CHE213 INNOVATION PROJECT REPORT

Modified Single drop experiment: Water as a continous phase

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Abstract—This experiment presents an innovative modification to the classical setup involving mass transfer from a single drop. In conventional experiments, the column is filled with an organic solvent such as MIBK, and aqueous acetic acid droplets fall under gravity. However, to address the high cost and limited availability of MIBK, we reverse-engineered the system: the column was filled with water, and droplets of MIBK containing dissolved acetic acid were introduced from the bottom, rising due to buoyancy. This reverse-phase approach not only significantly reduces MIBK usage but also introduces a novel perspective on drop dynamics and interfacial mass transfer in an inverted system.

The experiment investigates the impact of this change on drop size, terminal velocity, residence time, and mass transfer coefficients. Additionally, the setup explores the influence of upward droplet motion on interfacial resistance and internal circulation. Results demonstrate that the upward injection approach is both cost-effective and feasible for studying single-drop mass transfer, with promising implications for sustainable process design in chemical separations.

1. Introduction

The movement of liquid droplets in another liquid and the transfer of dissolved substances between them are crucial in chemical engineering. Studying single droplets helps in designing efficient liquid-liquid extraction systems, where droplet size affects mass transfer rates and settling speed influences equipment capacity. Traditionally, such experiments use an organic solvent-filled column, with aqueous droplets falling through the continuous phase. While effective, this setup can be costly when using large volumes of expensive solvents like MIBK.

In this study, we introduce a modified approach that addresses this issue by filling the column with water and injecting MIBK containing acetic acid from the bottom.

Therefore, We need to study the effect of drop size on residence time and effect of drop size on overall and individual mass transfer coefficients for a single drop.

2. Aim

- To determine the individual and overall mass transfer coefficients.

3. Apparatus and Materials

- Hot steel balls, Diameter:10mm, >50
- Water 28.1°C (room temperature)
- A insulated container (plastic)
- Thermocouple(temperature sensor) to measure temperature of water in container
- Tongs to drop the hot balls in water
- Heater to heat the steel balls
- Double sided tape
- Camera

4. 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:

$$\dot{Q} = hA(T_b - T_w)$$

Where:

- $\dot{Q}$ is the rate of heat transfer,
- h is the convective heat transfer coefficient,
- A is the surface area of the ball,
- T_b is the ball's temperature,
- T_w is the water's temperature.

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. The validity of this assumption depends on the Biot number ($Bi = \frac{hL_c}{k}$), where L_c is the characteristic 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.

The heat lost by each steel ball will be gained by the water (assuming negligible heat loss to the surroundings). This can be expressed through energy balance equations for both the steel balls and the water.

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:

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

The heat transferred from the ball to the water during this time step is:

$$Q_{ball} = m_b c_b (T_b(t) - T_b(t+dt))$$

The total heat gained by the water over a time step due to multiple steel balls is the sum of the heat transferred from each ball. This heat gain results in a temperature increase of the water:

$$\Delta T_w = \frac{Q_{total}}{m_w c_w}$$

5. Limitations of the experiment

- The largest ball size available in UOP lab are of diameter 10mm. So the total heat it can lose is of smaller magnitude to heat the water substantially (the exact figures will be shown later.)
- To heat the steels balls they are dropped in boiling water, temperature of the balls goes as high as 92 °C. Hence the ball can't be heated above this in UOP lab, therefore limited heat transfer.
- The time required for a single ball to lose 99% of heat is approx 26s. Now suppose if we select a higher time duration than 19s 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.
- In this experiment one person picks up steel balls from boiling water (It has to be done very carefully as the water is hot) and another person lifts it up by a tong and we required at least 10s and to do this so the time duration less than this between dropping balls also cannot be done practically.
- The steel balls are old and rusted, therefore they have a higher k(thermal conductivity) compared to steel hence increasing the biot number, therefore we have less accurate results by lumped system assumption.

6. Estimation of Convective Heat Transfer Coefficient (h)

To run the simulation we need to find the convective heat transfer coefficient and to estimate it h, a single hot steel ball at approximately 92°C (measured by thermal gun) was dropped into 5mL of water initially at room temperature (approximately 30°C). After 26 seconds, the temperature of the water increased by 4°C, reaching 34°C. Assuming negligible heat loss to the surroundings, we equate the heat lost by the steel ball to the heat gained by the water. There is no forced convection.

Step 1: Heat Gained by Water

$$Q = m_w c_{p,w} \Delta T_w$$
$$m_w = 5\,\text{g} = 0.005\,\text{kg}, \quad c_{p,w} = 4186\,\text{J/kg}\,°\text{C},$$
$$\Delta T_w = 4\,°\text{C}$$
$$Q = 0.005 \times 4186 \times 4 = 83.72\,\text{J}$$

Step 2: Use Newton's Law of Cooling

$$Q = hA\Delta T_{\text{avg}} t$$

We rearrange to solve for h:

$$h = \frac{Q}{A\Delta T_{\text{avg}} t}$$

Properties:

- Diameter $D = 10\,\text{mm} = 0.01\,\text{m}$
- Surface area $A = 4\pi r^2 = 4\pi\,(0.005)^2 = 3.14 \times 10^{-4}\,\text{m}^2$
- Time duration $t = 26\,\text{s}$
- Average temperature difference: $\Delta T_{\text{avg}} = \frac{(92-30)+(34-34)}{2} = \frac{62+0}{2} = 31°\text{C}$
- 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

$$h = \frac{83.72}{3.14 \times 10^{-4} \times 31 \times 26} = \frac{83.72}{0.2539} \approx 329.7\,\text{W/m}^2 \cdot °\text{C}$$

Result

The estimated convective heat transfer coefficient is: $\boxed{h \approx 329.74\,\mathrm{W/m^2 \cdot {}^\circ C}}$

This isn't perfectly correct as temperature difference and rate of heat transfer will change but this is an approximation.

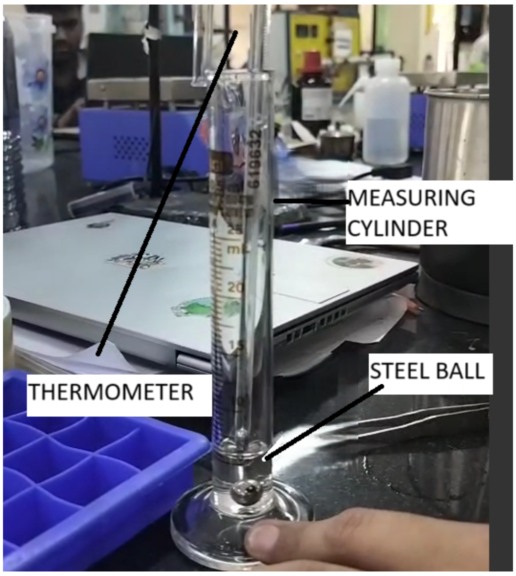

Figure 1. Setup to measure (h)

7. MATLAB Simulation

The simulation models the transient heat transfer between hot steel balls and water using MATLAB. It calculates the water temperature increase over time as successive hot balls are introduced, employing a lumped capacitance model for the balls and an energy balance for the water.

```
clear;clc;
T_b0 = 100; % Initial temperature of each steel ball (C)
T_w0 = 28;% Initial temperature of water (C)
m_b = 3.98*1e-3;% Mass of each steel ball (kg)
m_w = 350*1e-3; % Mass of water in the bucket (kg)
c_b = 490;% Specific heat capacity of steel (J/kgC)
c_w = 4186; % Specific heat capacity of water (J/kgC)
r_b = 0.005; % Radius of a steel ball (m)
% Surface area of the steel ball (used for convection) (m)
A_b = 4*pi*r_b^2;
rho_b = m_b/(4*pi*(r_b^3)/3);% Density of steel (kg/m^3)
V_b = (4/3)*pi*r_b^3; % Volume of the steel ball (m)
h = 329.74; % average Convective heat transfer coefficient (W/mC)
% measured from experiment
dt = 10; % time duration between dropping two consecutive balls
t_final = dt*50; % Total simulation time (s). Adding nearly 50 balls
time = 0:dt:t_final; % Time vector from 0 to t_final in steps of dt
T_w = zeros(size(time)); % Initialize water temperature array with zeros
T_w(1) = T_w0; % Set initial water temperature
balls = [];% Initialize an empty array to store temperatures of active steel balls
% Time loop for the simulation
for t = 2:length(time)
    current_time = time(t);  % Get current time in the loop
    % Drop a new hot steel ball every 10 seconds
    if mod(current_time, dt) == 0
        balls = [balls; T_b0];  % Add a new ball at 100C
    end
    Q_total = 0;  % Reset total heat transferred in this timestep
    % Loop over all balls currently in the water
    for i = 1:length(balls)
        T_ball = balls(i);  % Current temperature of the i-th ball
        % lumped system analysis
        T_new = T_w(t-1) + (T_ball - T_w(t-1)) * exp(- (h*A_b)/(rho_b*c_b*V_b) * dt);
        % Heat transferred from the ball to the water in this time step
        Q_i = m_b * c_b * (T_ball - T_new);
        % Accumulate the total heat gained by the water
        Q_total = Q_total + Q_i;
        % Update the balls temperature in the array
        balls(i) = T_new;
    end
    % Compute rise in water temperature
```

```
    ↪ due to heat received
    delta_Tw = Q_total / (m_w * c_w);
    % Update the water temperature for
    ↪ this timestep
    T_w(t) = T_w(t-1) + delta_Tw;
end

% Plot the water temperature over time
figure;
plot(time, T_w, 'b-', 'LineWidth', 2)
xlabel('Time (s)')
ylabel('Water Temperature (C)')
title('Water Temperature Rise with
    ↪ Convection from Steel Balls')
grid on
```

Code 1. Simulation Matlab code.

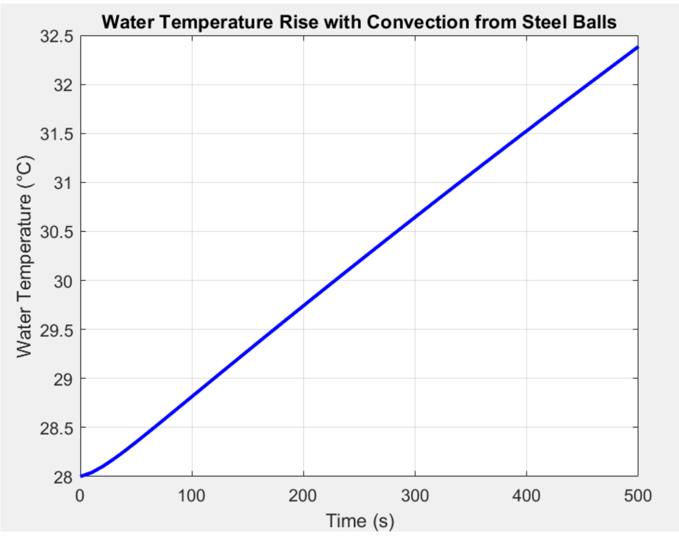

Figure 2. Simulated water temperature rise

Therefore, the final water temperature should be 32.38°C, assuming no heat loss to the surrounding.

8. Conduction between steel balls

When we'll drop the steel balls in water they'll touch each other, hence there will also be conduction, its not physically possible to keep a track of it. The solution proposed is at the base of the container there are a lot of pieces of double sided tape, providing spaces for steel balls to settle, additionally double sided tape has its own adhesiveness therefore balls can stick to it.

Figure 3. Plastic container used in experiment

9. Experimental Procedure

A batch-wise heat exchanger was modeled by dropping hot steel balls one by one into a container of cooler, stagnant water. The following steps were performed:

1. A large beaker was filled with a fixed volume of 350 mL of water initially at room temperature (approximately 28.1 °C).
2. Multiple steel balls (each with a diameter of 10 mm) were heated to approximately 92 °C by immersing them in boiling water.
3. One hot steel ball was dropped into the beaker every fixed interval (e.g., every 10 s). After each drop, the lid of the beaker was closed to minimize heat loss to the surroundings.
4. The temperature of the water was recorded after each steel ball using a temperature sensor.
5. The process was repeated until a total of 50 steel balls were dropped, and the corresponding increase in water temperature was noted.
6. The water temperature profile over time will be analyzed to estimate the overall heat transfer behavior of the system.

10. Actual Water temperature Rise

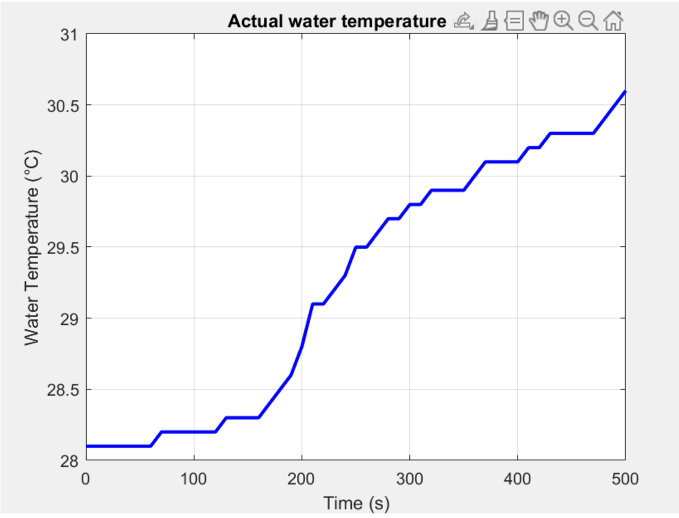

Figure 4. Plastic container used in experiment

The actual water temperature rises to 30.6°C, this was expected to be lower as the plastic box is not 100% insulated and to drop the steel ball the lid has to be opened which increase the heat loss, moreover when we take out steel balls from the boiling water to drop it in water it requires a finite time(of approx. 3s), therefore in this time period heat also gets lost to surroundings.

11. Calculating ΔT_{avg} simulated vs Actual

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:

$$\frac{Q_{\text{total}}}{t} = N \cdot h \cdot A \cdot \Delta T_{\text{avg}}$$

Rearranging to solve for the average temperature difference:

$$\Delta T_{\text{avg}} = \frac{Q_{\text{total}}}{N \cdot h \cdot A \cdot t}$$

Here,

- Q_{total} is the total heat gained by the water,
- N is the number of steel balls,
- h is the convective heat transfer coefficient,
- A is the surface area of one steel ball,
- t is the total time the balls were in contact with water,
- ΔT_{avg} is the average temperature difference driving the heat transfer.

- Simulated $\Delta T_{\text{avg}} = 2.4805$
- Experimental $\Delta T_{\text{avg}} = 1.4143$

12. Conclusion

This experiment successfully modeled a 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 to a batch-wise 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 $\text{W/m}^2 \cdot {}^\circ\text{C}$ allowed us to calculate ΔT_{avg} for both simulation and actual case.