

Thermodynamics

Steel ball in water bath with Simcenter™ Amesim™ Student Edition

Introduction

This exercise deals with heat transfer.

If a thermal mass at a certain temperature is surrounded by any fluid with another temperature, we will observe a temperature change of both. If system boundaries are in place and the system is considered adiabatic, a new overall temperature will be reached for the whole system.

Then we will use the Simcenter Amesim Student Edition, part of Simcenter™ portfolio, in order to validate easily and quickly the results.

→ As a practical example we look at a **steel sphere which is put into a water bath.**

Let's answer to the following questions:

In an isolated tank are 20 dm³ of pure water with a temperature of $T_W = 20\text{ }^{\circ}\text{C}$.

A steel sphere with the Volume $V_S = 1\text{ dm}^3$ and a temperature of $T_S = 40\text{ }^{\circ}\text{C}$ is placed into the tank at the time $t = 0\text{ s}$.

- a) Which final temperature T_E will the adiabatic system take on for $t \rightarrow \infty$?
- b) Which value has the temperature change of the steel sphere at the time $t = 0\text{ s}$?
- c) Which value of physical/thermodynamical work is necessary to cool down the sphere from $T_S = 40\text{ }^{\circ}\text{C}$ to T_E ?

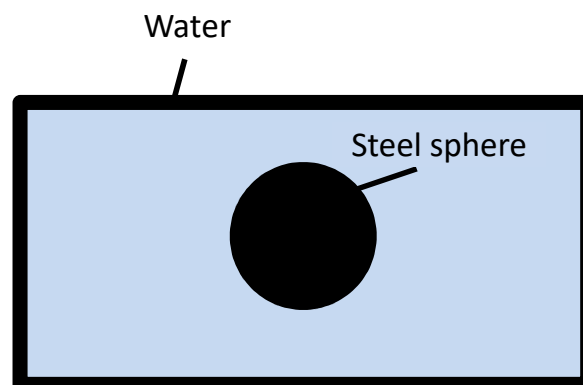
Theory and practical application

The following assumptions have to be taken into account:

- The tank has an insignificant small heat capacity
- The heat transfer between the ball and the water can be described with the heat transfer coefficient $h = 1000 \text{ W/(m}^2\text{K)}$
- The heat conduction in the water and the ball are ideal, i.e. the temperatures $T_w(t)$ and $T_s(t)$ of both subsystems are not a function of the position

Given material properties:

Material	Water	Steel St52
Density [kg/m^3]	998,2	7850
Spec. heat capacity [J/(kg K)]	4180	490



a) Law of thermodynamics:

$$\frac{dU}{dt} = \sum \dot{Q} + \sum \dot{W} = 0 \quad (1)$$

With $\sum \dot{Q} = 0$ and $\sum \dot{W} = 0 \rightarrow U_1 = U_2$

$$U_1 = m_W c_W T_{W,0} + m_S c_S T_{S,0} \quad (2)$$

$$U_2 = m_W c_W T_E + m_S c_S T_E \quad (3)$$

$$T_E = \frac{c_W T_{W,0} + c_S T_{S,0}}{c_W + c_S} \quad (4)$$

$$C_W = m_W c_W = \rho_W V_W c_W = 83,45 \frac{kJ}{kg} \quad (5)$$

$$C_S = m_S c_S = \rho_S V_S c_S = 3,847 \frac{kJ}{kg} \quad (6)$$

With this the final temperature equals to:

$$T_E = 20,88^\circ C \quad (7)$$

b) Law of thermodynamics for the steel ball

$$\frac{dU_S}{dt} = -\dot{Q} \quad (8)$$

$$\dot{Q} = h A_S (T_S(t) - T_W(t)) \quad (9)$$

Consequently the equation for the temperature change of the steel ball at $t=0$ s equals to:

$$h A_S (T_{W,0} - T_{S,0}) = m_S c_S \left[\frac{dT_S}{dt} \right]_{t=0} \quad (10)$$

$$\left[\frac{dT_S}{dt} \right]_{t=0} = \frac{h A_S}{c_S} (T_{W,0} - T_{S,0}) \quad (11)$$

With

$$A_S = \pi d^2 \text{ and } d = \sqrt[3]{\frac{6V_S}{\pi}}$$

$$A_S = \pi \left(\frac{6V_S}{\pi} \right)^{\frac{2}{3}} = 0,0484 \text{ m}^2 \quad (12)$$

Inserted in the equation of the temperature change:

$$\left[\frac{dT_S}{dt} \right]_{t=0} = -0,252 \frac{K}{s} \quad (13)$$

$$c) \quad U_{2_S} = m_S c_S (T_{S,0} - T_E) \quad (14)$$

$$U_{2_S} = \rho_S V_S c_S (T_{S,0} - T_E) \quad (15)$$

$$U_{2_S} = 7850 \frac{kg}{m^3} * 0,001 \text{ m}^3 * 0,49 \frac{kJ}{kg K} (40 \text{ }^\circ\text{C} - 20,88 \text{ }^\circ\text{C}) \quad (16)$$

$$U_{2_S} = \underline{73,5 \text{ kJ}} \quad (17)$$

Simulation, validation and practice with Simcenter Amesim Student Edition

In **SKETCH** mode, the model of the system (Figure 1: Simcenter Amesim model) can be built easily and fast, selecting the following components and connecting them together:

- In the Thermal library:**

Component	Icon	Comment
2 thermal mass (capacity)		Used to define the volume and mass of water and steel
1 conductive exchange		Used to define conductive heat exchange between thermal masses
1 heat flow sensor		
4 zero heat flow source		Used to plug the unused ports on thermal masses
2 solid definition icon		Used to define the thermodynamic properties of the solids
2 solid properties sensors		

- In the signal library:**

Component	Icon	Comment
1 Integrator		
1 signal sink		

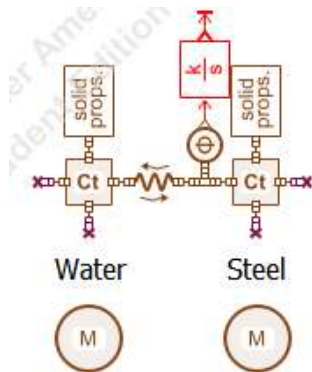


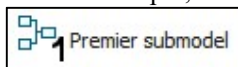
Figure 1: Simcenter Amesim model

Trick: You can easily rotate or flip your components on the sketch.

- Rotation: select the component and click with the mouse wheel (or use Ctrl + R)
- Flip: select the component and click with the mouse right button (or use Ctrl + M)

1. Selecting submodels

In this example, in **SUBMODEL** mode, submodels can be quickly selected using the “premier submodel”



2. Setting parameters

In **PARAMETER** mode, we will define the following values (default values are kept for other parameters):

Component	Icon	Parameters
Solid definition icon - Steel		<ul style="list-style-type: none"> • Solid type index = 1 • Material definition = user defined • Type of definition = constant values • Density of the material = 7850 kg/m³ • Specific heat of the material = 490 J/kg/K
Solid definition icon - Water		<ul style="list-style-type: none"> • Solid type index = 2 • Material definition = user defined • Type of definition = constant values • Density of the material = 998.2 kg/m³ • Specific heat of the material = 4180 J/kg/K
Thermal mass - Steel		<ul style="list-style-type: none"> • # temperature = 40 degC • Solid type index = 1 • Mass or volume = volume • Volume of material = 0.001 m³
Thermal mass - Water		<ul style="list-style-type: none"> • # temperature = 20 degC • Solid type index = 2 • Mass or volume = volume • Volume of material = 0.02 m³
Conductive exchange		<ul style="list-style-type: none"> • Contact surface = 0.0484 m²¹ • Thermal contact conductance = 1000 W/m²/degC

Trick: you can easily change the units in the parameter window. Just click on the unit of a parameter and select another one in the list of options.

¹ The contact surface can be deduced from the volume of the sphere as:

$$V = \frac{4 \cdot \pi \cdot R^3}{3} \text{ and } S = 4 \cdot \pi \cdot R^2$$

The question of part b) requires us to calculate the rate of temperature change. There's no standard component in Simcenter Amesim to do that calculation automatically. This is where we use the *post processing* tab in Simcenter Amesim.

In **SIMULATION** mode first have a look if you see the post processing tab. It looks like this:

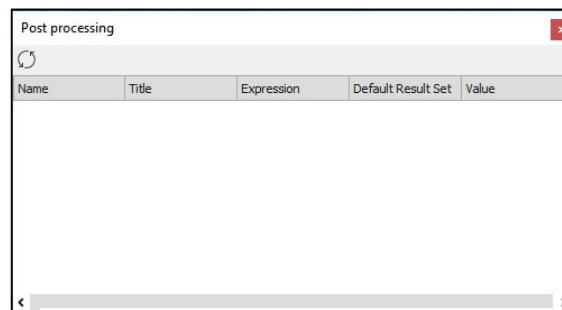


Figure 2: Post Processing Tab

If you don't see it in your Simcenter Amesim window, in the Menu bar, click on **Edit → Show/Hide → Post Processing**:

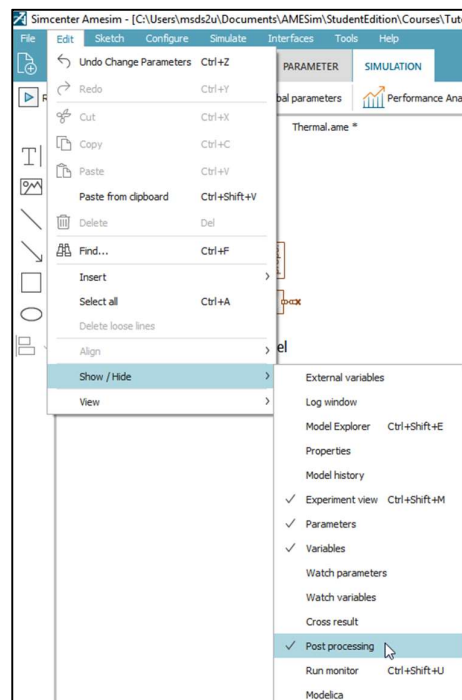


Figure 3: Activate Watch

Now we can add and create variables which we can be manipulated with mathematical operators. For this example there are three important columns.

- **Name:** Name under which you can call this variable elsewhere
- **Title:** Title of the variable
- **Expression:** this can be a value, mathematic operator or a reference to another variable's name

Post processing variables can be created either by right-clicking → **Add** or dragging and dropping a variable from a component into the post processing window. If you drag and drop a variable from a component it will be automatically linked to the current results of this component.

For our calculation we need the following post processing variables:

Name	Title	Expression	Source
T_W_0	Water temperature at t=0	ValueAt(t1@th_c,0)	Equation using variable from the water thermal capacity
T_S_0	Steel temperature at t=0	ValueAt(t1@th_c_1,0)	Equation using variable from the steel thermal capacity
c_p_s	Specific heat of steel	Cp0@th_solid_data	Drag and drop from solid properties of steel
h	Thermal conductance	tccond@the_conduction	Drag and drop from conductive exchange component
rho_S	Density of steel	rho0@th_solid_data	Drag and drop from solid properties of steel
V_S	Volume of steel	volume@th_c_1	Drag and drop from thermal mass of steel
A_S	Contact surface	(area@th_conduction)*1e-06	Drag and drop from conductive exchange component and convert from mm in m
C_pS	Heat capacity of steel	rho_S * V_S * c_p_s	Equation
dT	Temperature change rate	h*A_S/C_pS*(T_W_0-T_S_0)	Equation

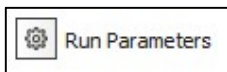
After that it should look like that:

Post processing			
Name	Title	Expression	Default Result Set
T_W_0	Water temperature at t=0	ValueAt(t1@th_c,0)	ref
T_S_0	Steel temperature at t=0	ValueAt(t1@th_c_1,0)	ref
c_p_s	Specific heat of steel	Cp0@th_solid_data	ref
h	Thermal conductance	tccond@th_conduction	ref
rho_S	Density of steel	rho0@th_solid_data	ref
V_S	Volume of steel	volume@th_c_1	ref
A_S	Contact surface	(area@th_conduction)*1e-6	ref
C_pS	Heat capacity of steel	rho_S * V_S * c_p_s	ref
dT	Temperature change rate	h * A_S / C_pS * (T_W_0 - T_S_0)	ref

Figure 4: Post processing variables

3. Running the simulation and analyzing the results

In **SIMULATION** mode, we can define the duration of the simulation in the Run Parameters



Since thermodynamic processes usually are slow, we choose a **Final time** of **2000** seconds. After that we can

run the simulation .

Then, it is easy and fast to plot temporal results, just dragging and dropping any variable from the variable window to the sketch. For instance, you can plot the temperature of the two thermal masses in order to get the evaluation of the temperature and see which final temperature they're settling for.

In our case, the final temperature is 20,88 °C, which is the answer for question a).

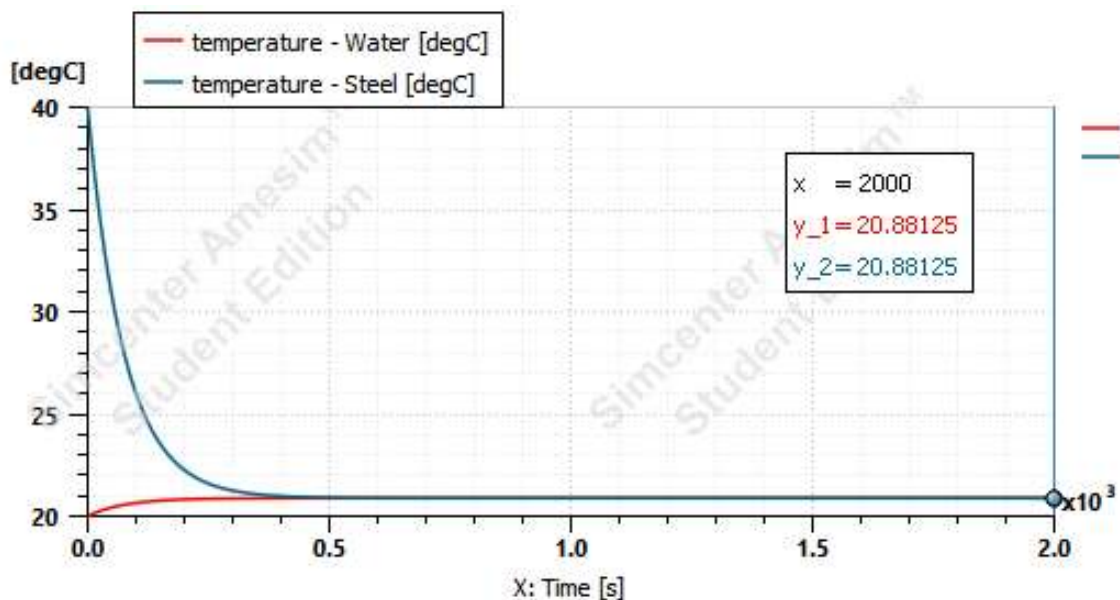


Figure 5: Final temperature of the system

To answer question b) we simply look into our post processing variables after the simulation ran through and we see that the temperature change rate $\Delta T = -0,252 \text{ K/s}$

Post processing				
Name	Title	Expression	Default Result Set	Value
T_W_0	Water temperature at t=0	ValueAt(t1@th_c,0)	ref	20
T_S_0	Steel temperature at t=0	ValueAt(t1@th_c_1,0)	ref	40
c_p_s	Specific heat of steel	Cp0@th_solid_data	ref	490
h	Thermal conductance	tccond@th_conduction	ref	1000
rho_S	Density of steel	rho0@th_solid_data	ref	7850
V_S	Volume of steel	volume@th_c_1	ref	0.001
A_S	Contact surface	(area@th_conduction)*1e-6	ref	0.0484
C_pS	Heat capacity of steel	rho_S * V_S * c_p_s	ref	3846.5
dT	Temperature change rate	$h * A_S / C_{pS} * (T_{W_0} - T_{S_0})$	ref	-0.251657

Figure 6: post processing results

Question c) is answered with the help of the integrator block. We can observe that 73540 J of heat are transferred until the final temperature settles in.

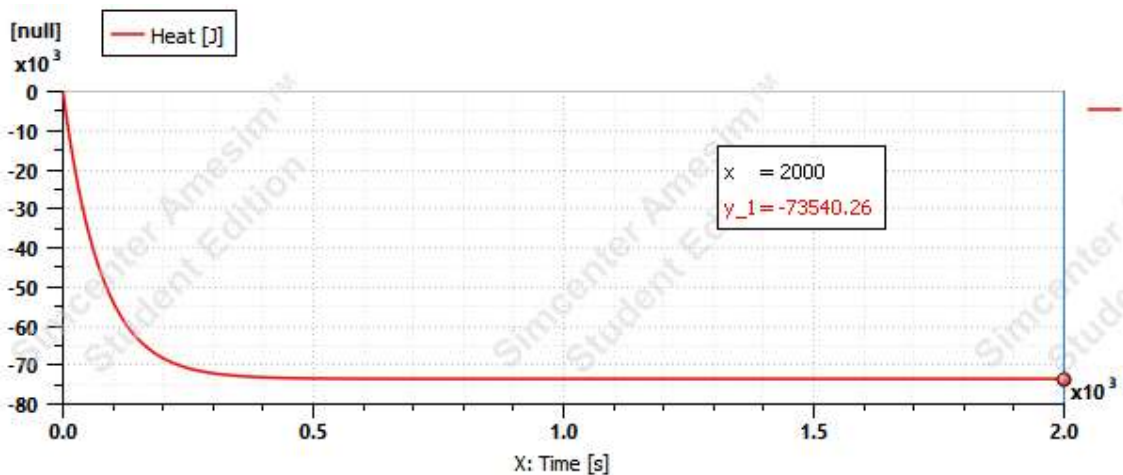


Figure 7 transferred heat

Conclusion

With this tutorial, we considered a thermodynamic system in form of a steel sphere in a water bath.

We have explained the temperature change due to convective heat transfer. We also described the equations defining the behavior of the system and we applied them on a concrete case with numerical values.

Finally, we built a simple thermodynamic model in Simcenter Amesim Student Edition in order to validate our results.