



## COBEM-2021-1850

# STUDY OF THE HEAT TRANSFER DURING THE QUENCHING OF A HADFIELD STEEL IN POLYMERIC SOLUTION

**Ana Paula Dias Carvalho Pereira**

**Renata Neves Penha**

Universidade Federal de Itajubá

anapdias@gmail.com

rnp@unifei.edu.br

**Abstract.** Hadfield steels are sought after by the railway and mining industries that require high mechanical strength and toughness, excellent cold workability and wear resistance. Considering the important participation of the mining industry in the Brazilian economy, the technological relevance of this work is justified. The hardening of this steel is traditionally carried out in water, which ensures high cooling rates, but not uniform, which results in very high residual stresses, which can reduce the useful life of tempered components. However, the use of polymeric solutions as a tempering medium also has high heat removal rates and allows for more uniform cooling as the vapor layer breaks up instantly. The objective of this work is to simulate the heat transfer, by calculating the heat transfer coefficients in the steel tempering process, comparing the traditional use of water with the use of polymeric solutions. Following ASTM D6200 parameters, the cooling curves were obtained in a solution of 8 and 10% PAG. Temperature variation over time is the boundary condition used in the regular thermal method to obtain the heat transfer coefficients at the interface of the metal and the tempering medium. It was determined that the difference between the cooling speed generated very different values for the heat transfer coefficient.

**Keywords:** *Quenching, Polymer quenchant, Heat transfer coefficient, Hadfield steel.*

## 1. INTRODUCTION

Austenitic manganese steel, or Hadfield steel as it became known after its inventor, Robert Abbot Hadfield, was developed in 1882. Initially, its chemical composition was 1.2% carbon and 12.5% manganese (Gousseland, 1974). This composition has not undergone much change.

Some noticeable characteristics sought in these steels are good mechanical strength, toughness, and wear resistance. The unique combination of these properties makes this steel the best option in various industrial sectors, such as railway, mining, and civil construction.

Hadfield steel has a good hardening capacity in service. The hardening effect in service happens due to the transformation plasticity phenomena. The presence of a twinned microstructure explains it (ADLER et al. 1986). Moreover, the quenching heat treatment also increases the resistance of the manganese steel. Quenching is a process that turns austenite into martensite, which provides an increase in steel hardness. (JOST and SCHMIDT, 1986).

The heat treatment of steels is the process that defines the quality, determination of material use, as well as its final cost. From this process, the mechanical properties of steel change. There are thermal treatments that reduce hardness to those that increase mechanical strength, according to the desired application (CHIAVERINI, 2003).

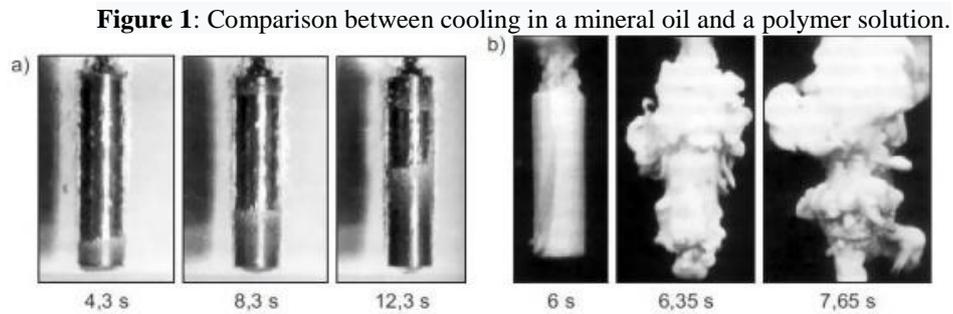
Quenching is a heat treatment that seeks to increase the material's hardness and mechanical resistance through microstructural transformation. Its target microstructure is martensite, which is a result of a diffusionless process (TOTTEN, 2007).

Quenching consists of the rapid immersion in a cooling medium, after the part austenitization. Upon coming into contact with the fluid, the heated body develops three consecutive stages: vapor film, nucleate boiling, and convection (BUCZEK, 2013 and HEMING et al., 2003)

The steel quenching can be carried out in the water as a cooling medium, but this medium generates a very high and non-uniform cooling rate between the surface and the interior of the steel part. This difference can generate surface stresses in the part and compromise some of the desired mechanical properties of a Hadfield steel.

To prevent the useful life of the part from being reduced, the quenching in a polymeric solution of 8 and 10% PAG (polyalkylene glycol) is studied. The concentration of the solutions sets the main parameter for the flexibility of the process, as they directly influence the heat exchange capacity of the fluids. Increasing the amount of polymer increases the viscosity of the solution, slowing down the cooling rate, and therefore reducing the ability to form martensite. This is because as the concentration increases, the vapor layer formed becomes thicker, making it difficult to collapse (RAMESH, 2016).

Quenching in polymeric medium ensures equally rapid cooling compared to quenching in water, but more evenly, as shown in Figure 1. When the hot metal is immersed in the polymer solution, a layer surrounding the part surface is formed. This layer separates the metal surface from the rest of the polymer solution. This layer is the result of the formation of superheated vapor. As cooling occurs, the vapor blanket suddenly breaks, resulting in high cooling rates, the nucleating boiling stage. The entire vapor blanket breaks instantly in polymeric solutions, as shown in Figure 1b, which provides more uniformity during the cooling process (BORSATO, 2014).



## 2. MATERIALS AND METHODS

### 2.1 Experimental method

For this study a Hadfield steel with a composition of 1.22% carbon and 13% manganese was used.

Quanchant studied in this work includes 8 and 10 % PAG solution. The cooling curves were acquired by a standard Inconel 600 probe, according to the ISO 9950, with 12.5 mm in diameter and 60 mm in length. A computer connected to a thermocouple, type K (NiCr/NiAl), inserted in the geometric center of the probe, registred the variation of temperature over time. These cooling curves were the input data for the calculation of the heat transfer coefficient,  $h$ .

The polymer solutions tests followed the ASTM D6462 standard. Quanchant temperature was 40°C with an agitation rate equal to 500rpm.

### 2.2 Regular thermal method

The thermal conductivity and specific heat properties vary according to the temperature, and in order to obtain the heat transfer coefficient during the hardening process of manganese steel, these data are provided by Tab. 1.

Table 1: Effects of temperature on the physical properties of 13 % Mn steel.

Temperature (K)	Specific Heat (J/Kg.K)	Thermal Conductivity (W/m.K)
273.15	494	13.2
323.15	510	14.0
373.13	527	14.9
423.15	553	15.7
473.15	573	16.5
523.15	590	17.4
573.15	603	18.0
623.15	607	18.6
623.15 – 923.15	-	-
973.15	-	21.8

Source: (NATHAL and ELBERT, 1985).

Using the values of thermal conductivity ( $\lambda$ ) and specific heat ( $c$ ) and having the density ( $\gamma$ ) of Hadfield steel as 6610 kg/m<sup>3</sup>, it was possible to calculate its thermal diffusivity ( $\alpha$ ) from Eq. 1.

$$\alpha = \frac{\lambda}{c \times \gamma} \quad (1)$$

Having the value of thermal diffusivity, it was possible to calculate the Kondratjev number ( $Kn$ ) with the aid of the cooling factor ( $m$ ) and the cubic form factor ( $F$ ). The last one being equal to 0.00000684. Kondratjev number was calculated from Eq. 2.

$$Kn = \frac{m \times F}{\alpha} \quad (2)$$

Using the values of the Kondratjev number it was possible to generalize a polynomial where the terms  $a$ ,  $b$  and  $c$  were calculated as follows:

$$a = -1 + Kn^2 \quad (3)$$

$$b = 1.437 \times Kn^2 \quad (4)$$

$$c = Kn^2 \quad (5)$$

Then, the generalized Biot number ( $Biv$ ) can be calculated with the help of the terms  $a$ ,  $b$  and  $c$  of the polynomial, like Eq. 6.

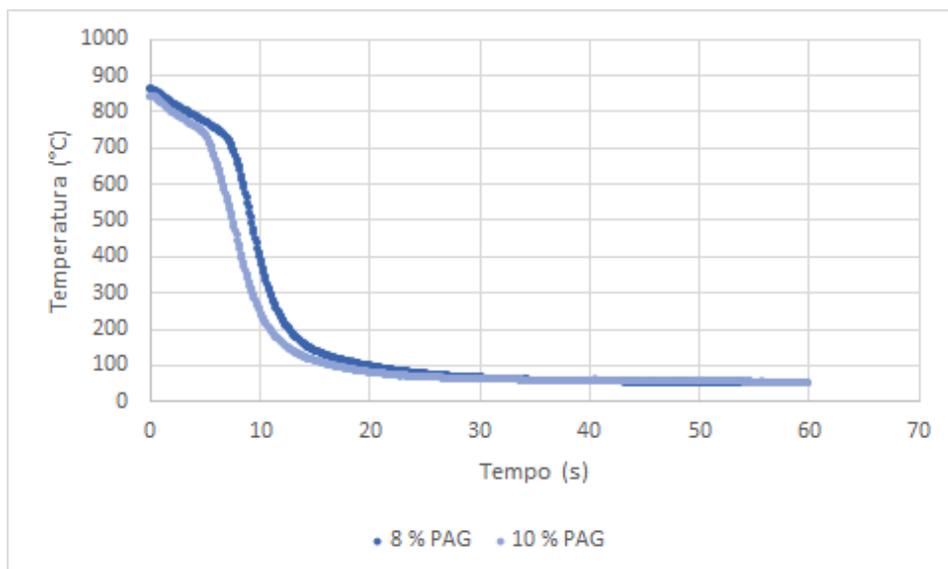
$$Biv = \frac{-b - \sqrt{(b^2 - 4) \times a \times c}}{2 \times b} \quad (6)$$

Finally, using the values of generalized Biot number, thermal conductivity, cubic form factor, sample volume ( $V$ ) and area ( $A$ ), the heat transfer coefficient ( $h$ ) was calculated from Eq. 7.

$$h = \frac{Biv \times \lambda \times V}{A \times F} \quad (7)$$

### 3. RESULTS AND DISCUSSION

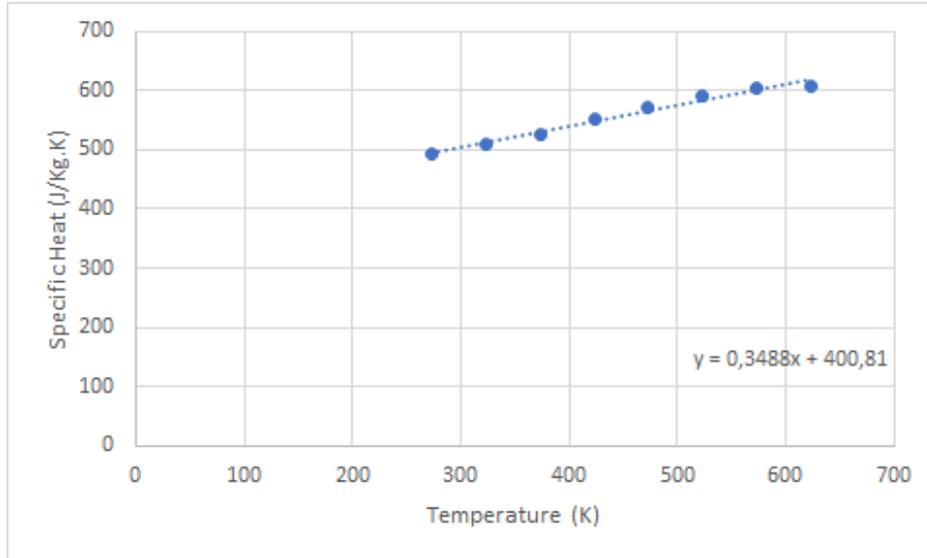
With the data obtained from the steel cooling curves in solutions at 8 and 10% PAG, it was possible to plot a comparative graph between them, as shown in Fig. 2.



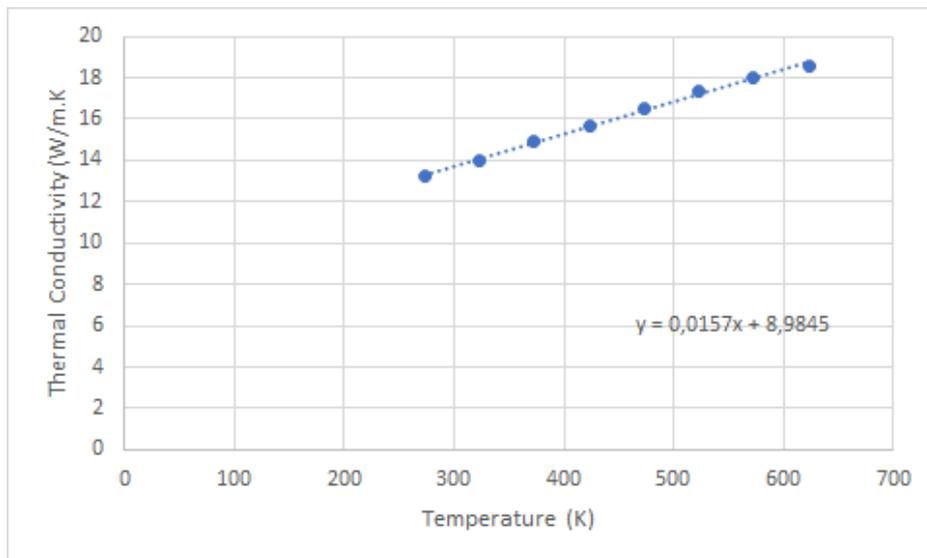
**Figure 2:** Cooling curves in different PAG solutions.

Observing the Fig. 2, it is possible to notice that the vapor phase with the 8% PAG solution is larger, causing the impression of a slower cooling curve. However, it can be seen that the curve of the 8% PAG solution achieves a higher cooling rate than that of the 10% PAG solution, as expected.

After obtaining the cooling worms for both solutions, the data in Tab 1 were interpolated, and an equation for specific heat and thermal conductivity was obtained from the adjustment of data in the Fig. 3 and Fig. 4 below.



**Figure 3:** Obtaining Temperature vs. Specific heat data setting.



**Figure 4:** Obtaining Temperature vs. Thermal conductivity data setting.

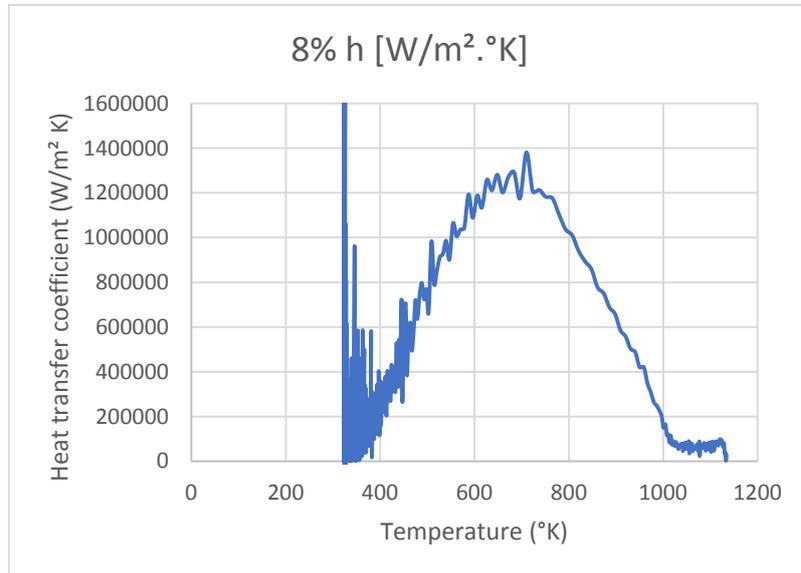
With these graphs it was possible to obtain Eq. 8 and Eq. 9 with adequate adjustment for thermal conductivity and specific heat.

$$y = 0.3488 x + 400.81 \tag{8}$$

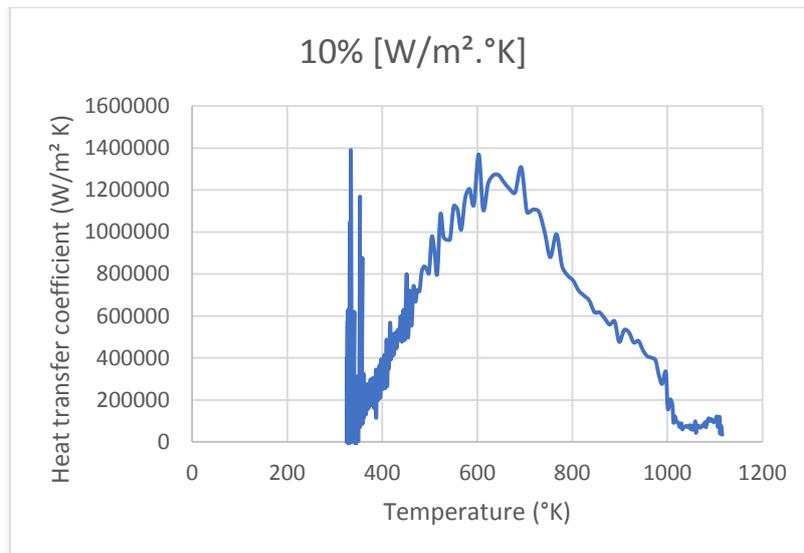
$$y = 0.0157 x + 8.9845 \tag{9}$$

Replacing the temperature values obtained from the cooling curves at 8 and 10% PAG in Eq. 8 and Eq. 9, it was possible to calculate the thermal diffusivity, Kondratjev number, the generalized Biot number and thermal diffusivity ( $m^2/s$ ).

The Temperature vs. Heat transfer coefficient curves can be seen in Fig. 5 and Fig. 6.



**Figure 5:** Curves 8% PAG for Temperature vs. Heat transfer coefficient.



**Figure 6:** Curves 10% PAG for Temperature vs. Heat transfer coefficient.

Using figures 2 and 5, it is proved that with a lower concentration of polymer, a lower vapor phase with a higher cooling rate is generated.

#### 4. CONCLUSION

It can be concluded that the specific heat and thermal conductivity increase with increasing temperature.

It can also be concluded that the use of a less concentrated PAG solution ensures high rates of heat exchange and, as a result, a faster rate of cooling. Furthermore, it can be concluded that the highest heat transfer rates occur at temperatures close to 50°C and 400°C for both concentrations and PAG.

## 5. REFERENCES

- Adler, P.H.; Olson, G.B.; Owen, W.S. Strain hardening of Hadfield manganese steel. *Metallurgical transaction*, v. 17, 1986, p. 1725 - 1737.
- Borsato, B.R., Avaliação da substituição dos meios de resfriamento convencionais por solução polimérica no tratamento térmico de têmpera do aço SAE 4340. Trabalho de conclusão de curso UTFPR, 2014.
- Buczek, A., Telejko, T., Investigation of heat transfer coefficient during quenching in various cooling agents. *International Journal of Heat and Fluid Flow*, v. 44, pp. 359-364, Dec. 2013.
- Gousseland, P. Mines, Metals and Materials. Materials for the mining industry. Symposium. Vail, Colorado, 1974, p. 7 - 10.
- Heming, C., Xieqing, H., Jianbin, X., Comparison of surface heat-transfer coefficients between various diameter cylinders during rapid cooling. *Journal of Materials Processing Technology*, v. 38, pp. 399-402, Jul. 2003.
- Jost, N.; Sshmditd, I. Friction-Induced martensitic transformation in austenitic manganese steels. *Wear*, v. 111. 1986, p. 377 - 389.
- Nathal, M.V. and Elbert, L.J., *Metall. Trans. A*, Vol 16, 1985, p 1849-1870.
- Ramesh, G., Prabhu, K.N., Effect of polymer concentration on wetting and cooling performance during immersion quenching. *Metallurgical and Materials Transactions B*, v. 47, pp. 859-881, Dec. 2016.
- Totten, G. E., *Steel heat treatment handbook*, 2 ed., New York, CRC Press, 2007.