CH 3522: Unit Operations Lab

Shell and Tube Heat Exchanger

Batch - R, Group - 05
Date of Experiment: 12th February, 2025
Date of Submission: 25th February, 2025

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1. Objectives

- To calculate the heat transfer rate.
- To observe the variation of inlet and outlet temperatures of both hot and cold fluids which are being circulated in the heat exchanger.
- To calculate the Log-Mean-Temperature-Difference (LMTD) and the heat transfer rate.
- To calculate the Overall Heat Transfer Coefficient for the Shell and Tube heat exchanger.

2. Introduction

Heat exchanger is a device in which heat is transferred from one fluid to another. The necessity for doing this arises in a multitude of industrial applications. Common examples of heat exchangers are the radiator of a car, the condenser at the back of a domestic refrigerator and the steam boiler of a thermal power plant. Heat exchangers are classified in three categories:

1) Transfer Type
2) Storage Type
3) Direct Contact Type

3. Theory

A transfer type of heat exchanger is one in which both fluids pass simultaneously through the device and heat is transferred through separating walls. In practice, most of the heat exchangers used are transfer type ones.

The transfer type exchangers are further classified according to flow arrangement as

1) Single Pass
2) Multiple Pass

A simple example of the transfer type of heat exchanger can be in the form of a tube type arrangement in which one of the fluids is flowing through the inner tube and the other through the annulus surrounding it. The heat transfer takes place across the walls of the inner tube.
Heat transfer rate, LMTD and overall heat transfer coefficient can be calculated as follows:

$$Q = MC_p(T_o - T_i) \quad (1)$$

$$\Delta T_{LMTD} = \frac{\Delta T_o - \Delta T_i}{ln\frac{\Delta T_o}{\Delta T_i}} \quad (2)$$

$$U = \frac{Q}{A\Delta T_{LMTD}} \quad (3)$$

Where Q is amount of heat transfer, U is overall heat transfer coefficient and T_{LMTD} is log mean temperature difference. M, C_p, T_o, T_i are mass flow rate, specific heat, outlet temperature and inlet temperature respectively. ΔT_o, ΔT_i and A are outlet temperature difference, inlet temperature difference and heat transfer area respectively.

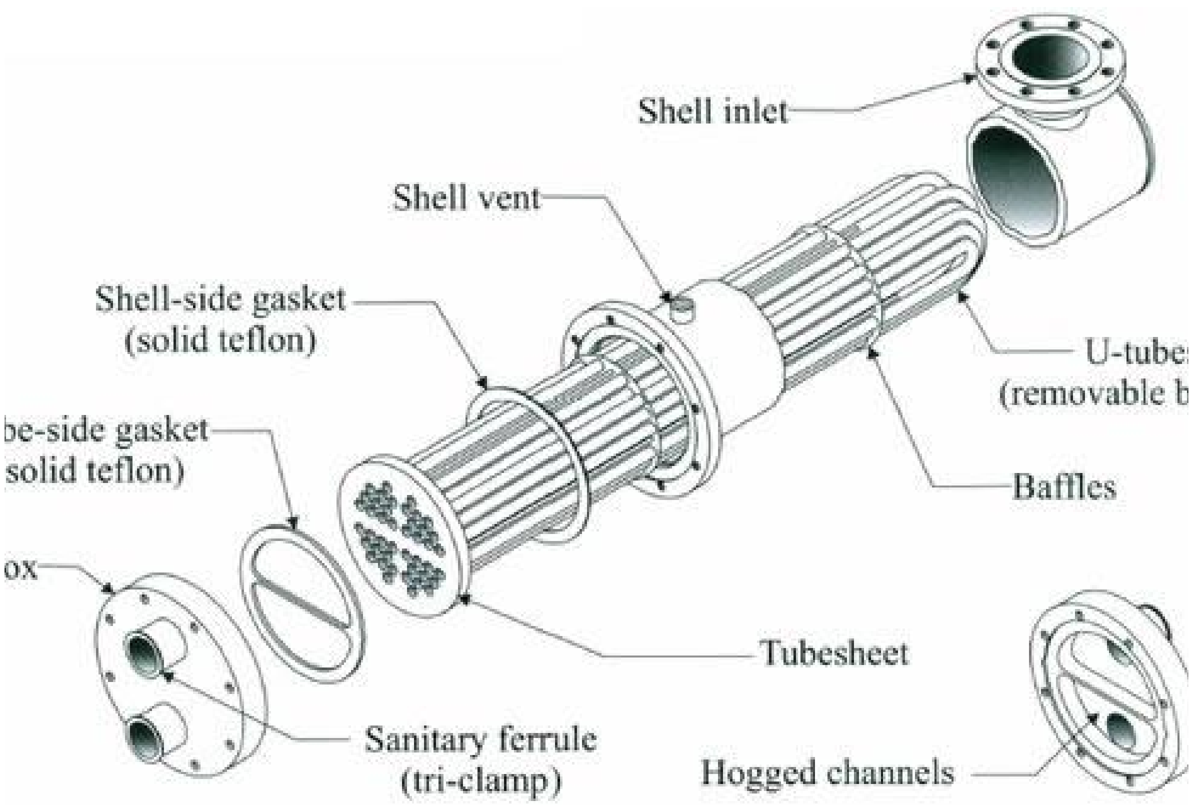


Figure 1: Internal Mechanism of Shell-Tube Heat Exchangers

4. Apparatus Required

The apparatus required for this experiment are listed below;

- Shell and tube heat exchanger unit.
- Water: used as both hot and cold fluid.
- Heating source which is built within the unit.
- Flow regulators and flow-meters for both hot and cold fluid channels.
- Switchable temperature display based on probe positions.

5. Schematic of Experimental Setup

Experimental setup includes the following components:

Figure 2: The Complete Set-up for Shell-Tube H.E. Experiment

The apparatus consists of a fabricated shell inside which tubes with baffles on the outer side are fitted. The present set-up is 1-2 pass shell and tube heat exchanger. The hot water flows through the inner tube while the cold water flows through the shell side. Valves are provided to control the flow rate of hot and cold water. For flow measurement rotameters are provided at inlet of cold water and outlet of hot water line. A magnetic drive pump is given to circulate the hot water from a recycled type water tank, which is fitted with a heater and digital temperature controller.

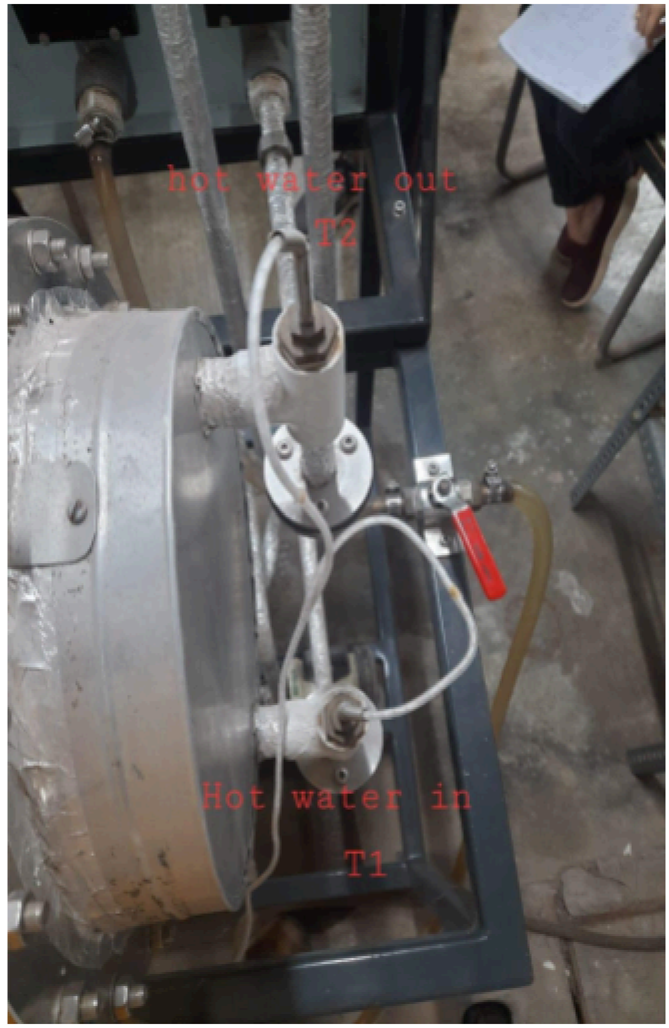


Figure 3: Position of All the Thermocouples around the H.E.

6. Procedure

- Turn on the hot-fluid inlet valve and set it to a specific flow rate of 100 LpH, observed quantitatively using the rotameter. The hot fluid begins circulating in the heat exchanger.
- Switch on the inbuilt heating source to heat the fluid inside (water) and set the temperature to approximately 60°C, here 57.2°C is used.
- Allow sufficient time for the stored fluid to reach the set temperature before circulating it through the heat exchanger via the hot-water valve.
- Open the cold-fluid inlet valve and adjust its flow rate to 125,150 and 175 LpH respectively for each reading.
- After setting a flow rate for either fluid, wait for approximately 1 minute to ensure steady-state conditions with no perturbations in the rotameter levels.

- Once steady-state is achieved and the stored water reaches the set temperature, measure temperatures at four locations using probes. The switch on the temperature display allows sequential viewing of these readings.
- Record the inlet and outlet temperatures of both hot and cold fluids, obtaining a total of four temperature readings.
- Tabulate the data, noting flow rates and corresponding temperature values at the specified locations.
- For a fixed hot-fluid flow rate, vary the cold-fluid flow rate and repeat the measurements for two additional flow rates, forming the first set of data.
- Change the hot-fluid flow rate for 3 times as 50, 125, and 175LpH and repeat the process, measuring temperatures for three different cold-fluid flow rates while keeping the hot-fluid flow rate constant.

7. Experimental Observations

In the following table, we include the observations of our experiment and the laboratory datasheet is also provided at the end of this report.

Hot Water (LPH)	Cold Water(LPH)	Hot in T1 (℃)	Hot out T2 (℃)	Cold in T3(℃)	Cold out T4(℃)
50	70	61.1	42.6	29.5	39.9
50	155	60.2	47.3	29.9	43.7
50	195	59.7	39.0	29.7	35.9
125	70	61.5	46.1	29.7	43.2
125	155	60.2	44.2	30.1	40.1
125	195	61.0	45.3	30.1	40
175	70	60.5	50.1	29.7	45.9
175	155	59.5	47.6	30	42.4
175	195	60.6	47.5	30	41.5

Table 1: The Observed Data

8. Sample Calculations

Experimental Determinations:

At first we provide the properties of water and the heat exchanger used.

$\rho_{hot\ water} = 982.6\ kg/m^3,\ C_{p,hot} = 4185\ J/kgK\ @\ 60^oC.$

$\rho_{cold\ water} = 995.71\ kg/m^3,\ C_{p,cold} = 4178\ J/kgK\ @\ 30^oC.$

$D_o\ (outer\ diameter) = 0.016\ m,\ D_i\ (inner\ diameter) = 0.013\ m$

L (each tube's length) = 0.5 m, and N (number of parallel tubes) = 24.

Hence, the inner area for heat exchange $(A_i) = 2 \times \pi \times (D_i/2) \times L \times N = 0.4901\ m^2$.

The outer area for heat exchange $(A_o) = 0.6032\ m^2$.

Now, we provide the calculation in accordance with what our objectives are (for the first data sample).
Heat gained by cold water per unit time:

$Q_{cold} = \rho_{cold} \times (volumetric\ flow\ rate) \times C_{p,cold} \times (T_4 - T_3)\ J$

$Q_{cold} = 995.71 \times (70 \times 0.001) / 3600) \times 4178 \times (39.9 - 29.5) = 841.2598\ W$

Similarly, heat lost by hot water per unit time:

$Q_{hot} = 982.6 \times (50 \times 0.001) / 3600) \times 4185 \times (61.1 - 42.6) = 1056.6020\ W$

Now, the LMTD is calculated using the equation 2 mentioned in the "*Theory*" section.

$$\Delta T_{LMTD} = \frac{(T_1 - T_3) - (T_2 - T_4)}{ln(\frac{(T_1 - T_3)}{(T_2 - T_4)})} = \frac{(61.1 - 29.5) - (42.6 - 39.9)}{ln(\frac{(61.1 - 29.5)}{(42.6 - 39.9)})} = 11.7484\ K.$$

This follows the calculation of inner and outer surface heat transfer coefficient by using the equation 3 mentioned in the "*Theory*" section. In an ideal scenario $Q_{hot} = Q_{cold}$. However the inefficiency of the heat exchanger causes heat loss due to which they are not equal. Now using average Q value and by putting the inner and outer area values and using the LMTD we get the following two values,

$U_i = 164.8089\ W/m^2K,\ U_o = 133.907\ W/m^2K.$

Similarly we complete these calculations for the rest of the 8 scenarios from table 1 and the values are provided in the "*Results*" section in table 2.

<u>Theoretical Determinations:</u>

We have shown the calculations for cooling of hot water.

The inner cross sectional area of the tube is $A'_i = \pi \times (D_i/2)^2 = 1.3273 \times 10^{-4}\ m^2$.

The velocity of the hot water inside the tube is thus $v_i = (volumetric\ flow\ rate\ /\ A'_i)$.

$$v_i (first\ sample) = \frac{50 \times 0.001}{3600 \times A'_i} = 0.1046\ m/s.$$

Reynold's number, $Re = \frac{\rho_{hot} \dot{V}_{hot} D_i}{\mu_{hot}} = 2870.767$

Prandtl's number, $Pr = \frac{\mu_{hot} C_{p,\,hot}}{K_{hot}} = 2.9936$

Nusselt number, $Nu = 0.023 \times (Re)^{0.8} \times (Pr)^{0.3} = 186.63$

The inner surface heat transfer coefficient, $h_i = \frac{Nu \times K_{hot}}{D_i} = 9344.587\ W/m^2K.$

These calculations were backed by some important theoretical values which are listed in the following,

$\mu_{hot} = 0.0004656\ Pa.s$ (dynamic viscosity of hot water),

$\mu_{cold} = 0.000797\ Pa.s$ (dynamic viscosity of cold water),

$K_{hot} = 0.65091\ W/mK$ (thermal conductivity of hot water),

$K_{cold} = 0.61450\ W/mK$ (thermal conductivity of cold water).

Figure 4: General internal structure of a Shell-Tube H.E.

Now, the calculations for the heating of the cold water follows a similar pathway. But the region through which it flows needs additional work to form equipment specifications and measurements like pitch and shell diameter. Also the expression for Nusselt number of heating is as follows,

$$\text{Nusselt number, } Nu = 0.023 \times (Re)^{0.8} \times (Pr)^{0.4} \tag{4}$$

After obtaining that value, we can use the following formula to obtain the theoretical value of overall heat transfer coefficient U,

$$\frac{1}{U_{theoretical}} = \frac{1}{h_o} + \frac{D_o}{h_i D_i} + \frac{D_o ln(D_o/D_i)}{2K} \quad (5)$$

where, K is the thermal conductivity value of the tube and shell material and considering carbon steel which is standard to use and for it the value is 54 W/mK. The complete tabulations are provided in tables 3, 4 & 5 in the "*Results*" section.

9. Results & Discussions

The calculations for U_i & U_o are provided in the following table (table 2) which are experimental values of overall heat transfer coefficient.

Hot Water (LPH)	Cold Water (LPH)	Q cold (W)	Q hot (W)	Q avg (W)	LMTD (K)	Ui (W/m^2K)	Uo (W/m^2K)
50	70	841.259	1056.602	948.931	11.748	164.809	133.907
50	155	2471.778	736.7657	1604.272	12.534	261.165	212.197
50	195	1397.092	1182.252	1289.672	11.851	222.044	180.411
125	70	1092.020	2198.875	1645.447	12.068	278.210	226.046
125	155	1791.144	2284.545	2037.844	13.042	318.822	259.043
125	195	2230.841	2241.710	2236.275	14.520	314.250	255.328
175	70	1310.424	2078.936	1694.680	13.350	259.009	210.445
175	155	2221.019	2378.782	2299.901	13.999	335.205	272.354
175	195	2591.381	2618.659	2605.020	15.099	352.036	286.029

Table 2: Experimentally Obtained HTC

The theoretically obtained values of the dimensionless quantities for cooling of hot water are given in table 3 and for the heating of the cold water, the values are provided in table 4.

Table 5 combines these two tables' results and provides the theoretical values of overall heat transfer coefficient.

V (m/s) hot water	Re	Pr	Nu	$h_i\ (W/m^2K)$
0.105	2870.768	2.994	186.630	9344.587
0.105	2870.768	2.994	186.630	9344.587
0.105	2870.768	2.994	186.630	9344.587
0.262	7176.919	2.994	388.449	19449.665
0.262	7176.919	2.994	388.449	19449.665
0.262	7176.919	2.994	388.449	19449.665
0.366	10047.687	2.994	508.437	25457.429
0.366	10047.687	2.994	508.437	25457.429
0.366	10047.687	2.994	508.437	25457.429

Table 3: Theoretical values for cooling of hot water

V (m/s) cold water	Re	Pr	Nu	$h_o\ (W/m^2K)$
0.097	1933.126	5.419	192.441	7390.943
0.214	4280.494	5.419	363.484	13960.044
0.269	5385.137	5.419	436.764	16774.482
0.097	1933.126	5.419	192.441	7390.943
0.214	4280.494	5.419	363.484	13960.044
0.269	5385.137	5.419	436.764	16774.482
0.097	1933.126	5.419	192.441	7390.943
0.214	4280.494	5.419	363.484	13960.044
0.269	5385.137	5.419	436.764	16774.482

Table 4: Theoretical values for heating of cold water

The theoretical values of overall HTC are as follows:

Hot Water (LPH)	50	50	50	125	125	125	175	175	175
Cold Water (LPH)	70	155	195	70	155	195	70	155	195
U in W/m^2K	3358.2	4271.6	4502.8	4360.3	6035.9	6508.1	4663.9	6633.9	7208.7

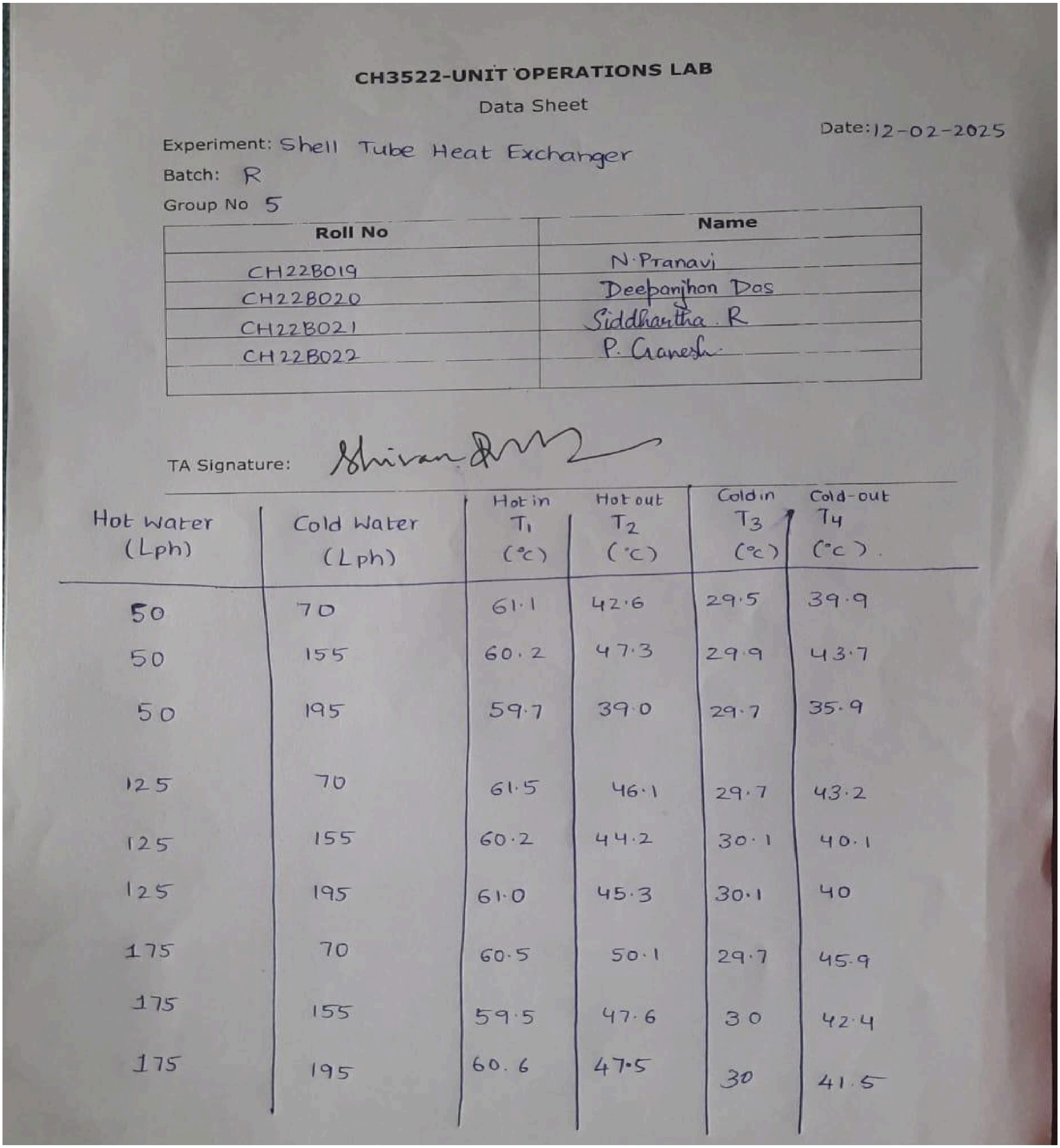
Table 5: Theoretical Overall HTC Values

10. Conclusions

- We were able to calculate the overall heat transfer coefficient experimentally and theoretically and meet all of our objectives of this experiment.
- We see that liquid has a high Reynolds number indicating turbulent regime which will lead to good heat transfer between the mediums.
- Increasing the flow rates of liquid leads to more efficient mixing and hence the time to reach the steady state temperatures will reduce.
- The Prandtl number is greater than 1 which implies the heat transfer mechanism is dominated by convection which is also known by the fact that the flow is turbulent.
- The heat loss by the hot fluid and the heat gained by the cold liquid are not same in magnitude suggesting non-idealities in the system. This can include the heat loss due to heat absorption by the metal surfaces in the tubes of the heat exchanger.

11. References

- The Engineering Toolbox to obtain dynamic viscosity values.
- VaxaSoftware to obtain the specific heat capacity of liquid water at specific temperature.
- Valves Instruments Plus Ltd provided a list to obtain the water density.
- The Engineering Toolbox to obtain thermal conductivity values.
- Toolbox to obtain the idea of theoretical values of overall heat transfer coefficients.
- Engineering Article Blog to obtain the idea to perform suitable calculations for shell-tube.
- The Engineering Toolbox to obtain the thermal conductivity of metals.
- The GitHub repository contains all the related data and coded scripts used for calculations.



CH3522-UNIT OPERATIONS LAB

Data Sheet

Date: 12-02-2025

Experiment: Shell Tube Heat Exchanger

Batch: R

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Figure 5: Laboratory Data 1