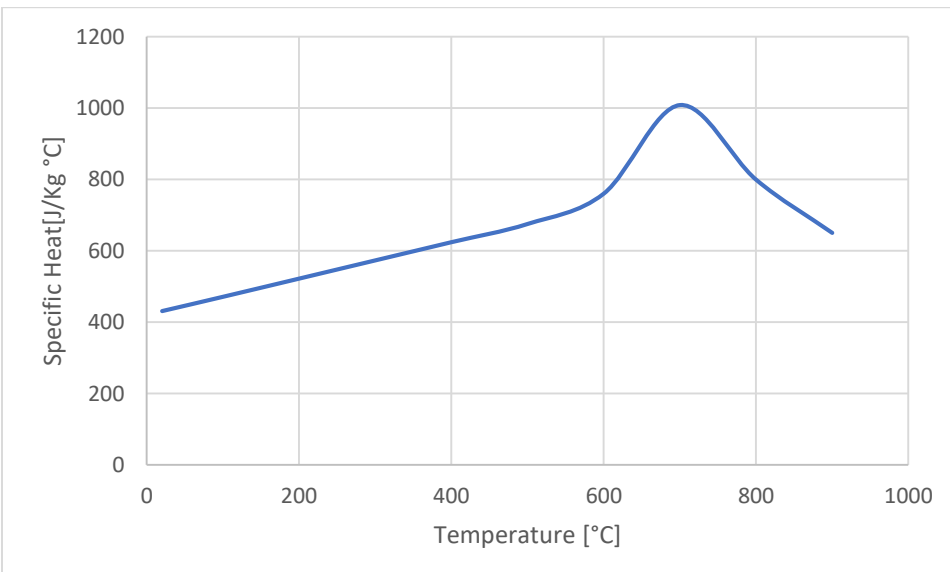

Figure 2: Specific heat values in function of temperature

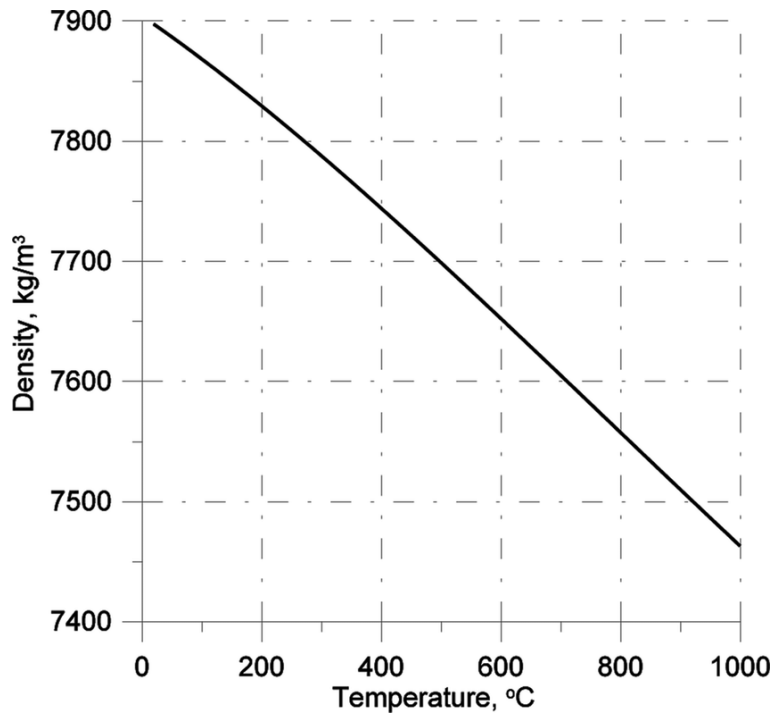

Figure 3: Steel density vs Temperature

1. Estimate the required heat transfer coefficient

For an initial cooling rate of 8°/sec we must have:

$$\left.\frac{dT}{dt}\right|_{t=0} = -\frac{hA}{mC_p}(T_i - T_\infty) = -8$$

By solving for heat transfer coefficient h, we can obtain:

$$h = \frac{8\, mC_p}{A(T_i - T_\infty)}$$

With:

C_p: the specific heat, from Figure 1 we can say that its value for 450° is 650 J/kg °C

m: Mass of the piece, which is its volume times its density, the density in this case for 450° is around 7730kg/m^3

$$m = \rho\, V = 7730kg/m^3 \times 0{,}05m \times 0{,}025m \times 0{,}4m = 3{,}865kg$$

A: Heat exchange surface, in this case, the sum of all surfaces in the piece.

$$A = 2 \times (0{,}4m \times 0{,}05m) + 2 \times (0{,}4m \times 0{,}025m) + 2 \times (0{,}025m \times 0{,}05m) = 0{,}0625m^2$$

T_i: Initial temperature of 900°C/1173,15°K

T_∞: Water temperature of 20°C/293,15°K

So by applying the highlighted equation numerically we obtain:

$$h = \frac{8\,{}^{°C}/_{sec} \times 3{,}865kg \times 650\,{}^{J}/_{kg\,°C}}{0{,}0625m^2(900°C - 20°C)} = 365{,}42\ {}^{W}/_{m^2\,°C}$$

2. How much time is needed to bring the product to 50°C and plot the cooling rate

By using the Steel Temperature function obtained earlier, we can express:

$$T(t_{50}) = T_\infty + (T_i - T_\infty)e^{-\frac{hA}{mC_p}t_{50}} = 50$$

$$e^{-\frac{hA}{mC_p}t_{50}} = \frac{50 - T_\infty}{T_i - T_\infty} \rightarrow -\frac{hA}{mC_p}t_{50} = ln\left(\frac{50 - T_\infty}{T_i - T_\infty}\right)$$

$$\rightarrow t_{50} = -\frac{ln\left(\frac{50 - T_\infty}{T_i - T_\infty}\right)mC_p}{hA}$$

$$\rightarrow t_{50} = -\frac{ln\left(\frac{50 - 20}{900 - 20}\right) \times 3{,}865\ kg\ \times 650\,{}^{J}/_{kg\,°C}}{365{,}42\,{}^{W}/_{m^2\,°C}\ \times 0{,}0625m^2}$$

$$\rightarrow t_{50} = 371{,}66\ sec$$

Therefore, to reach 50°, it requires 371,66 seconds

Cooling rate function: $\left|\frac{dT}{dt}\right| = \frac{hA}{mC_p}(T_i - T_\infty)e^{-\frac{hA}{mC_p}t} \rightarrow 8e^{-0{,}009\,t}$

By plotting it to Excel we obtain the Cooling rate plot.

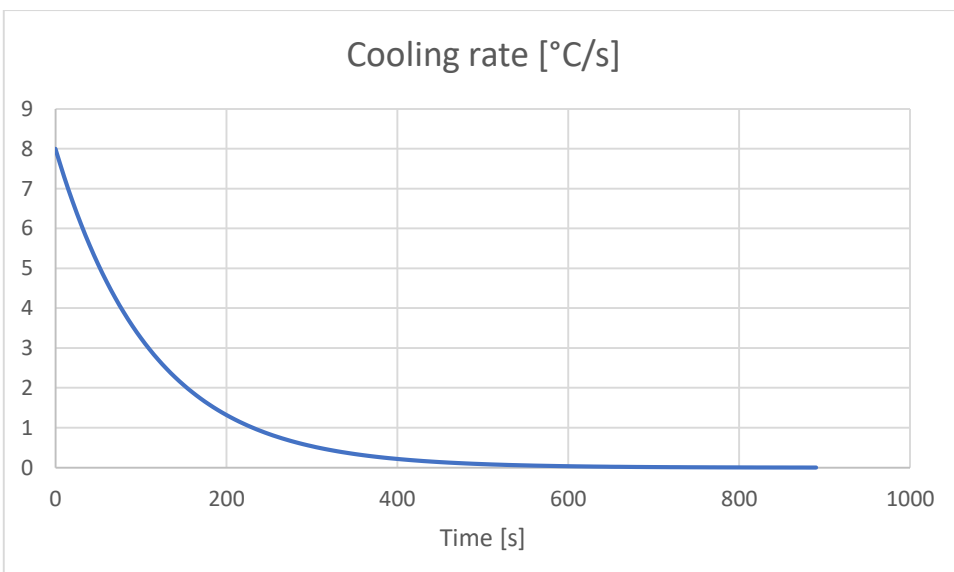

Figure 4: Cooling rate plot

3. How much mass of water is required to keep the temperature within the range?

Assuming an initial water temperature of 20°C.

Then to stay within range, the heat energy stored in the steel, should not heat the water more than 25°C, so we assume it the temperature of equilibrium.

$$m_s C_{Ps}(T_{is} - T_e) = m_w C_{Pw}(T_e - T_{iw})$$

Solving for the mass of water required m_w: (Taking the water properties at 20°C)

$$m_w = \frac{m_s C_{Ps}(T_{is} - T_e)}{C_{Pw}(T_e - T_{iw})}$$

$$m_w = \frac{3{,}865\ kg \times 650\,{}^{J}/_{kg\ °C} \times (900°C - 25°C)}{4182\,{}^{J}/_{kg\ °C} \times (25°C - 20°C)}$$

$$m_w = 105{,}13\ kg$$

To keep the water temperature within range, 105,13kg of water is needed.

4. Graph the variation of temperature of product and actual heat transfer with time

The temperature function: $T(t) = T_\infty + (T_i - T_\infty)e^{-\frac{hA}{mC_p}t} \rightarrow 20 + 880e^{-0{,}009\,t}$

Heat transfer function: $|\dot{Q}| = hA(T_\infty - T(t)) \rightarrow 20098{,}1e^{-0{,}009\,t}$

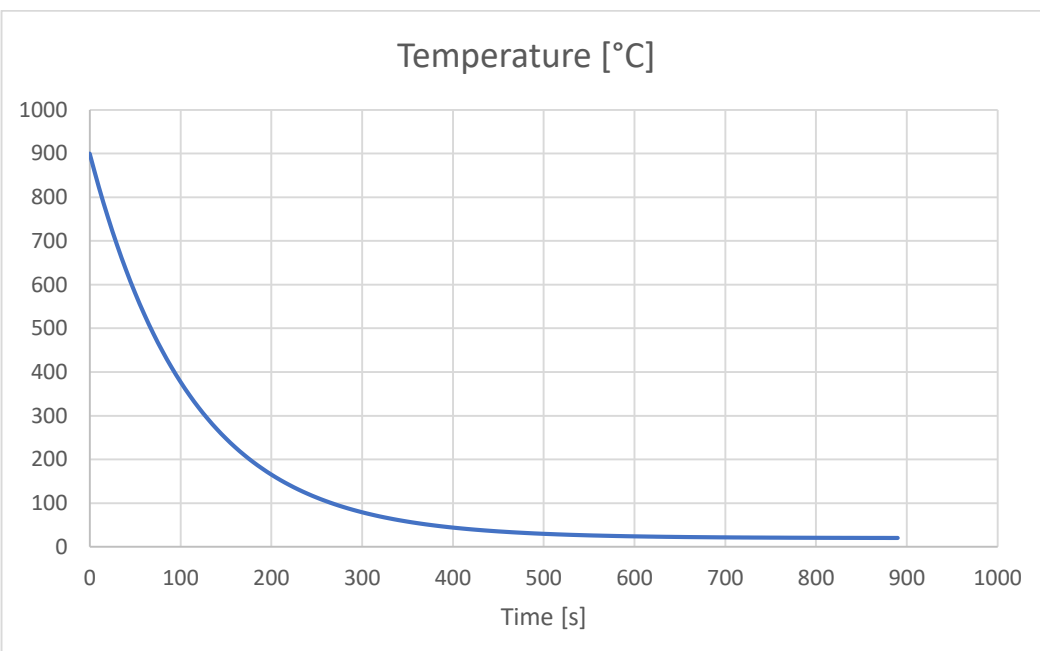

Figure 5: Temperature plot

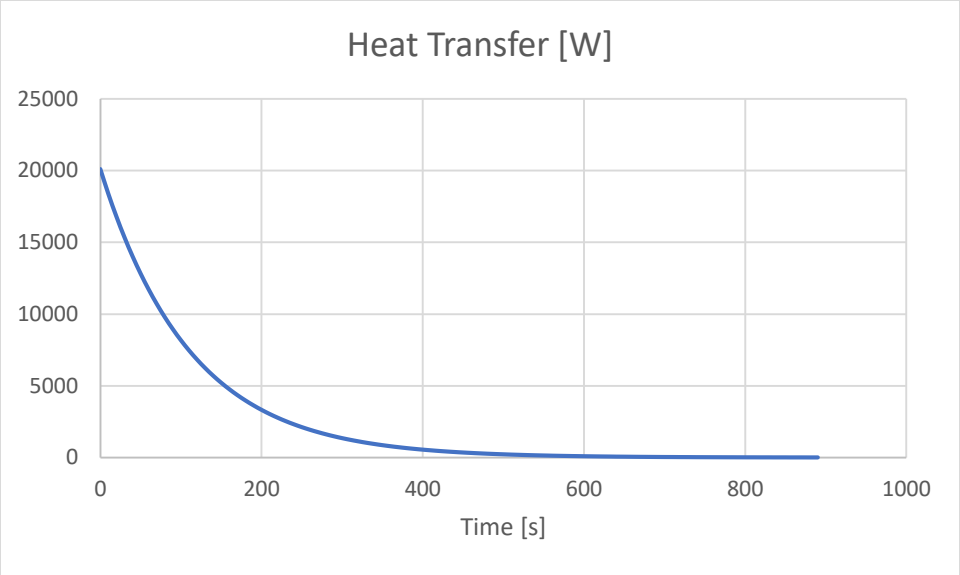

Figure 6: Heat Flux plot