MODELING A HEAT EXCHANGER USING STEEL BALLS

CHE212: Heat Transfer

Unit Operations Lab: Group 24
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INTRODUCTION

- The experiment simulates a heat exchanger using hot steel balls dropped into a cooler water bath, modeling transient solid–fluid heat transfer.
- Utilizes Newton's law of cooling and energy balance equations to estimate heat transfer coefficients and water temperature rise.
- This experiment helps visualize how heat transfers from solids to liquids in a stepwise manner.
- The setup provides a simplified yet effective analogy for studying transient heat exchange in solid–fluid systems and offers insight into the estimation of the convective heat transfer coefficient.
- We were told to modify this ppt after presentation, first two merge the simulated and actual plots on one graph and second to predict how much temp will fall down in air in 3sec which we measured by natural convection correlations.

EXPERIMENTAL SETUP

Temperature measuring sensor

Closed container filled with normal water

Boiling container containing steel balls

The bottom of the container was taped to ensure that the steel balls remained separated, with gaps maintained between them and no conduction takes place between them

INNOVATIVE ASPECTS

- To show that this setup using steels balls indeed models a heat exchanger, which tries to simulate the structure of batchwise industrial packed bed heat exchangers, therefore this setup is theoretically rich than simple heat exchangers.
- We transform a time-dependent batch experiment into a model of spatially-resolved <u>**co-current**</u> heat exchanger, allowing anyone to grasp heat exchanger concepts without the need for complex, flow-synchronized systems.
- We adapted <u>LMTD</u> to a dynamically fluctuating system, accounting for non-ideal behaviors like non-uniform temperature distribution and environmental heat loss.

METHODOLOGY

- First of all, to start we need to find the convective heat transfer coefficient (h) between steel ball and water at room temperature (because the water will mostly be around room temperature for this experiment). In this process, we ignore the effect of one ball on other. To measure h, we took a measuring cylinder with 5ml of water and dropped one steel ball in it, here we can't just apply lumped system analysis to find h, because T_∞ is not constant
- A boiling container was used to heat water until it reached boiling temperature, Around 50-70 steel balls were placed in the boiling water and heated until some time (to reach 99% of the boiling water temperature it should theoretically take 86.7s).
- A separate plastic beaker (to avoid heat loss) was filled with water (350ml) at room temperature (at that time 28.0 °C, and a temperature sensor was fixed inside it to continuously display the water's temperature).
- The beaker was covered with a lid to reduce convective heat loss to the surroundings. This has to be repeated after each ball is dropped.

METHODOLOGY

- After ensuring that the steel balls were completely heated, the balls were transferred one by one into the normal water beaker with help of tongs, this has to be done carefully because the balls are very hot and they are prone to slipping.
- Each steel ball was added at a fixed time interval of 10 seconds.
- The temperature sensor in the beaker continuously displayed the real-time temperature changes as each ball was added.
- In the process, we dropped a total of 50 balls in water at an interval of 10s. (Why 10s? this experiment manually can't be done in less than 10s, also if we do it for a large time interval say 15s, there won't be much difference in temperature but only loss in surroundings).
- The entire process was repeated three times to verify the consistency and accuracy of the results, also we failed 4 times because we weren't able to do it consistently.
- Next, we compare the practical results with our simulation.

THEORY

- The process of heat exchange between the hot steel balls and the cold water is governed by convective heat transfer. As the balls cool down, they release heat to the surrounding water. The rate of heat transfer from the ball to the water is governed by Newton's Law of Cooling at any instant of time: $Q = hA(Tb - Tw)$
- How did we even calculate h? After 26 seconds, the temperature of the water increased by 4°C, reaching 33.9°C. Assuming negligible heat loss to the surroundings, we equate the heat lost by the steel ball to the heat gained by the water. $Q = hA\Delta Tavg$, and we took average of the final and initial temperature difference,
- In this experiment,we are dealing with a transient process where the temperature of the steel balls decreases over time, and the temperature of the water increases. We can apply a lumped system analysis to each steel ball, assuming that the temperature within each ball is relatively uniform at any given time.

THEORY

- The validity of this assumption depends on the Biot number ($Bi = hLc / k$), where Lc is the charac teristic length and k is the thermal conductivity of the steel. If $Bi < 0.1$, the lumped system analysis is generally considered valid. For this steel ball biot number is significantly lower than 0.1, therefore lumped system analysis is valid.
- For a single steel ball cooling in the water, the lumped system analysis leads to the following temperature evolution over a small time step dt:

$$T_b(t+dt) = T_w(t)+(T_b(t)-T_w(t))\exp\left(-\frac{hA_b}{\rho_b c_b V_b}dt\right)$$

- How Simulation code works? Each ball transfers heat by convection, modeled with an exponential decay of its temperature over time using the convective heat transfer coefficient h. The code updates water temperature incrementally based on the total heat received from all balls at each timestep, applying first-law energy balance and assuming uniform internal temperature in each ball due to a low Biot number.

RESULTS

Estimation of Convective Heat Transfer Coefficient

Use Newton's Law of Cooling

$$Q = hA\Delta T t$$

We rearrange to solve for h:

$$h = Q/(A\Delta T_{avg}\, t)$$

- Time duration $t = 26$ s
- Average temperature difference:

$\Delta T_{avg} = ((92-30)+(34-34))/2 = 31°C$

- Initial water temperature is = 30 °C
- Final water temperature is = 34 °C
- Initial steel ball temperature is = 92 °C
- Final steel ball temperature is = 34 °C

$h = 83.72/(3.14 \times 10-4 \times 31 \times 26)$

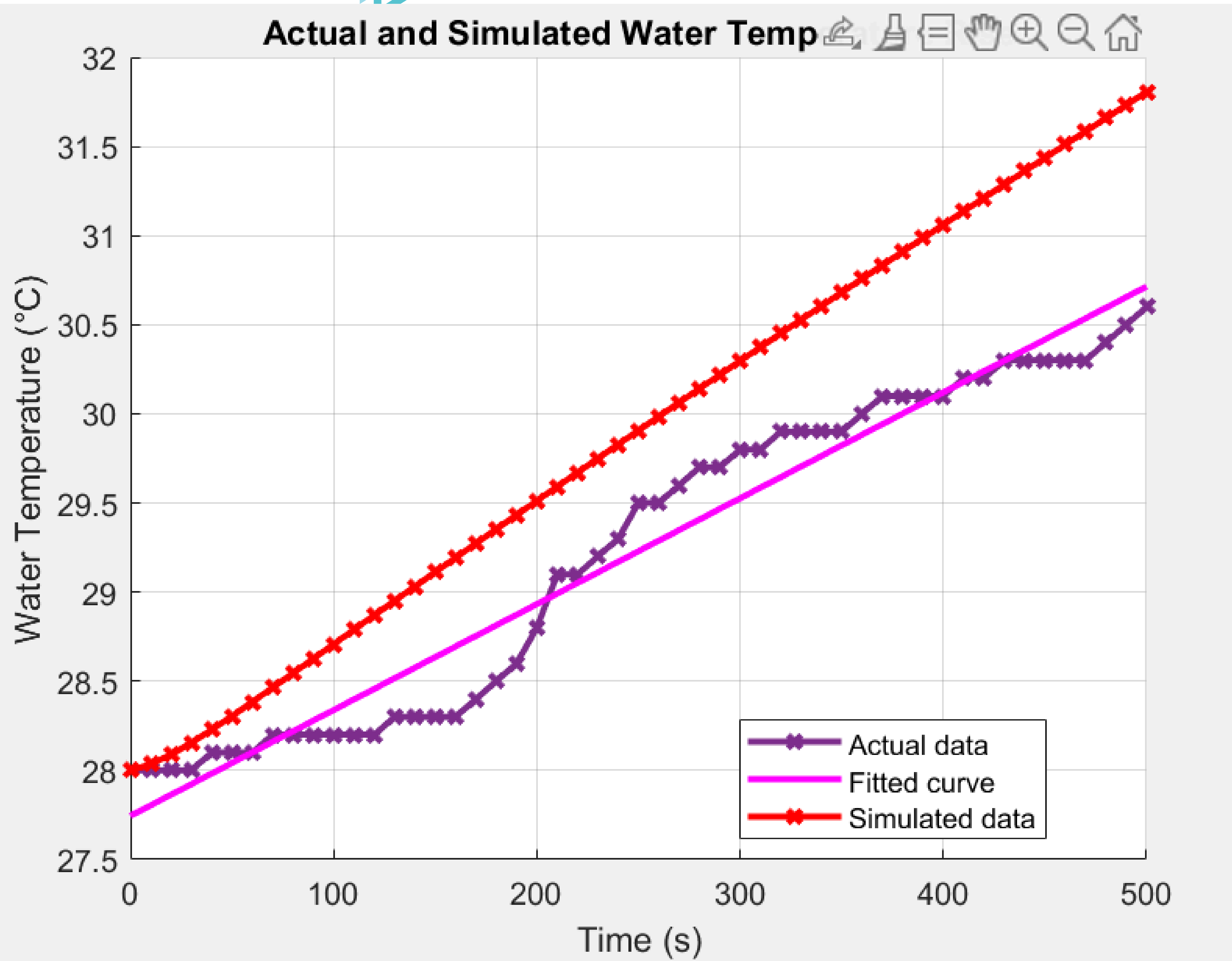
$= 83.72/0.2539$

≈ 329.7 W/m2 · °C

$Q = m * Cw * \Delta Tw$

Estimated convective heat transfer coefficient : $h \approx 329.74$ W/m2 · °C

RESULTS

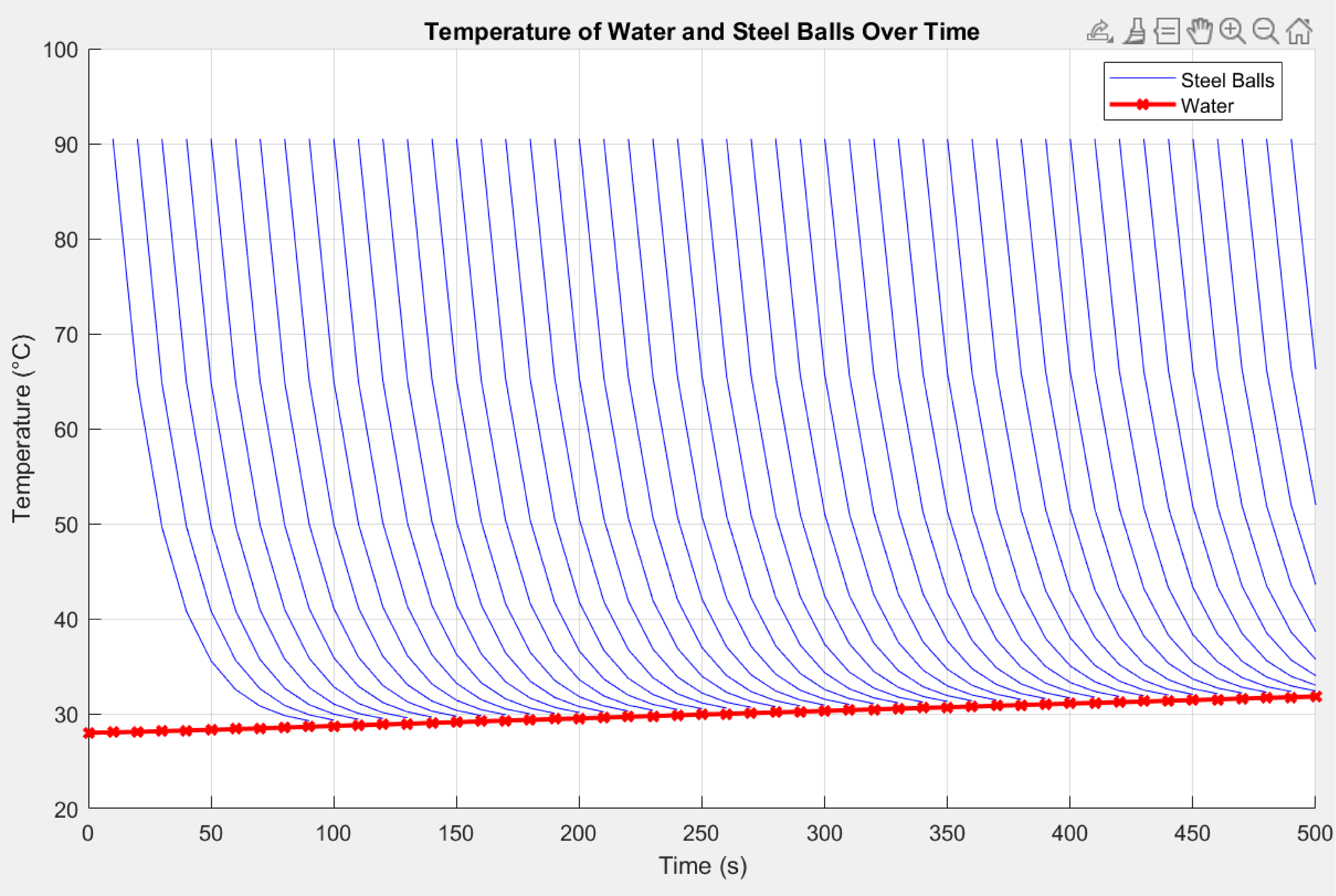


Actual and Simulated Water Temp
Water Temperature (°C)
Time (s)
32
31.5
31
30.5
30
29.5
29
28.5
28
27.5
0
100
200
300
400
500
Actual data
Fitted curve
Simulated data

RESULTS

- In simulation the temperature goes as high as 31.80°C, but in reality it goes only upto 30.6°C
- To relate the heat gained by the water to the convective heat transfer coefficient, we assume Newton's law of cooling applies to each steel ball individually.
- For N balls dropped sequentially into the water, the total heat transferred to the water over total contact time t can be expressed as: $Q_{total} = N \cdot h \cdot A \cdot \Delta T_{avg}$.
- The temperature difference will change with time, so we can try to find ΔT_{avg}.'s for both heat exchangers, simulated and experimental,
- **Results : Simulated ΔTavg: 2.2049 °, Experimental ΔTavg: 1.4143 °C**
- We can see the average temperature difference in experimental case is much smaller, this is due to the significant heat lost by the ball before it is being dropped in water. and the balls don't get perfectly heated to 100°C.

CO-CURRENT HEAT EXCHANGER



Limitations of the Experiment

- Ball Size (10 mm): Heat capacity is low, so it can't raise the water temperature much.
- Max Heating Temperature (~92 °C): Balls are heated in boiling water and can't go beyond this, limiting heat transfer. As mentioned next point we calculated actual T so its not 92.
- The time required for a single ball to lose 99% of heat is approx. 26.1 s. Now suppose if we select a higher time duration between dropping two consecutive balls, the experiment doesn't make much sense because a ball increases the temperature very little and the heat lost to surroundings will also increase, hence there will be much inaccurate results in this case. We handled this case in simulation by predicting h and ball temperature dropped to 90.5°C.
- Practical Handling Limit (<10 s not feasible): At least 10 seconds are needed to safely pick and drop each hot ball using tongs.
- Rusted Steel Balls: Higher thermal conductivity due to rust may increase the Biot number, making lumped system assumptions less accurate.

CONCLUSION

- This experiment successfully modeled a co-current heat exchanger using hot steel balls introduced sequentially into water at lower temperature.
- The rise in water temperature over time confirmed that heat was transferred from the steel balls to the water, validating the analogy between a batch-wise heat exchanger and a flow heat exchanger.
- The lumped capacitance model applied to each ball enabled and estimation of the convective heat transfer coefficient for one ball, which was found to be approximately 329.7 $W/m^2°C$ allowed us to calculate ΔTavg for both simulation and actual case.

THANK YOU