Coursework 1 – Transient Conduction

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1 *Part A: Using lumped capacitance*

1.1 Assumptions

- Internal temperature of the steel ball is uniform at any time t.
- No change in water temperature
- No heat transfer by radiation
- Material is standard carbon steel
- Material properties constant (taken at average temperature $T = 469^oC$)

1.2 Properties

Table 1: Properties from problem

Property	Value	Unit
Characteristic length, L	5	cm
Diameter, D	10	cm
Temperature of the water, T_w	38	^oC
Initial temperature of steel ball, $T_{s,1}$	900	^oC
Final temperature of steel ball, $T_{s,2}$	200	^oC
Heat transfer coefficient, h	600	W/m^2K

Table 2: Properties from literature

Property	Value at $T_{avg}(469\ ^oC)$	Unit	Source
Specific heat capacity, Cp	552	$J \cdot kg^{-1}K^{-1}$	[2]
Density	7.8 x 10^3	$kg \cdot m^{-3}$	[1]
Conductivity	40	$W \cdot m^{-1}K^{-1}$	[2]

The density of steel is assumed to be constant over the temperature range so the value in table 2, which is given at 300K, is assumed to be accurate. To confirm this assumption is acceptable the elongation was calculated using the ISO 834 standard equations[2]. This showed the overall change in volume of the sphere was 3% over the full temperature range of the problem. As $V \propto \rho$ this change is low enough to be discounted and for the assumption to be justified.

1.3 Schematic

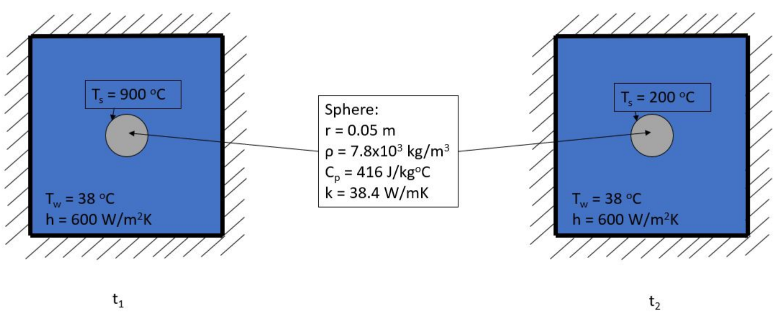

Figure 1: Part A schematic at initial and final state.

1.4 Analysis

Energy balance for closed system gives the following equation.

$$\dot{Q} = hA(T_s - T_f) = C_p \rho V \frac{dT_c}{dt} \tag{1}$$

Where $\dot{Q}$ is heat $[W]$, h is the heat transfer coefficient $[W/m^2K]$, A is the surface area between the ball and water $[m^2]$, T_s is the temperature of the steel ball $[^oC]$, T_f is the temperature of the water $[^oC]$, C_p is the specific heat capacity $[J/mK]$, ρ is the density of the steel ball$[kg/m^3]$, V is the volume of the steel ball $[m^3]$ and t is the time $[s]$.

Rearranging (1) to separate the variables gives.

$$\frac{1}{T_s - T_f} dT_c = \frac{hA}{C_p \rho V} dt \tag{2}$$

Which integrates to give.

$$\ln\left(\frac{T_{s1} - T_f}{T_{s2} - T_f}\right) = \frac{hA}{C_p \rho V}(t_2 - t_1) \tag{3}$$

Where t_i and T_{si} are the time [s] and temperature $[^oC]$ receptively at state i.

Rearranging (3) to make t_2 the subject gives.

$$t_2 = \frac{C_p \rho V}{hA}\left(\ln\left(\frac{T_{s1} - T_f}{T_{s2} - T_f}\right)\right) \tag{4}$$

Substituting in the values for the variables given in Figure 1 gives the final value.

$$\boldsymbol{t_2 = 205s} \tag{5}$$

Where t_2 is the time for the steel ball to reach a temperature of 200^oC under given assumptions.

2 *Part B: Lumped capacitance justification*

The lumped capacitance method is only valid if the ratio of the conductive heat transfer to convective heat transfer is low. This ratio is known as the Biot number, Bi, and is given by.

$$Bi = \frac{h \cdot L_c}{k} \tag{6}$$

Where h is convective coefficient $[W/m^2K]$, L_c is the characteristic length [m] and k is the conductivity $[W/m \cdot K]$.

Applying the values from Tables 1 and 2, choosing to set $L_c = R$ and substituting into equation 6 gives:

$$Bi = 0.7 \tag{7}$$

If $Bi > 0.1$ then the lumped capacitance method is no longer applicable as the assumptions made introduce non-trivial errors [1]. This means that the result in part A likely inaccurate.

It is worth noting however that the choice of L_c is significant. it is common to select L_c to be the maximum distance over which a temperature gradient would occur, as has been done above, but the method from the mathematical derivation is to use $L_c = \frac{V}{A_s}$ which for a sphere gives $L_c = \frac{R}{3}$. This means the use of $L_c = R$ will tend to overestimate the value of Bi. In this case however, using $L_c = \frac{R}{3}$ gives $Bi = 0.25$ so the result can still be assumed to be inaccurate despite the overestimate.

3 *Part C: Transient conduction*

$$t = \frac{f_0 \rho C_p R^2}{k} \tag{8}$$

4 *Part D: Non-infinite water bath*

5 *Part E: Equilibrium temperature*

References

[1] T. L. Bergman and Frank P. Incropera, editors. *Fundamentals of heat and mass transfer*. Wiley, Hoboken, NJ, 7th ed edition, 2011.

[2] Jean-Marc Franssen and Paulo Vila Real. *Fire Design of Steel Structures : EC1: Actions on Structures; Part 1-2: Actions on Structure Exposed to Fire; EC3: Design of Steel Structures; Part 1-2: Structural Fire Design*, volume Second revised edition of *ECCS-SCI Eurocode Design Manuals*. Ernst & Sohn, [Place of publication not identified], 2015.