



الجامعة الألمانية الأردنية
German Jordanian University

School of Medical Sciences

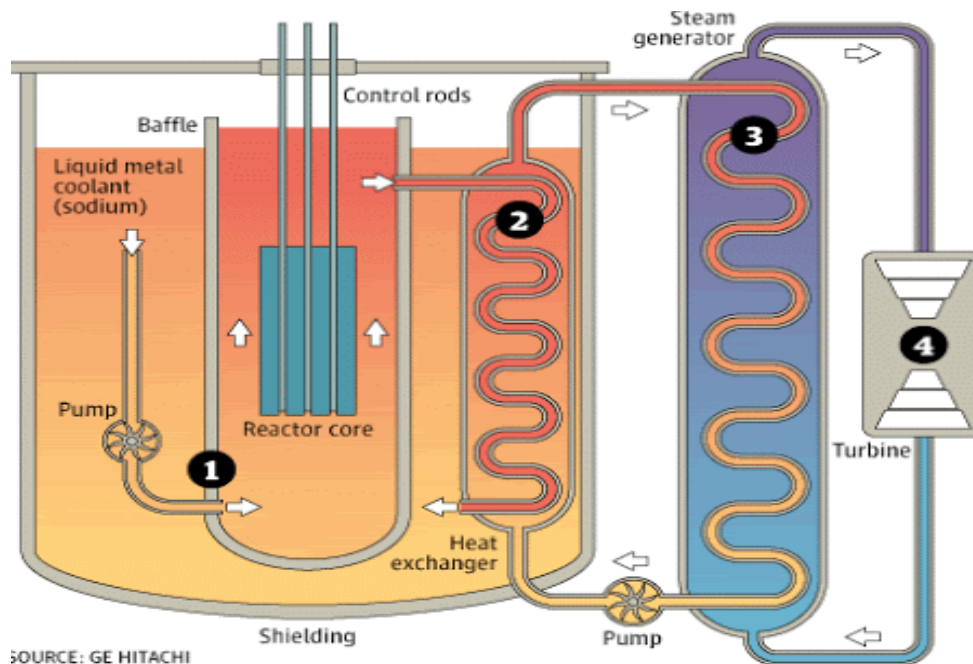
Pharmaceutical and Chemical Engineering Department

Laboratory Manual

For

Reaction Engineering and Heat Transfer Lab

PCE 362



Edition: 2021

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Lab: Chemical Reaction Lab M109

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PREFACE

Fluid, Heat and Reaction Engineering Laboratory is a practical course that is related to theories covered in heat transfer and chemical reaction engineering courses. Upon successful completion of this course, the student will be able to:

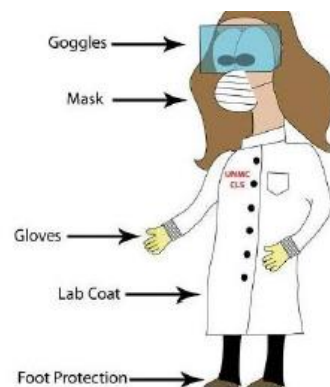
- Applying reaction engineering concepts, heat, and mass transfer principles on different experimental fields.
- Determination of the major components of each type of reactors and heat exchangers.
- Determination of the overall efficiency for different types of heat exchangers.
- Determination of reaction kinetics using batch, tubular, CSTR and CSTR in series reactors experiments.
- Perform chemical engineering and heat transfer calculations related to each experiment.
- Present the experimental findings in clear graphs/tables.
- Compare the experimental results with the corresponding ones that are reported in literature or calculated from physical principles to explore the degree of agreement /disagreement.
- The student must master the basic skills of writing technical reports in both forms full and short.

What Will You Need to Bring With You to Lab?

It is important to come prepared for your laboratory session. You will be required to bring:

Your manual, a lab-coat and protective eyewear (goggles or glasses with side-shields) as well as a calculator.

Please note you will not be allowed to enter the lab if you do not come prepared with a lab-coat, goggles and solved Pre-lab.



Lab Preparation and Lab Reports:

You must be prepared for the experiment **BEFORE** you come to lab in order to complete the experiment in the allotted time. Each lab section is full and there will be neither make-up sessions nor space for you to work in other sections. If you miss a lab, you **MUST** discuss the issue with the course instructor (preferably beforehand) to see what options you have.

Lab Reports:

Short Reports must be graded, one for each group, **AT THE BEGINNING** of the lab session that follow the one you perform the experiment in. If you do not complete the report and turn it in at the beginning of the next lab, you will **NOT** be allowed to participate in the lab that day.

After each lab session you will be required to analyze the data you collected, analyze the sources of error, and make discussion and conclusions about the work you did.

Short Report should consist of the following:

- Formal Cover Page
- Data Tables and Graphs.
- Sample of Calculations.
- Results and Discussion.
- Conclusion and Recommendations.
- References.

Your **Full report** **MUST** be graded, one for each student, two weeks after performing the experiment. It should consist of the following:

- Formal Cover Page.
- Abstract.
- Table of Contents.
- List of Figures and Tables.
- List of Symbols.
- Introduction.
- Theory.
- Experimental Details (apparatus and procedure).
- Results and Discussion.
- Conclusion and Recommendations.

- References.
- Appendices.

Assessment Policy		
Short Reports	One short report for each group must be submitted one week after taking the experiment.	25%
Full Report	One full report for each student must be submitted two weeks after performing the experiment.	10%
Quizzes	Average mark of all Quizzes marks that will be take during the semester.	15%
Evaluation	Behavior during the lab session, sticking to lab rules, coming prepared and on time	10%
Final Exam**	Including all experiments	40%

** Final Exam might be a written exam or divided into two parts: a written part and a practical part.

Regulations	
Signing the Consent Form	During your first lab session, you have to read and sign the consent form given in the next page of this manual and hand it to your TA (or instructor).
Attendance	<ul style="list-style-type: none">• Attendance in all class sections is REQUIRED.• You should inform the instructor as soon as possible if you must miss a class.• University attendance regulations state that if you may miss more than two lab sessions for unexcused reasons or risk, you will be permanently dismissed from the lab. Dismissal from the lab automatically results in removal from the lecture.• If you miss any lab experiment, you will get ZERO in its report.• Any student that is more than 20 minutes late to the lab will be asked to leave.• There will be no chance for a make-up lab in this situation.
Online-sessions	Regarding the online-given lab sessions: If you don't submit your report on the assigned time, you will be considered ' <u>absent</u> ' on that session.
Reports	All cases of cheating, plagiarism, or dishonesty will receive a zero and be reported to the Dean of Students. All work you submit MUST be your own. Unless specifically noted in class, EACH student must turn in his/her own lab reports.



الجامعة الألمانية الأردنية
German Jordanian University

School of Applied Medical Sciences
General Chemistry Lab. – Chem106

Consent Form

Student Full Name:

Student ID Number:

Student Emergency Contact Telephone Number:

Commitment to safety in the lab

You are not allowed to enter the lab if you don't have your lab coat, eye goggles and pre-lab.

- Safety glasses and the lab coat must be worn at all times in the lab while working at or about the benches or you will be dismissed from the lab.
- Prepare for each lab by reading and studying the experiment and all associated instructions and answer the Pre-lab questions prior to coming to the lab.
- Arrive on time to the lab and listen carefully to your instructor.
- Notify the instructor (or supervisor) immediately of any accident, regardless of how minor you may think it is.
- Sturdy, closed shoes (no sandals, etc.) must be worn in the lab.
- Long hair must be tied or otherwise secured behind the head.
- No visitors in the lab, including children.
- No food, drink, tobacco products, chewing gums in the lab.
- Broken glass must be handled with proper safety precautions; all broken glass must be discarded in a designated container.
- All spills must be cleaned up immediately. Any questions about how to do so, consult with your instructor or supervisor.
- After handling chemicals, always wash your hands thoroughly, especially after a spill on your hands. In most cases, flushing with large amounts of water lessens or prevents injury in cases of cuts, burns or spills on the skin.
- Notify your instructor (or supervisor) of medical/health conditions relevant to safety before your first experiment. These include (but are not limited to): pregnancy as it becomes known, a history of seizures or fainting, neurological disorders that may compromise the safe handling of labware, chemical or latex allergies, serious vision or hearing impairments, hemophilia, hepatitis B, anosmia (inability to smell).
- Know the locations of fire extinguishers, eyewashes, emergency showers, nearest exits.
- Never work alone in the lab.
- Never leave an experiment while substances are heating or reacting.
- Carefully read the label on all chemicals before dispensing. Dispense small amounts of chemicals to avoid excess and dispose of any excess according to your instructor's directions.
- Leave your work area and glassware clean and wash your hands before leaving the lab

- If you miss the safety advisory for a particular lab experiment or assignment, you will NOT be allowed to do the experiment.

I acknowledge that I have received, read, and understand the safety information presented to me.

In doing so, I certify that I will follow the above policies, follow all instructions from University faculty and staff, follow all laboratory safety rules, and only perform exercises and activities in a safe and responsible manner. I further understand that the activities of this class (or project) will require me to perform exercises with chemicals and other potentially hazardous materials under the supervision of University faculty and staff, and that I can be dismissed if I violate this agreement.

Name _____ Instructor _____

Signature _____ TA _____

Date _____ TA signature _____

BATCH REACTOR

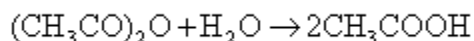
DETERMINATION OF THE RATE EXPRESSION FOR THE HYDROLYSIS OF ACETIC ANHYDRIDE TO ACETIC ACID USING “ADIABATIC BATCH REACTOR”

Objective

- To determine the rate equation for the hydrolysis of acetic anhydride to acetic acid in an adiabatic batch reactor.

Theory

The hydrolysis of acetic anhydride in water, in the presence of a catalyst of sulphuric acid is described by:



This reaction can be assumed to have simple power law kinetics of the form $r = -k C^n$ if the reaction is zero order in water. The concentration of the protonic acid remains constant for the duration of the run and thus k is a catalytic rate constant that includes this concentration, also in power law form. For any system of this particular type the instantaneous value of the acetic anhydride concentration can be eliminated between the material and thermal balance equations to give a linear equation (which can therefore be subjected to a statistical test). Use of this equation requires that values of the gradient of temperature with respect to time be found.

If the concentration of acetic anhydride at any time is C , then the rate of the reaction is given by:

$$r = -\frac{dC}{dt} \tag{1}$$

with $C = C_0$ at $t = 0$. The heat generation rate is:

$$(-\Delta H)r = \rho \bar{C}_p \cdot \frac{dT}{dt} \tag{2}$$

With $T = T_0$ at $t=0$. Substituting equation (1) in equation (2), integrating with respect to time and using the boundary conditions, we obtain:

$$(C_0 - C)(-\Delta H) = \overline{\rho C} (T - T_0) \quad (3)$$

For the n^{th} order case, the rate may be expressed in Arrhenius form:

$$r = k C^n = A e^{\frac{-E}{RT}} C^n \quad (4)$$

Rearranging equation (3) gives:

$$C = C_0 - \beta(T - T_0)$$

Where,

$$\beta = \frac{\overline{\rho C}}{-\Delta H}$$

Using equations (4) and (2), we obtain:

$$\beta \frac{dT}{dt} = A e^{\frac{-E}{RT}} [C_0 - \beta(T - T_0)]^n \quad (5)$$

Using $T=T_\infty$ when the reaction is complete gives:

$$(C_0 - 0) = \beta(T_\infty - T_0) \text{ and thus,}$$

$$\beta = \frac{C_0}{(T_\infty - T_0)}$$

Substituting for β in equation (5) and rearranging, we have:

$$\frac{\frac{dT}{dt}}{\frac{T_\infty - T_0}{C_0} \left[C_0 - C_0 \frac{T - T_0}{T_\infty - T_0} \right]^n} = A e^{(-E/RT)}$$

Taking logarithms of both sides of this equation gives:

$$\ln|\text{LHS}| = \ln|A| - (E/RT) \quad (6)$$

And so a plot of $\ln(\text{LHS})$ vs. $1/T$ should be linear with an intercept of $\ln(A)$ and a gradient of $-E/R$.

Apparatus

Fig. 1 shows the batch reactor used in the experiment.

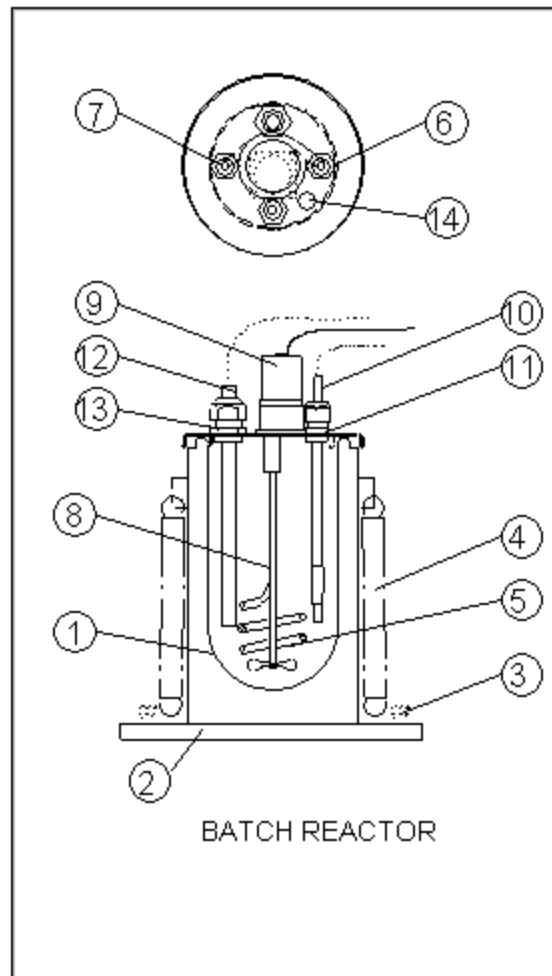


Fig. 1: Batch Reactor.

The reactor vessel (1), which is in the form of a vacuum insulated flask, is set on a baseplate (2) which is designed to be located on four studs on the service unit and secured by the thumbnuts (3). Springs (4) are used to secure the reactor to the baseplate.

The reactor is equipped with a stainless steel heat transfer coil (5) to which the hot water circulator of the CEX service unit can be attached. Alternatively for reaction demonstrations below ambient temperature, accessory CW-16 (the chilled water

circulator), can be connected. The coil is supported by glands (6) and (7) in the lid of the reactor.

To assist the heat transfer as well as to provide good mixing of the reactants, a propeller agitator (8) driven by an electric motor (9) is also mounted in the lid.

The motor speed can be varied from the service unit.

An efficient vacuum insulation surrounding the reactor allows negligible heat to be removed or added to the system during the course of a reaction. This allows the progress of an exothermic reaction to be monitored simply by observing the rise in temperature over a period of time. A temperature probe and transmitter are supplied, the probe being inserted in the gland (11) in the place of the sensor supplied with the CEX service unit. The intention is that the probe then be connected to the Armfield interface unit, the IFD3, and the software supplied used to monitor the progress of the reaction and diagnose the results.

An access hole (14) in the lid is used as a vent and also as a means of charging the reactor initially with reagents.

When not in use, the reactor can be drained by carefully removing the lid complete with appendages and removing the reactor from the service unit to take to a suitable waste drain.

Procedure

WARNING: Extreme care should be taken whilst handling either acetic acid or acetic anhydride. Both chemicals are highly corrosive and care should be taken to avoid contact or inhalation of vapor.

DO NOT add acetic anhydride directly to sulphuric acid, as the reaction is violent and will cause the chemicals to be sprayed into the air.

The reaction described in this experiment should be carried out in a fume cupboard. On completion, the reaction products should be discarded into a copious flow of cold water, taking care to avoid inhalation of vapor.

- Ensure the reactor has been set up with the special temperature sensor and computer interface for the adiabatic reaction as described previously
- If possible the reactants should be at approximately 30°C before mixing. If they are cooler than this, the reaction will take much longer to complete.
- Charge the reactor with 100ml of acetic anhydride and 250ml of demineralized water.
- Start the reactor agitator and adjust the variable speed drive to position '5.0'.
- Add 150ml of glacial acetic acid (since the water and acetic anhydride are mutually insoluble, but are both soluble in acetic acid, this ensures that the reaction mixture is homogeneous - the acetic acid does not form part of the reaction).
- Start the data logger program choosing 15 seconds as the interval between samples and 1500 seconds as the total running time of the experiment (a longer duration will be required if the temperature of the reactants is less than 30°C). It is essential to log data until the temperature in the reactor begins to fall again.
- Immediately add 25ml of 18 M sulphuric acid as the catalyst. The reaction will commence.
- Switch off the agitator.
- When the reaction has completed, the temperature data can be viewed within the software, either in tabular or graphical format. The data should be saved as an excel file. It is then possible to carry out the second part of the analysis described above, by calculating the terms of equation (6), and plotting the graph described.

- In order to find the best straight line fit to the data, it will be necessary to extract only the points from the linear region of data from a graph of temperature against time for the experiment. This will entail discarding the first few points, and also any points after the temperature reaches the peak value.
- It will then be necessary to find the best value for n in equation (6) by trial and error, refining the value until the best straight line fit is obtained.
- Repeat the procedure described above using 15mL and 40mL of sulphuric acid.

Question to be answered in lab. report:

- Construct the appropriate graph in order to determine the reaction order, the activation energy and Arrhenius constant.
- Explain the relation between the amount of sulfuric acid used and reactants conversion and show it graphically.

Nomenclature

Symbol	Definition	Unit
A	Arrhenius frequency factor	
C	acetic anhydrite concentration at time t	(mol/dm ³)
C ₀	acetic anhydrite concentration at t=0	(mol/dm ³)
\bar{C}_p	mean heat capacity	(J/kg. K)
E	activation energy	(J/mol)
H	molar enthalpy	(J/mol)
k	specific rate constant	
r	reaction rate	
R	gas constant	(J/mol.K)
T	reactor temperature	K
ρ	density	(kg/ dm ³)

CONTINUOUS STIRRED TANK REACTOR

Determination of the rate expression for saponification of ethyl acetate using “*Continuous Stirred Tank Reactor*”.

Objective

- To measure the variation in conversion of reactants with respect to time in a continuous stirred tank reactor, and hence determine the reaction order and the rate constant.
- To determine the effect of inadequate mixing on the reaction rate.

Theory

The reaction chosen is the saponification of ethyl acetate by sodium hydroxide as it can be carried out under safe conditions of temperature and pressure and is well documented.



This reaction carried out in a CSTR eventually reaches steady state when a certain amount of conversion of the starting reagents has taken place. The steady state conditions will vary depending on concentration of reagents, flow rate, volume of reactor and temperature of reaction.

The conductivity of the reacting solution in the reactor changes with the degree of conversion and this provides a convenient method for monitoring the progress of the reaction.

If given an infinite amount of time, the reaction would continue until one or both of the reagents had been completely converted. Thus, the theoretical final concentration of sodium acetate in the reactor will be the lesser of the concentrations of sodium hydroxide and ethyl acetate in the feed.

For the continuous reactor operating at steady state, the volume maybe assumed constant, the limiting reactant to be the sodium hydroxide, the reaction rate constant k can be calculated as follow:

$$k = \frac{F_a + F_b}{V} \times \frac{a_0 - a_1}{a_1^2} \quad (1)$$

Where,

F_a : The volumetric flow rate of NaOH [mL/min]

F_b : The volumetric flow rate of CH₃COOC₂H₅ [mL/min]

V : Volume of the reactor = 1 L

a_0 : The initial concentration of NaOH in the reactor [mol/dm³]

a_1 : The steady state concentration of NaOH in the reactor [mol/dm³]

The initial NaOH concentration (a_0) will be calculated as follow:

$$a_0 = \frac{F_a}{F_a + F_b} \times a_\mu \quad (2)$$

Where a_μ is the concentration of NaOH in feed vessel [mol/dm³]

NaOH concentration at any time (a_t) can be calculated as follow :

$$a_t = (a_\infty - a_0) \times \left(\frac{\Lambda_0 - \Lambda_t}{\Lambda_0 - \Lambda_\infty} \right) + a_0 \quad (3)$$

Where,

a_∞ : The concentration of NaOH after infinite time ≈ 0 .

a_t : The concentration of NaOH after time t

Λ_0 : The initial conductivity of the solution when there is no product.

Λ_1 : The steady state conductivity of the solution

Λ_∞ : Conductivity of the solution after infinite time

The initial conductivity of the solution is a result of the presence of NaOH and CH₃COONa:

$$\Lambda = \Lambda_a + \Lambda_c \quad (4)$$

Where,

Λ : The conductivity of the solution at time t .

Λ_a : Conductivity of NaOH at time t

Λ_c : Conductivity of CH_3COONa at time t

Initially, as there is no sodium acetate produced yet, the conductivity of the solution is of the NaOH, so:

$$\Lambda_0 = \Lambda_{a0}$$

Similarly, after infinite time, the conductivity of the solution is of the Sodium acetate assuming that all the NaOH has been consumed.

$$\Lambda_\infty = \Lambda_{c\infty}$$

We can relate the conductivity of the sodium hydroxide to its concentration by the following relationship:

$$\Lambda_{a0} = 0.195(1 + 0.0184(T - 294)) \times a_0 \quad \text{For } T \geq 294 \text{ K} \quad (5)$$

Similarly, the theoretical final conductivity of sodium acetate is related to its concentration by the following:

$$\Lambda_{c\infty} = 0.07(1 + 0.0248(T - 294)) \times C_\infty \quad \text{For } T \geq 294 \text{ K} \quad (6)$$

Where,

T : Temperature [K]

$\Lambda_{a0}, \Lambda_{c\infty}$: Initial and infinite conductivity of NaOH and CH_3COONa respectively [S]

C_∞ : Concentration of the Sodium acetate after infinite time = a_0 [mol/dm³]

Using these start and end values for the conductivity measurements we can calculate values of sodium hydroxide concentration (a_1) and sodium acetate concentration (c_1) and the degree of conversion (X_a) for each of the samples of conductivity taken over the period of the experiment.

We can define the conversion of sodium hydroxide as the amount reacted, as a percentage of the initial amount present

$$X_a = \frac{a_0 - a_t}{a_0} \quad (7)$$

Apparatus

Fig. 1 shows the CSTR used in the experiment, while Fig 2 describes the process flow sheet.

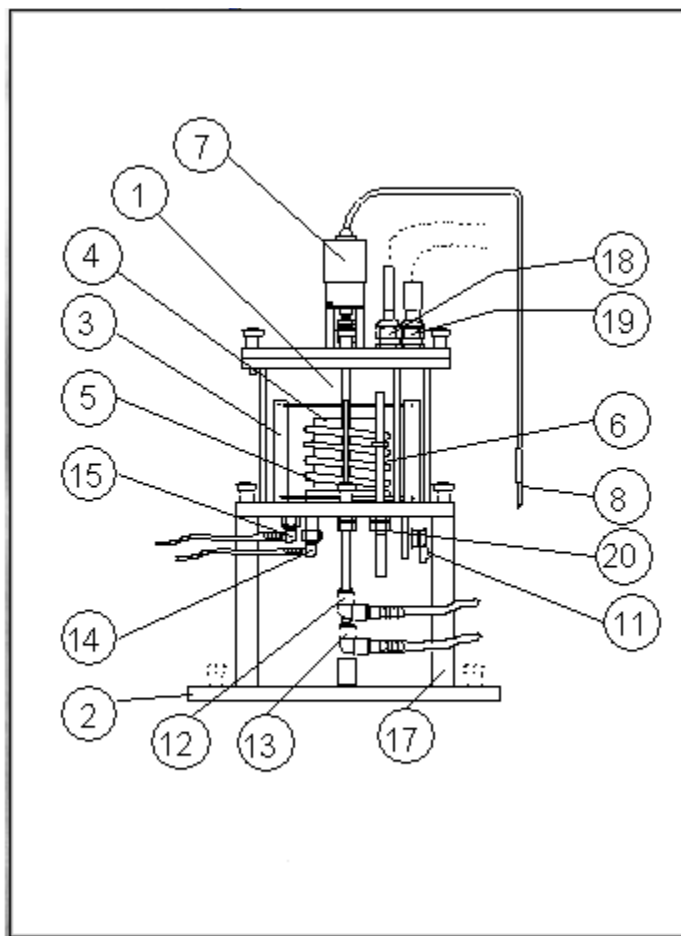


Fig. 1: Continuous Stirred Tank Reactor.

The reactor (1) is set on a baseplate (2) which is designed to be located on four studs on the service unit and secured by thumbnuts. Three pillars (17) support the reactor vessel above the baseplate to allow access to the valves and connectors in the reactor base.

NOTE: The reactor is positioned on the service unit with a single support pillar (17) foremost.

Inside the reactor, a stainless steel coil (5) provides the heat transfer surface for either heating or cooling the reactant chemicals. If heating is being carried out, the coil

connectors (12) and (13) are connected to the supply and return flexible tubing of the hot water circulator which is incorporated in the service unit.

A turbine agitator (4) works in conjunction with a baffle arrangement (3) to provide efficient mixing and heat transfer. The agitator is driven by electric motor (7) mounted on the lid of the reactor, the motor is driven by a variable speed unit in the service bench and is connected electrically to this by jack plug (8).

Glands in the reactor lid (18) and (19) are to house the conductivity probe (CP) and temperature sensor (TS) which are supplied with the service unit. The larger of the two glands is for the conductivity probe. The glands are unscrewed by hand, the probes inserted completely into the reactor until they rest on the reactor base and then the glands re-tightened by hand.

Chemical reagents are pumped into the reactor separately through connectors (14) and (15) in the base of the reactor. The two feed pumps of the service unit are connected to either of these.

As reagents are being pumped into the reactor, the level increases until it finally overflows the stand pipe (6) and flows to drain (or to be collected if required). This stand pipe is adjustable in height by loosening the hexagon backing nut (20), moving to the new position and re-tightening. A stop prevents the stand pipe from being completely removed and when on the stop the reactor will operate at half full volume.

To operate at full volume, the stand pipe is pushed upwards until the mark etched on the tube is level with the bottom of the backing nut.

When the reactor is not being used it can be drained through valve (11) which is shown offset from center for diagrammatic purposes.

Method

To add known concentrations of sodium hydroxide and ethyl acetate to the reactor and monitor the rate of conversion to sodium acetate and ethyl alcohol. Graphical method can then be used to estimate the rate constant.

Procedure

- Make up 5.0 liter batches of 0.05M sodium hydroxide and 0.05M ethyl acetate in water.
- Remove the lids of the reagent vessels and carefully fill with the reagents to a level approximately 50mm from the top. Refit the lids.
- Adjust the set point of the temperature controller to 26°C.
- Set the pump speed control to give 60 ml/min flow rate for each reactant.
- Set the agitator speed controller dial to 7.00.
- Switch on the hot water circulator, both feed pumps, agitator motor, and start sampling data.
- Use the IFD channel history window to monitor the progress of the reaction.
- Repeat this procedure for a stirred reactor with no baffle and for un-stirred reactor with no baffle (The baffle arrangement may be removed by removing the conductivity and temperature probes then removing the lid of the reactor. The baffle arrangement simply lifts out).
- On completion of the exercise, rinse the feed tanks with demineralized water and pump the water through the reactor to rinse out the chemicals.

Question to be answered in lab. report:

- Construct a graph showing the change in conductivity of the solution versus time.
- Explain the relation between reactor physical configuration of and the reactants conversion and show it graphically.

Nomenclature

Symbol	Definition	Unit
a_{μ}	Sodium hydroxide concentration in feed vessel	mol/dm ³
a_0	Sodium hydroxide concentration in mixed feeds	mol/dm ³
a_1	Sodium hydroxide concentration at steady state	mol/dm ³
a_t	Sodium hydroxide concentration at time t	mol/dm ³
a_{∞}	Sodium hydroxide concentration at infinite time	mol/dm ³
C_{∞}	Sodium acetate concentration at infinite time	mol/dm ³
Λ_0	Initial conductivity of the solution	mS
Λ_1	Steady state conductivity of the solution	mS
Λ_{∞}	Conductivity of the solution at infinite time	mS
Λ_a	Sodium hydroxide conductivity	mS
Λ_c	Sodium acetate conductivity	mS
F_a	Sodium hydroxide Volumetric flow rate	mL/min
F_b	Ethyl acetate volumetric flow rate	mL/min
k	Reaction rate constant	
r	Reaction rate	
T	Reaction temperature	K

V	Volume of reactor	mL
X_a	Sodium hydroxide conversion	-

CONTINUOUS STIRRED TANK REACTORS IN SERIES

Determination of the rate expression for saponification of ethyl acetate using “*Continuous Stirred Tank Reactors in Series*”.

Objective

To measure the variation in conversion of reactants with respect to time in a continuous stirred tank reactors in series, and hence determine the rate constant.

Theory

The reaction chosen is the saponification of ethyl acetate by sodium hydroxide as it can be carried out under safe conditions of temperature and pressure and is well documented.



This reaction carried out in CSTRs in series eventually reaches steady state when a certain amount of conversion of the starting reagents has taken place. The steady state conditions will vary depending on concentration of reagents, flow rate, volume of reactor and temperature of reaction.

The conductivity of the reacting solution in the reactor changes with the degree of conversion and this provides a convenient method for monitoring the progress of the reaction.

If given an infinite amount of time, the reaction would continue until one or both of the reagents had been completely converted. Thus, the theoretical final concentration of sodium acetate in the reactor will be the lesser of the concentrations of sodium hydroxide and ethyl acetate in the feed.

For the continuous reactor operating at steady state, the volume may be assumed constant, the limiting reactant to be the sodium hydroxide, the reaction rate constant k can be calculated as follow:

For the first CSTR:

$$k = \frac{F_a + F_b}{V} \times \frac{a_0 - a_1}{a_1^2} \quad (1)$$

Where,

F_a : The volumetric flow rate of NaOH [mL/min]

F_b : The volumetric flow rate of CH₃COOC₂H₅ [mL/min]

V : Volume of the reactor = 702 mL

a_0 : The initial concentration of NaOH in the reactor [mol/dm³]

a_1 : The steady state concentration of NaOH in the reactor [mol/dm³]

The initial NaOH concentration (a_0) will be calculated as follow:

$$a_0 = \frac{F_a}{F_a + F_b} \times a_\mu \quad (2)$$

Where a_μ is the concentration of NaOH in feed vessel [mol/dm³]

NaOH concentration at any time t (a_t) can be calculated as follow:

$$a_t = (a_\infty - a_0) \times \left(\frac{\Lambda_0 - \Lambda_t}{\Lambda_0 - \Lambda_\infty} \right) + a_0 \quad (3)$$

Where,

a_∞ : The concentration of NaOH after infinite time ≈ 0 .

a_t : The concentration of NaOH after time t

Λ_0 : The initial conductivity of the solution when there is no product.

Λ_1 : The steady state conductivity of the solution

Λ_∞ : Conductivity of the solution after infinite time

The initial conductivity of the solution is a result of the presence of NaOH and CH₃COONa:

$$\Lambda = \Lambda_a + \Lambda_c \quad (4)$$

Where,

Λ : The conductivity of the solution at time t .

Λ_a : Conductivity of NaOH at time t

Λ_c : Conductivity of CH_3COONa at time t

Initially, as there is no sodium acetate produced yet, the conductivity of the solution is of the NaOH, so:

$$\Lambda_0 = \Lambda_{a0}$$

Similarly, after infinite time, the conductivity of the solution is of the Sodium acetate assuming that all the NaOH has been consumed.

$$\Lambda_\infty = \Lambda_{c\infty}$$

We can relate the conductivity of the sodium hydroxide to its concentration by the following relationship:

$$\Lambda_{a0} = 0.195(1 + 0.0184(T - 294)) \times a_0 \quad \text{For } T \geq 294 \text{ K} \quad (5)$$

Similarly, the theoretical final conductivity of sodium acetate is related to its concentration by the following:

$$\Lambda_{c\infty} = 0.07(1 + 0.0248(T - 294)) \times C_\infty \quad \text{For } T \geq 294 \text{ K} \quad (6)$$

Where,

T : Temperature [K]

$\Lambda_{a0}, \Lambda_{c\infty}$: Initial and infinite conductivity of NaOH and CH_3COONa respectively [S]

C_∞ : Concentration of the Sodium acetate after infinite time = a_0 [mol/dm³]

Using these start and end values for the conductivity measurements we can calculate values of sodium hydroxide concentration (a_t) and sodium acetate concentration (c_t) and the degree of conversion (X_a) for each of the samples of conductivity taken over the period of the experiment.

We can define the conversion of sodium hydroxide as the amount reacted, as a percentage of the initial amount present

$$X_a = \frac{a_0 - a_t}{a_0} \quad (7)$$

For the second and the third CSTRs, the same procedure will be followed with keeping in mind replacing the initial variables with the steady states for the previous reactor.

Apparatus

Fig. 1 shows the process flow sheet.

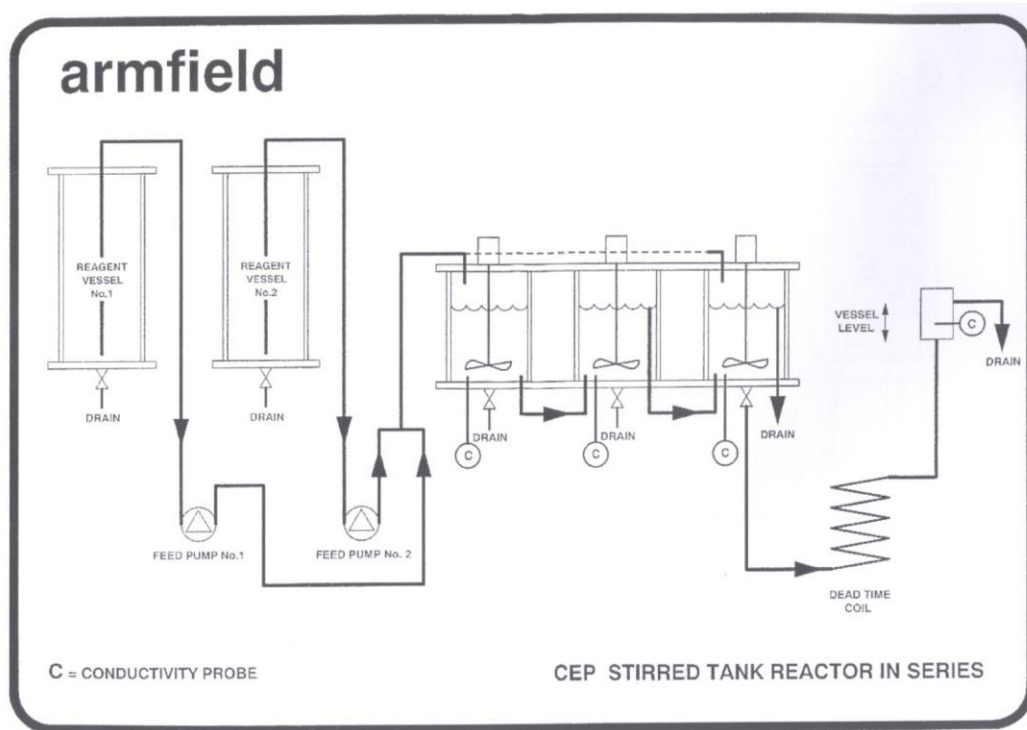


Fig. 1: Process flow sheet

Method

To add known concentrations of sodium hydroxide and ethyl acetate to the reactor and monitor the rate of conversion to sodium acetate and ethyl alcohol. Graphical method can then be used to estimate the reaction order and the rate constant.

In order to complete the demonstration we need the following equipment

- The CEP Stirred Tank Reactor in Series Bench
- The IFD6 unit and its connecting cables

Procedure

- Make up 5.0 litre batches of 0.05M sodium hydroxide and 0.05M ethyl acetate in water.
- Remove the lids of the reagent vessels and carefully fill with the reagents to a level approximately 50mm from the top. Refit the lids.
- Adjust the set point of the temperature controller to 26°C.
- Set the pump speed control to give 60 ml/min flow rate for each reactant.
- Set the agitator speed controller dial to 7.00.
- Switch on the hot water circulator, both feed pumps, agitator motor, and start sampling data.
- Use the IFD channel history window to monitor the progress of the reaction.
- On completion of the exercise, rinse the feed tanks with demineralised water and pump the water through the reactor to rinse out the chemicals.

Question to be answered in lab. report:

- determine the rate constant.
- Explain the relation between reactants conversion and time for each reactor and show it graphically on the same graph.

Nomenclature

Symbol	Definition	Unit
a_{μ}	Sodium hydroxide concentration in feed vessel	mol/dm ³
a_0	Sodium hydroxide concentration in mixed feeds	mol/dm ³
a_1	Sodium hydroxide concentration at steady state	mol/dm ³
a_t	Sodium hydroxide concentration at time t	mol/dm ³
a_{∞}	Sodium hydroxide concentration at infinite time	mol/dm ³
C_{∞}	Sodium acetate concentration at infinite time	mol/dm ³
Λ_0	Initial conductivity of the solution	mS
Λ_1	Steady state conductivity of the solution	mS
Λ_{∞}	Conductivity of the solution at infinite time	mS
Λ_a	Sodium hydroxide conductivity	mS
Λ_c	Sodium acetate conductivity	mS
F_a	Sodium hydroxide Volumetric flow rate	mL/min
F_b	Ethyl acetate volumetric flow rate	mL/min
k	Reaction rate constant	
r	Reaction rate	
T	Reaction temperature	K
V	Volume of reactor	mL

X_a Sodium hydroxide conversion

-

TUBULAR REACTOR

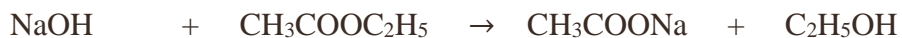
Determination of the rate expression for saponification of ethyl acetate using “*Tubular Reactor*”.

Objective

- To measure the variation in conversion of reactants with respect to residence time in a tubular ‘plug flow’ reactor, and hence determine the rate constant.
- To measure the variation in conversion of reactants with respect to residence time in a tubular ‘plug flow’ reactor.

Theory

The reaction chosen is the saponification of ethyl acetate by sodium hydroxide as it can be carried out under safe conditions of temperature and pressure and is well documented.



This reaction carried out in a Tubular Reactor eventually reaches steady state when a certain amount of conversion of the starting reagents has taken place. The steady state conditions will vary depending on concentration of reagents, flow rate, volume of reactor and temperature of reaction.

The conductivity of the reacting solution in the reactor changes with the degree of conversion and this provides a convenient method for monitoring the progress of the reaction.

If given an infinite amount of time, the reaction would continue until one or both of the reagents had been completely converted. Thus, the theoretical final concentration of sodium acetate in the reactor will be the lesser of the concentrations of sodium hydroxide and ethyl acetate in the feed.

For the continuous reactor operating at steady state, the volume maybe assumed constant, the limiting reactant to be the sodium hydroxide, the reaction rate constant k can be calculated as follow:

For the first CSTR:

$$k = \frac{F_a + F_b}{V} \times \frac{a_0 - a_1}{a_1^2} \quad (1)$$

Where,

F_a : The volumetric flow rate of NaOH [mL/min]

F_b : The volumetric flow rate of CH₃COOC₂H₅ [mL/min]

V : Volume of the reactor = 400 mL

a_0 : The initial concentration of NaOH in the reactor [mol/dm³]

a_1 : The steady state concentration of NaOH in the reactor [mol/dm³]

The initial NaOH concentration (a_0) will be calculated as follow:

$$a_0 = \frac{F_a}{F_a + F_b} \times a_\mu \quad (2)$$

Where a_μ is the concentration of NaOH in feed vessel [mol/dm³]

NaOH concentration at any time t (a_t) can be calculated as follow:

$$a_t = (a_\infty - a_0) \times \left(\frac{\Lambda_0 - \Lambda_t}{\Lambda_0 - \Lambda_\infty} \right) + a_0 \quad (3)$$

Where,

a_∞ : The concentration of NaOH after infinite time ≈ 0 .

a_t : The concentration of NaOH after time t

Λ_0 : The initial conductivity of the solution when there is no product.

Λ_1 : The steady state conductivity of the solution

Λ_∞ : Conductivity of the solution after infinite time

The initial conductivity of the solution is a result of the presence of NaOH and CH₃COONa:

$$\Lambda = \Lambda_a + \Lambda_c \quad (4)$$

Where,

Λ : The conductivity of the solution at time t .

Λ_a : Conductivity of NaOH at time t

Λ_c : Conductivity of CH_3COONa at time t

Initially, as there is no sodium acetate produced yet, the conductivity of the solution is of the NaOH, so:

$$\Lambda_0 = \Lambda_{a0}$$

Similarly, after infinite time, the conductivity of the solution is of the Sodium acetate assuming that all the NaOH has been consumed.

$$\Lambda_\infty = \Lambda_{c\infty}$$

We can relate the conductivity of the sodium hydroxide to its concentration by the following relationship:

$$\Lambda_{a0} = 0.195(1 + 0.0184(T - 294)) \times a_0 \quad \text{For } T \geq 294 \text{ K} \quad (5)$$

Similarly, the theoretical final conductivity of sodium acetate is related to its concentration by the following:

$$\Lambda_{c\infty} = 0.07(1 + 0.0248(T - 294)) \times C_\infty \quad \text{For } T \geq 294 \text{ K} \quad (6)$$

Where,

T : Temperature [K]

$\Lambda_{a0}, \Lambda_{c\infty}$: Initial and infinite conductivity of NaOH and CH_3COONa respectively [S]

C_∞ : Concentration of the Sodium acetate after infinite time = a_0 [mol/dm³]

Using these start and end values for the conductivity measurements we can calculate values of sodium hydroxide concentration (a_t) and sodium acetate concentration (c_t) and the degree of conversion (X_a) for each of the samples of conductivity taken over the period of the experiment.

We can define the conversion of sodium hydroxide as the amount reacted, as a percentage of the initial amount present

$$X_a = \frac{a_0 - a_t}{a_0} \quad (7)$$

Apparatus

Fig. 1 shows the tubular reactor used in the experiment, while Fig1.2 describes the process flow sheet.

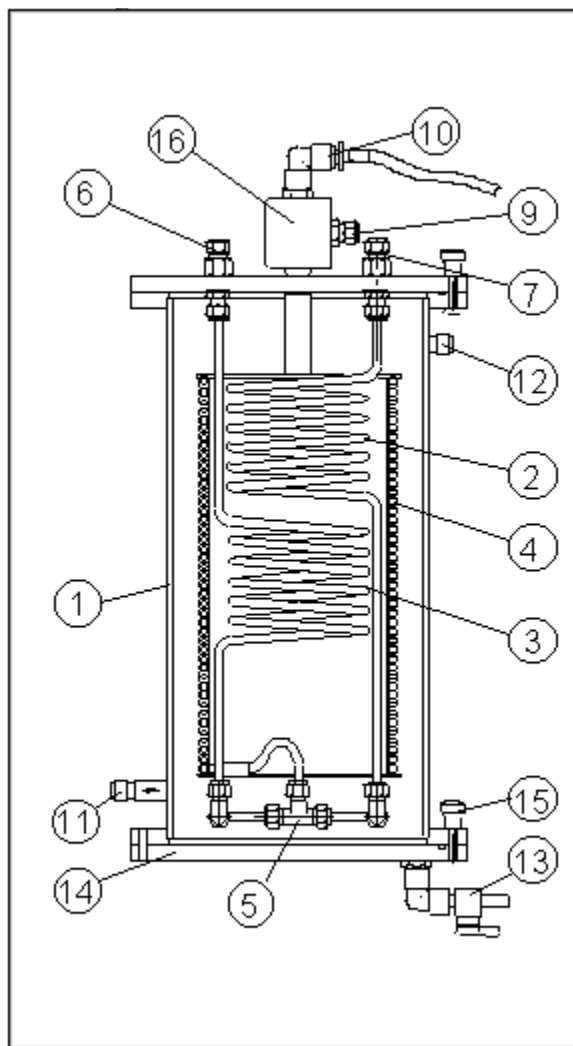


Fig. 1.1: Tubular Reactor

The reactor vessel (1) is set on a baseplate (14) which is designed to be located on four studs on the service unit and secured by the thumbnuts (15).

NOTE: The reactor is positioned on the service unit with non-return valve (11) on the left hand side of the reactor at the rear.

The tubular reactor in which the chemical reaction takes place is a flexible coil (4) wound around an acrylic former. Total volume of the reactor coil is 0.4 litres. Reactants in the

tube are maintained at constant temperature by circulation of water through the vessel from the hot water circulator of the service unit.

Reactants are pumped from the two feed tanks by the peristaltic feed pumps and enter the reactor through connectors (6) and (7) in the lid of the vessel. Each reactant is pre-heated by heat transfer coils (2) and (3) before being blended together in "T" fitting (5).

The reactants pass up through the reactor coil and leave the reactor vessel through the conductivity probe housing (16). A gland (9) in this housing allows the conductivity probe (CP) to be held in the stream of reactants emerging from the reactor. Flexible tubing from the hose nozzle (10) is used to guide the reactants to drain.

In order to maintain a constant temperature throughout the reactor coil, the coil bundle is submerged in circulating water which is automatically maintained at a pre-selected temperature by the temperature controller (TIC) in the CEX console. The actual temperature of the circulating water and therefore the reactants is relayed to the controller by a sensing probe (TS) which is held in a gland in the lid. Water enters from the circulator at non-return valve (11) - this prevents water draining back through the priming vessel of the circulator when the pump is stopped. Water leaves the reactor at overflow (12) and returns to the circulator.

When not in use, the reactor can be drained using valve (13) in the base.

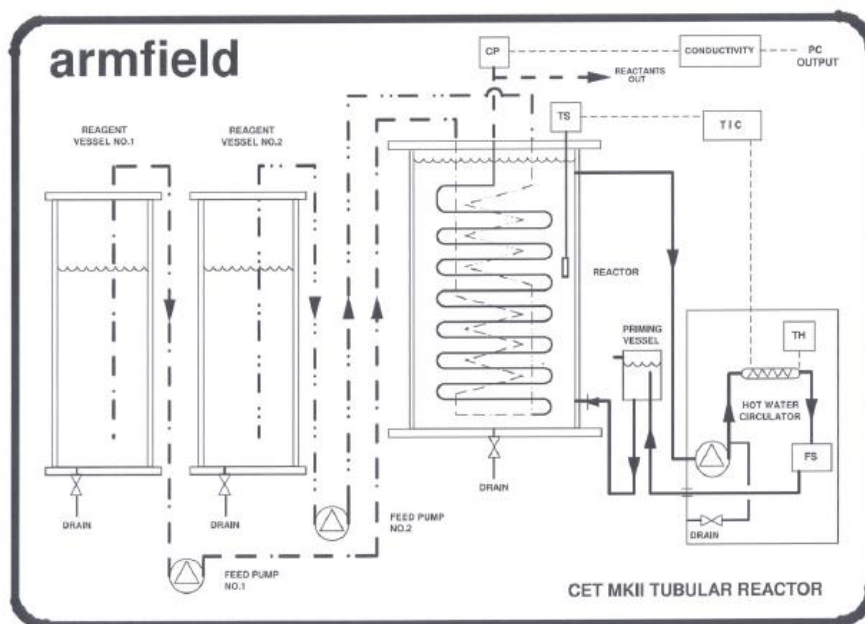


Fig. 1.2: Process flow sheet

Method

To add known concentrations of sodium hydroxide and ethyl acetate to the reactor and monitor the rate of conversion to sodium acetate and ethyl alcohol. Graphical method can then be used to estimate the rate constant.

In order to complete the demonstration you need a number of pieces of equipment

- The CEX Service Bench
- The CET Tubular Reactor
- The IFD6 unit and its connecting cables

Procedure

- Make up 5.0 liter batches of 0.05M sodium hydroxide and 0.05M ethyl acetate in water.
- Remove the lids of the reagent vessels and carefully fill with the reagents to a level approximately 50mm from the top. Refit the lids.
- Prior to priming the hot water circulating pump, it is convenient to fill the reactor with cold water up to the overflow (return to the circulator) using a suitable hose from a domestic supply through the temperature sensor gland (8) in the lid of the reactor. Non-return valve (11) prevents water flowing out of the reactor. Ensure the temperature sensor is re-fitted and the gland tightened securely by hand.
- Adjust the set point of the temperature controller to 26°C.
- Set the pump speed control to give 80 ml/min flow rate for each reactant.
- Switch on the hot water circulator. The temperature of the water in the reactor vessel will begin to rise and will be automatically maintained at the desired set-point (e.g. 26°C in this instance).
- Switch on both feed pumps.
- Reactants will flow from both feed vessels and enter the reactor through the connections in the lid. Each reactant passes through pre-heat coils submerged in the water in which they are individually brought up to the reaction temperature. At the base of the tubular reactor coil, the reactants are mixed together in a "T" connection and begin to pass through the coil. The reacting solution will emerge

from the coil through connector (16) in the lid where a probe continuously senses the conductivity. This is related to degree of conversion by the software.

- Use the IFD channel history window to monitor the progress of the reaction. Once a steady state is achieved, click the 'sample now' button on the Mimic Diagram screen, and the results will automatically be recorded in tabular format.
- Repeat this procedure for flow rates of 60 and 40 ml/min for both reactants.
- On completion of the exercise, rinse the feed tanks with demineralized water and pump the water through the reactor to rinse out the chemicals. The reactor can be left with water in the coil ready for the next experiment.

Questions to be answered in lab. Report:

- determine the rate constant.
- Explain the relation between the residence time t_r and the reactants feed rate as well as the reactants conversion and show it graphically.

Nomenclature

Symbol	Definition	Unit
a_{μ}	Sodium hydroxide concentration in feed vessel	mol/dm ³
a_0	Sodium hydroxide concentration in mixed feeds	mol/dm ³
a_1	Sodium hydroxide concentration at steady state	mol/dm ³
a_t	Sodium hydroxide concentration at time t	mol/dm ³
a_{∞}	Sodium hydroxide concentration at infinite time	mol/dm ³
C_{∞}	Sodium acetate concentration at infinite time	mol/dm ³
Λ_0	Initial conductivity of the solution	mS
Λ_1	Steady state conductivity of the solution	mS
Λ_{∞}	Conductivity of the solution at infinite time	mS
Λ_a	Sodium hydroxide conductivity	mS
Λ_c	Sodium acetate conductivity	mS
F_a	Sodium hydroxide Volumetric flow rate	mL/min
F_b	Ethyl acetate volumetric flow rate	mL/min
k	Reaction rate constant	
r	Reaction rate	
T	Reaction temperature	K
V	Volume of reactor	mL
X_a	Sodium hydroxide conversion	-

DIFFUSION OF LIQUIDS

The determination of diffusion coefficient of sodium hydroxide solution

Objective

- To determine the diffusion coefficient of NaCl solution.

Theory

An irreversible flow originates from the high concentrations to the low ones, when in a multi-component thermodynamic system there is a gradient of concentration. This flow is called diffusion. The diffusion tends to give back the system to its balance state, of constant concentration. The diffusion is described by Fick's Law. Binary mixing will be only considered for the exposition of such law, although similar developments are possible for multi-component mixings.

The solution concentration will be determined indirectly from the conductivity datum. The expression used will be the following:

$$\frac{dk}{dt} = \frac{D_A \cdot N \cdot \pi \cdot D^2 \cdot M \cdot C_M}{4 \cdot V \cdot x} \quad (1)$$

Where:

$\frac{dk}{dt}$: Rate of change of conductivity with time ($\Omega^{-1} \cdot s^{-1}$)

M : Molarity of the saline solution (M)

N : Number of capillaries (317)

x : Capillary length (0.5cm)

D : Diameter of capillary (0.1cm)

V : Volume of water in outer vessel (L)

C_M : Electrical conductivity change for unit molarity change ($\Omega^{-1} \cdot M^{-1}$)

Apparatus

Fig. 1 shows the diffusion apparatus used in the experiment.

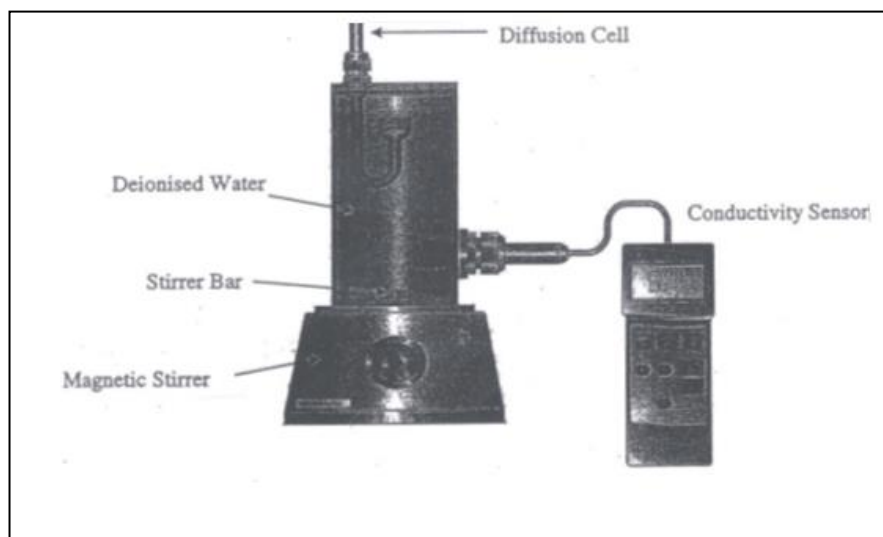


Fig. 8.1: Diffusion cell apparatus.

Method

A small volume of concentrated solution is placed on one side of the capillaries, inside the glass diffusion cell, while the other side consists initially of a large volume of pure solvent (water). As diffusion of the solute occurs, the concentration within the large volume increases and is monitored with a conductivity meter. The mixture is continuously agitated with a magnetic stirrer to ensure uniform concentration within the bulk liquid.

Procedure

Part A: To find the ratio between the concentration of a saline solution and the conductivity (C_M).

- Prepare 1 liter of 2 M and 1M NaCl solution, use the 2 M solution to prepare 1 liter of 0.01, 0.02,0.03,0.04 ,0.05 M NaCl solutions.
- Measure the conductivity of each diluted solution by pouring it inside the glass vessel, clean the vessel using distilled water.

Part B: To study the diffusion of a solute in a liquid solvent and to find the diffusivity coefficient.

- Fill the cell completely with 1M NaCl and clean any excess from the solution from the cell outside and capillary ends using filter paper.
- Put the cell in its position within the vessel. Fill the vessel with distilled water (approximately 1.2 L) until the water level surpass 5 mm above the diffusion cell.
- Turn on the magnetic stirrer on moderate speed. Turn on the conductmeter and record it's reading every 30 s min until the system reaches steady state.
- Clean the cell and vessel with distilled water. Repeat the same procedure for 2M solution.

Question to be answered in lab. report:

- Construct the conductivity versus concentration graph and calculate C_M .
- Draw the conductivity variation with time and find the slope.
- Calculate the diffusivity coefficient and compare the value you got with literature value.
- Explain Fick's law and its applications.

Nomenclature

Symbol	Definition	Unit
$\frac{dk}{dt}$	Rate of change of conductivity with time	$\Omega^{-1}.s^{-1}$
D_A	Diffusion Coefficient	
M	Molarity of the saline solution	M
N	Number of capillaries	-
x	Capillary length	cm
D	Diameter of capillary	cm
V	Volume of water in outer vessel	L
C_M	Electrical conductivity change for unit molarity change	$\Omega^{-1}.M^{-1}$

JACKETED VESSEL WITH COIL AND STIRRER (1)

Objective

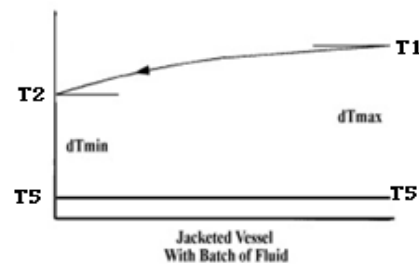
- To determine the overall heat transfer coefficient using logarithmic mean temperature difference containing a fixed batch of liquid and a continuous flow in a stirred vessel when heated using an outer jacket.
- To calculate the overall efficiency for a continuous flow in a stirred vessel when heated using an outer jacket.

Theory

The volume V of the water being heated can be assumed 1-Liter
(As signed on the vessel)

The LMTD is defined as:

$$\text{LMTD} = \frac{dT_{\max} - dT_{\min}}{\ln\left(\frac{dT_{\max}}{dT_{\min}}\right)}$$



Hence from the above diagrams of temperature distribution

$$\text{LMTD} = \frac{(T1 - T5) - (T2 - T5)}{\ln\left(\frac{(T1 - T5)}{(T2 - T5)}\right)}$$

It is necessary to correct the mass flow rates according to water density because the values given by rotameter refers to $T=25^\circ\text{C}$, $\rho=1 \text{ g/mL}$

$$\dot{m}(T) = \dot{m}(25^\circ\text{C}) * \frac{\rho(T)}{\rho(25^\circ\text{C})}$$

The water density and specific heat capacity are dependent upon the mean fluid temperature T_{mean}

$$T_{\text{mean}} = \frac{T_{\text{inlet}} + T_{\text{out}}}{2}$$

The power emitted from the hot stream \dot{Q}_e

$$\dot{Q}_e = \dot{m}_{h(T_{mean})} C_{p(T_{mean})} (T_1 - T_2)$$

Where:

$$T_{mean} = \frac{T_1 + T_2}{2}$$

In order to calculate the overall heat transfer coefficient the following parameters must be used with consistent units:

$$U = \frac{\dot{Q}_e}{A \times \text{LMTD}}$$

Where

\dot{Q}_e : Heat emitted from hot stream (Watts)

LMTD: Logarithmic mean temperature difference (K)

A: Heat transfer area of heat exchanger (m^2)

The heat transfer area may be calculated from:

$$d_m = \frac{d_o + d_i}{2}$$

And

$$A = \pi d_m H$$

Where

d_o : vessel wall outside diameter (0.1542 m)

d_i : vessel wall Inside Diameter (0.1524 m)

d_m : vessel wall mean diameter (m)

H: Height of vessel contents (0.06m)

For the continuous Flow Only:

The power absorbed by the cold stream \dot{Q}_a

$$\dot{Q}_a = \dot{m}_c C_{p(T_{mean})} [T_5 - T_4]$$

Where

$$T_{mean} = \frac{T_5 + T_4}{2}$$

The difference between the heat emitted \dot{Q}_e and the heat absorbed \dot{Q}_a represent the losses or gains to the surroundings. As the vessel is not insulated these may be positive or negative due to temperature differences.

Heat lost to surroundings \dot{Q}_s

$$\dot{Q}_s = \dot{Q}_e - \dot{Q}_a$$

Apparatus

Fig. 6.1 shows the jacketed vessel connected to the service unit, Fig. 6.2 shows the process flow sheet.

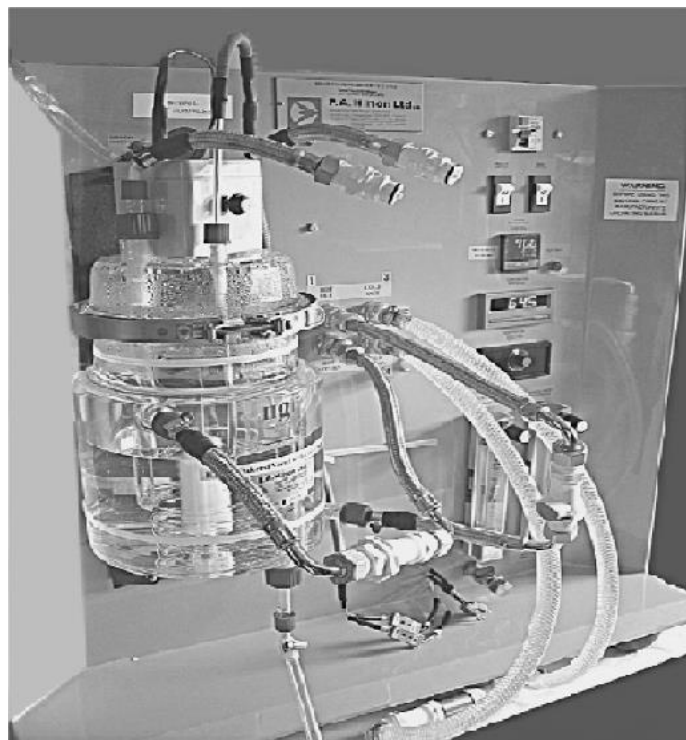


Fig. 6.1: The jacketed vessel connected to the service unit.

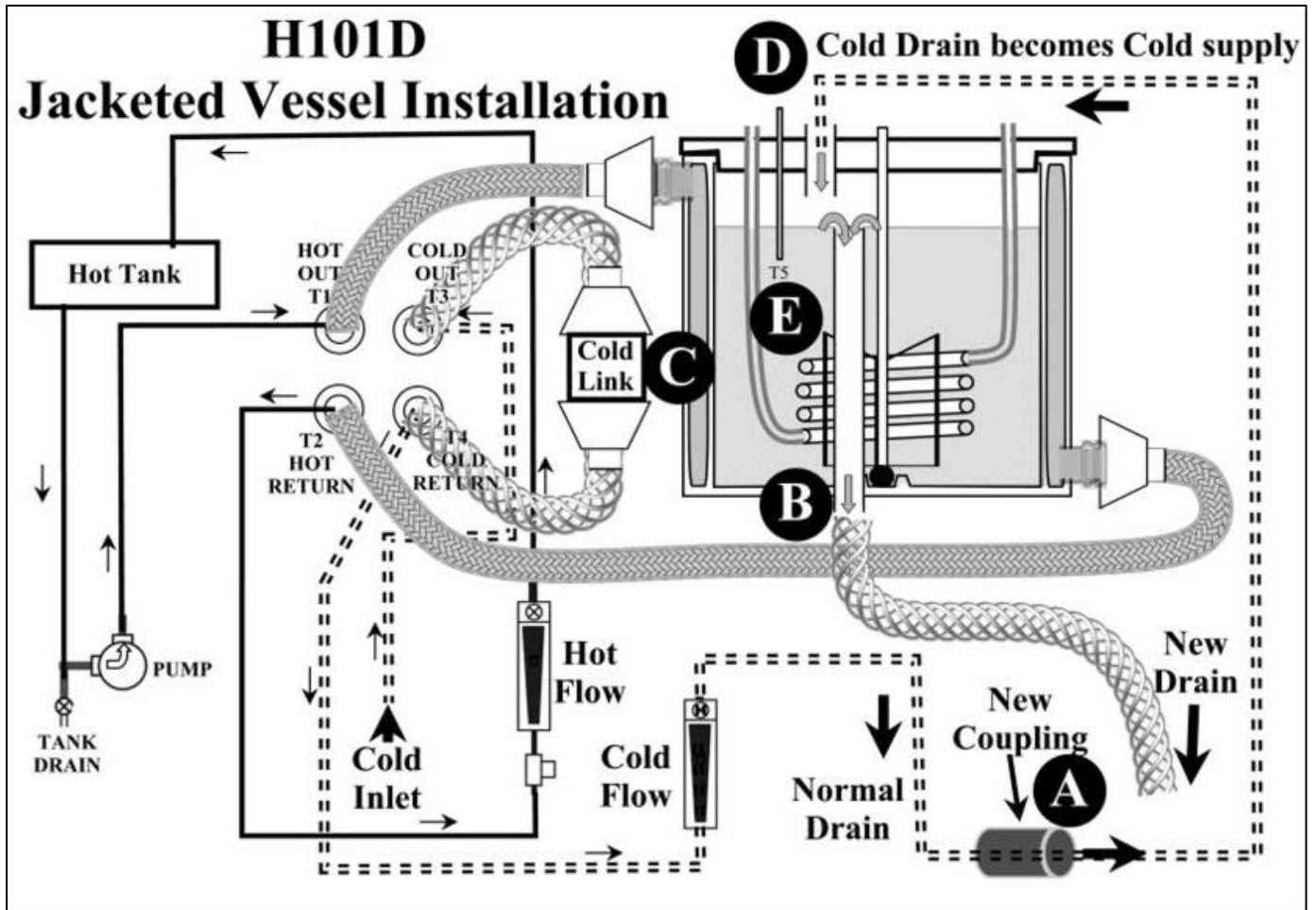


Fig. 6.2: process flow sheet.

Table 6.1: Jacketed vessel with coil and stirrer specifications

Vessel wall inside diameter	0.1524m
Vessel wall outside diameter	0.1542m
Coil tube outside diameter	0.0063m
Coil tube bore diameter	0.0049m
Effective length of coil tube	1.15m
Height of vessel contents	0.06m

Procedure

Part A: Batch Process

- Adjust the overflow in the vessel to the 1-litre height.
- Turn on the 'MAIN SWITCH' and replenish the hot circuit as the jacket fills.
- Turn on the 'HEATER SWITCH'.
- Set the hot water temperature controller to 60°C.
- Set the cold-water flow rate V_{cold} to Zero.
- Set the hot water flow rate V_{hot} to 32 g/sec.
- Stirrer ON, speed 100%.
- T5 probe 15mm below surface.
- Allow the hot water circuit to reach the 60°C set point. Then turn off the Main Switch
- Open the 'Cold Water Flow Control' to begin filling the vessel. When the water level reaches the top of the overflow pipe and just begins to overflow, close the cold-water valve.
- Turn on the 'MAIN SWITCH' and 'HEATER SWITCH'.
- Switch ON the stirrer and set speed to 100%.
- Record T5 (Vessel Contents) and start the stopwatch. This is the start of the heating process.
- Record the temperatures T5, T1, T2 and V_{hot} at 1 Minute intervals until T5 reach a constant value.

Part B: Continues Process

- Adjust the overflow in the vessel to the 1-litre height.
- Turn on the 'MAIN SWITCH' and replenish the hot circuit as the jacket fills.
- Turn on the 'HEATER SWITCH'.
- Set the hot water temperature controller to 60°C.
- Set the cold-water flow rate V_{cold} to 8g/sec.
- Record the temperatures T5, T1, T2, T4, V_{cold} and V_{hot} at 1 Minute intervals until T5 reach a constant value.
-

Questions to be answered in lab. Report:

- Calculate LMTD for batch and continues processes.
- Draw T5 and LMTD Vs. Time on the same graph. Discuss your graph
- For Batch Process, calculate U and \dot{Q}_e for each 1 min. intervals and draw them on the same graph. Discuss your results
- For Continues Process, calculate U, \dot{Q}_e , \dot{Q}_a and \dot{Q}_s for each 1 min. Intervals and draw them on the same graph. Discuss your results.

SYMBOLS AND UNITS

<u>Symbol</u>		<u>Units</u>
V_{cold}	Cold stream flow rate	g/sec
V_{hot}	Hot stream flow rate	g/sec
T1	Vessel Contents temperature	°C
T2	Hot fluid into jacket temperature	°C
T3	Hot fluid out of jacket temperature	°C
T4	Hot fluid into coil temperature	°C
T5	Hot fluid out of coil temperature	°C
T6	Cold fluid into vessel temperature	°C
Δt_{hot}	Decrease in hot fluid temperature	K
Δt_{Cold}	Increase in cold fluid temperature	K
dT hot	Decrease in hot fluid temperature	K
dT cold	Increase in cold fluid temperature	K
H	Overflow height above floor of vessel	m
d_i	Inside diameter of vessel wall	m
d_o	Outside diameter of vessel wall	m
d_{mean}	Mean diameter	m
V	Volume	m ³
T_{mean}	Mean temperature	°C
ρ	Density of stream fluid	kg litre
C_p	Specific Heat of stream fluid	kJkg ⁻¹ K ⁻¹
\dot{Q}_e	Heat flow rate from hot stream	Watts
\dot{Q}_a	Heat flow rate to cold stream	Watts
\dot{Q}_f	Heat loss to surroundings	Watts
LMTD	Logarithmic mean temperature difference	K
A	Heat transfer surface area	m ²
U	Overall heat transfer coefficient	Wm ⁻² K ⁻¹
η_{Thermal}	Thermal efficiency	%
$d_{\text{coil}i}$	Submerged coil tube inside diameter	m
$d_{\text{coil}o}$	Submerged coil tube outside diameter	m
$d_{\text{coil}m}$	Submerged coil tube mean diameter	m
L	Submerged coil tube effective length	m
dTmax	Maximum temperature difference across heat exchanger	K
dTmin	Minimum temperature difference across heat exchanger	K

JACKETED VESSEL WITH COIL AND STIRRER (2)

Objective

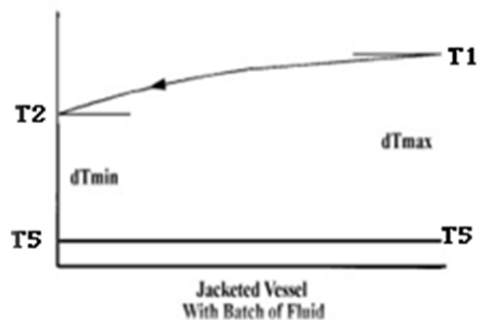
- To determine the overall heat transfer coefficient using logarithmic mean temperature difference containing a fixed batch of liquid and a continuous flow in a stirred vessel when heated using a submerged coil.
- To calculate the overall efficiency for continuous flow in a stirred vessel when heated using a submerged coil.

Theory

The volume V of the water being heated can be assumed 1-Liter (as signed on the vessel)

The LMTD is defined as:

$$\text{LMTD} = \frac{dT_{\max} - dT_{\min}}{\ln\left(\frac{dT_{\max}}{dT_{\min}}\right)}$$



Hence from the above diagrams of temperature distribution

$$\text{LMTD} = \frac{(T1-T5) - (T2 - T5)}{\ln\left(\frac{(T1-T5)}{(T2 - T5)}\right)}$$

It is necessary to correct the mass flow rates according to water density because the values given by rotameter refers to $T=25\text{ }^{\circ}\text{C}$, $\rho=1\text{ g/mL}$

$$\dot{m}(T) = \dot{m}(25^{\circ}\text{C}) * \frac{\rho(T)}{\rho(25^{\circ}\text{C})}$$

The water density and specific heat capacity are dependent upon the mean fluid temperature T_{mean}

$$T_{mean} = \frac{T_{inlet} + T_{out}}{2}$$

The power emitted from the hot stream \dot{Q}_e

$$\dot{Q}_e = \dot{m}_{h(T_{mean})} C_{p(T_{mean})} [T_1 - T_2]$$

Where:

$$T_{mean} = \frac{T_1 + T_2}{2}$$

In order to calculate the overall heat transfer coefficient the following parameters must be used with consistent units:

$$U = \frac{\dot{Q}_e}{A \times \text{LMTD}}$$

Where

\dot{Q}_e : Heat emitted from hot stream (Watts)

LMTD: Logarithmic mean temperature difference (K)

A: Heat transfer area of heat exchanger (m^2)

The heat transfer area may be calculated from:

$$d_m = \frac{d_o + d_i}{2}$$

And

$$A = \pi d_m H$$

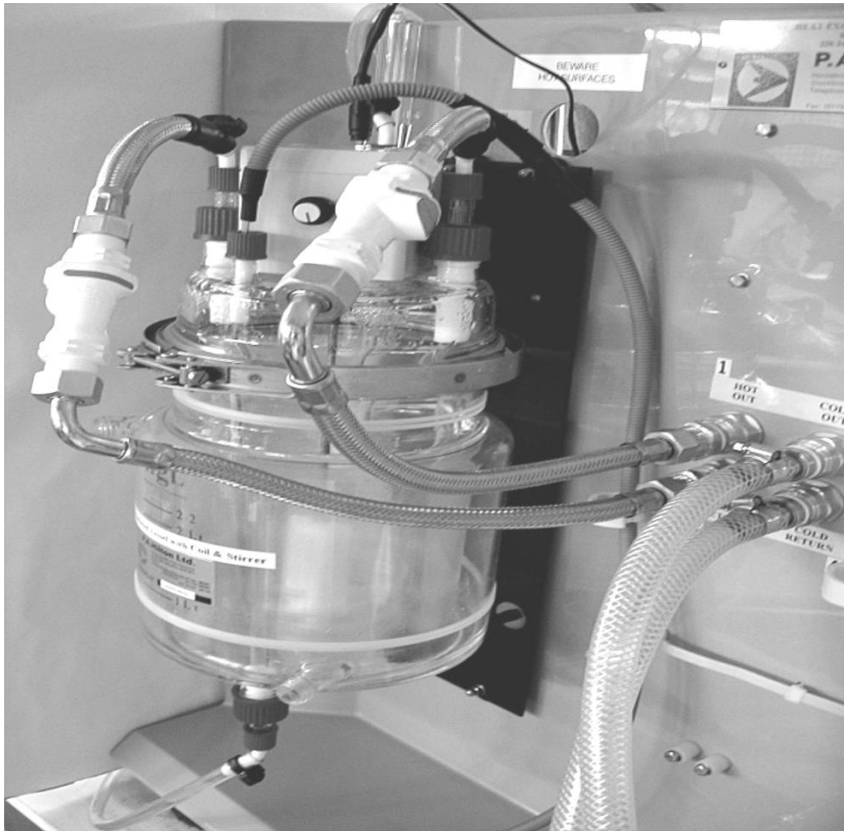
Where

d_o : Heat transfer tube outside diameter (0.0063 m)

d_i : Heat transfer tube inside diameter (0.0049m)

d_m : Heat transfer tube mean diameter (m)

H: Effective length of coil tube (1.15m)

For the continuous Flow Only:

The power absorbed by the cold stream \dot{Q}_a

$$\dot{Q}_a = \dot{m}_c(T_{mean}) C_{p(T_{mean})} [T_5 - T_4]$$

Where

$$T_{mean} = \frac{T_5 + T_4}{2}$$

The difference between the heat emitted \dot{Q}_e and the heat absorbed \dot{Q}_a represent the losses or gains to the surroundings. As the vessel is not insulated these may be positive or negative due to temperature differences.

Heat lost to surroundings \dot{Q}_s

$$\dot{Q}_s = \dot{Q}_e - \dot{Q}_a$$

Apparatus

Fig. 7.1 shows the jacketed vessel connected to the service unit, Fig. 7.2 shows the process flow sheet.

Fig. 7.1: The jacketed vessel connected to the service unit.

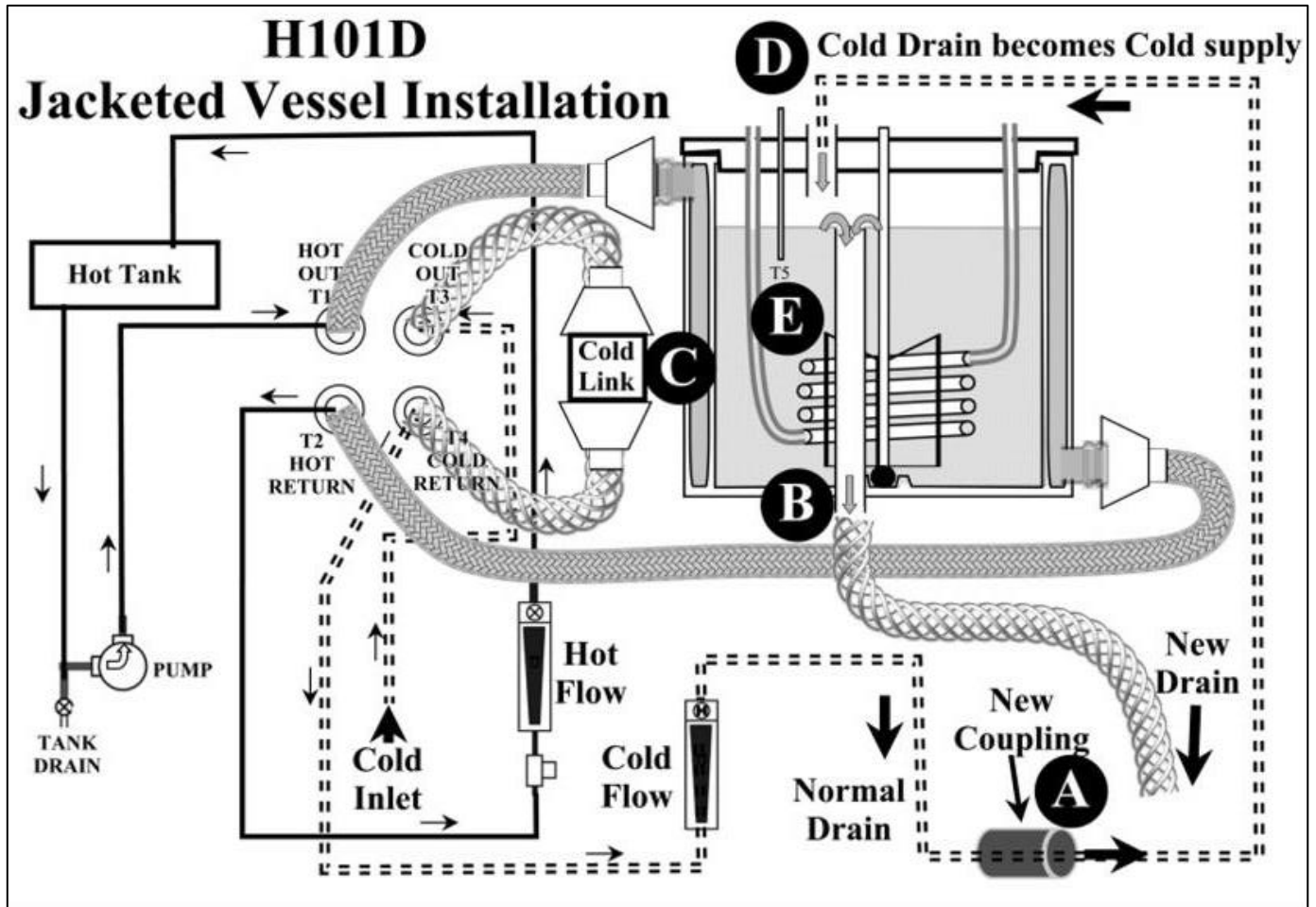


Fig. 7.2: process flow sheet.

Table 7.1: Jacketed vessel with coil and stirrer specifications

Vessel wall inside diameter	0.1524m
Vessel wall outside diameter	0.1542m
Coil tube outside diameter	0.0063m
Coil tube bore diameter	0.0049m
Effective length of coil tube	1.15m
Height of vessel contents	0.06m

Procedure

Part A: Batch process

- Adjust the overflow in the vessel to the 1-litre height.
- Turn on the 'MAIN SWITCH' and replenish the hot circuit as the jacket fills.
- Turn on the 'HEATER SWITCH'.
- Set the hot water temperature controller to 60°C.
- Set the cold water flow rate V_{cold} to Zero.
- Set the hot water flow rate V_{hot} to 32g/sec.
- Stirrer ON, speed 100%.
- T5 probe 15mm below surface.
- Allow the hot water circuit to reach the 60°C set point. Then turn off the Main Switch
- Open the 'Cold Water Flow Control' to begin filling the vessel. When the water level reaches the top of the overflow pipe and just begins to overflow, close the cold-water valve.
- Turn on the 'MAIN SWITCH' and 'HEATER SWITCH'.
- Switch ON the stirrer and set speed to 100%.
- Record T5 (Vessel Contents) and start the stopwatch. This is the start of the heating process.
- Record the temperatures T5, T1, T2 and V_{hot} at 1 Minute intervals until T5 reach a constant value.

Part B: Continuous process

- Adjust the overflow in the vessel to the 1-litre height.
- Turn on the 'MAIN SWITCH' and replenish the hot circuit as the jacket fills.
- Turn on the 'HEATER SWITCH'.
- Set the hot water temperature controller to 60°C.
- Set the cold-water flow rate V_{cold} to 8g/sec.
- Record the temperatures T5, T1, T2, T4, V_{cold} and V_{hot} at 1 Minute intervals until T5 reach a constant value.

Questions to be answered in lab. report:

- Calculate LMTD for batch and continues processes.
- Draw T5 and LMTD Vs. Time on the same graph. Discuss your graph
- For Batch Process, calculate U and \dot{Q}_e for each 1 Minute intervals and draw them on the same graph. Discuss your resultts
- For Continues Process, calculate U, \dot{Q}_e , \dot{Q}_a and \dot{Q}_s for each 1 Minute intervals and draw them on the same graph. Discuss your results
- Compare your results you get from both coil and jacket as heating mental (which is more efficient and why?)

SYMBOLS AND UNITS

<u>Symbol</u>		<u>Units</u>
V_{cold}	Cold stream flow rate	g/sec
V_{hot}	Hot stream flow rate	g/sec
T1	Vessel Contents temperature	'C
T2	Hot fluid into jacket temperature	'C
T3	Hot fluid out of jacket temperature	'C
T4	Hot fluid into coil temperature	'C
T5	Hot fluid out of coil temperature	'C
T6	Cold fluid into vessel temperature	'C
Δt_{hot}	Decrease in hot fluid temperature	K
Δt_{Cold}	Increase in cold fluid temperature	K
dT hot	Decrease in hot fluid temperature	K
dT cold	Increase in cold fluid temperature	K
H	Overflow height above floor of vessel	m
d_i	Inside diameter of vessel wall	m
d_o	Outside diameter of vessel wall	m
d_{mean}	Mean diameter	m
V	Volume	m^3
T_{mean}	Mean temperature	'C
ρ	Density of stream fluid	kg litre
C_p	Specific Heat of stream fluid	$\text{kJkg}^{-1}\text{K}^{-1}$
\dot{Q}_e	Heat flow rate from hot stream	Watts
\dot{Q}_a	Heat flow rate to cold stream	Watts
\dot{Q}_f	Heat loss to surroundings	Watts
LMTD	Logarithmic mean temperature difference	K
A	Heat transfer surface area	m^2
U	Overall heat transfer coefficient	$\text{Wm}^{-2}\text{K}^{-1}$
η_{Thermal}	Thermal efficiency	%
$d_{\text{coil}i}$	Submerged coil tube inside diameter	m
$d_{\text{coil}o}$	Submerged coil tube outside diameter	m
$d_{\text{coil}m}$	Submerged coil tube mean diameter	m
L	Submerged coil tube effective length	m
dTmax	Maximum temperature difference across heat exchanger	K
dTmin	Minimum temperature difference across heat exchanger	K

EXTENDED CONCENTRIC TUBE HEAT EXCHANGER

Objective

- To calculate the overall efficiency at different fluid rates.
- To calculate the mean temperature efficiency.
- To recognize the difference between co-current and counter-current flows.
- To determine the overall heat transfer coefficient using logarithmic mean temperature difference for counter-current and co-current flows

Theory

The overall thermal efficiency:

$$\eta_{\text{Thermal}} = \frac{\dot{Q}_a}{\dot{Q}_e} \times 100(\%)$$

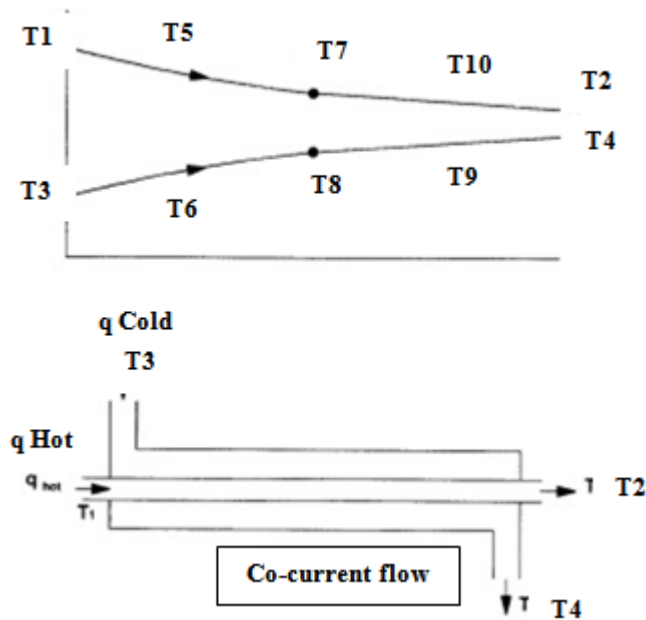
\dot{Q}_a : (power absorbed by the cold stream)=

$$\dot{Q}_a = \dot{V}_{\text{cold}} \rho(\text{cold}) C_{p,\text{cold}} [T_4 - T_3]$$

\dot{Q}_e : (the power emitted by the hot stream)=

$$\dot{Q}_e = \dot{V}_{\text{Hot}} \rho(\text{hot}) C_{p,\text{hot}} [T_1 - T_2]$$

A useful measure of the heat exchanger performance is the temperature efficiency. The temperature change in each stream (hot and cold) is compared with the maximum temperature difference between the two streams. This could only occur in a perfect heat exchanger of infinite size with no external losses or gains.

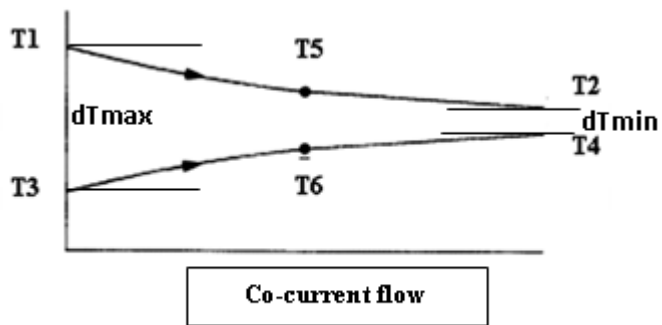
Co-Current Flow

The temperature efficiencies of the hot and cold streams for counter-current are given as:

$$\eta_{\text{Hot}} = \frac{T1 - T2}{T1 - T3} \times 100\% \quad \eta_{\text{Cold}} = \frac{T4 - T3}{T1 - T3} \times 100\%$$

The mean temperature efficiency

$$\eta_{\text{Mean}} = \frac{\eta_{\text{Hot}} + \eta_{\text{Cold}}}{2}$$



The logarithmic mean temperature difference LMTD

$$\text{LMTD} = \frac{dT_{\max} - dT_{\min}}{\ln\left(\frac{dT_{\max}}{dT_{\min}}\right)}$$

$$\text{LMTD} = \frac{(T1-T3) - (T2 - T4)}{\ln\left(\frac{(T1-T3)}{(T2 - T4)}\right)}$$

The Overall heat transfer coefficient U

$$U = \frac{\dot{Q}_e}{A \times \text{LMTD}}$$

Where

A: Heat transfer area of heat exchanger (m^2)

\dot{Q}_e : Heat emitted from hot stream (Watts)

LMTD: Logarithmic mean temperature difference (K)

The heat transfer area may be calculated from -

$$d_m = \frac{d_o + d_i}{2}$$

And

$$A = \pi d_m L$$

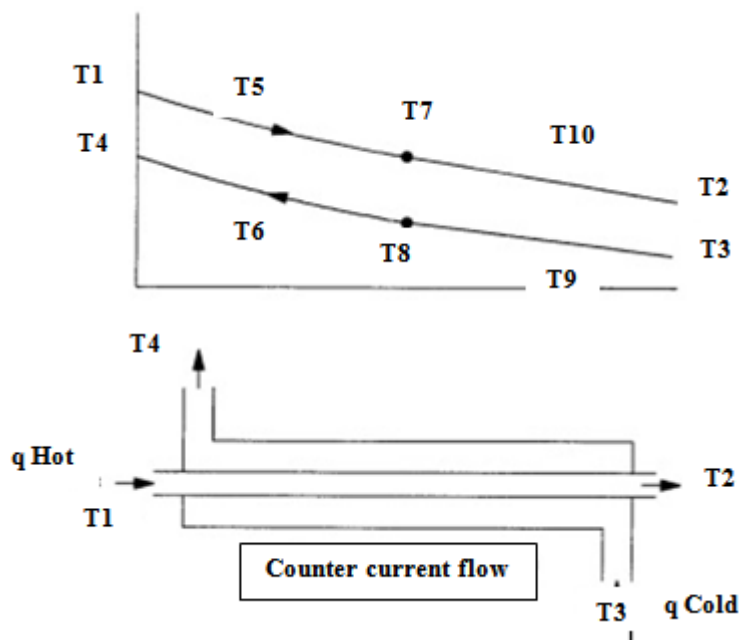
Where

d_o : Heat transfer tube outside diameter (m)

d_i :Heat transfer tube inside diameter (m)
 d_m :Heat transfer tube mean diameter (m)
 L :Heat transfer tube effective length (m)

Counter-Current Flow

For the counter-current flow system, the calculation procedure is similar but the difference in LMTD formula as follow:



$$\text{LMTD} = \frac{(T1 - T4) - (T2 - T3)}{\ln\left(\frac{(T1 - T4)}{(T2 - T3)}\right)}$$

The temperature efficiencies of the hot and cold streams for counter-current are given as:

$$\eta_{\text{Hot}} = \frac{T1 - T2}{T1 - T3} \times 100\% \quad \eta_{\text{Cold}} = \frac{T4 - T3}{T1 - T3} \times 100\%$$

The mean temperature efficiency

$$\eta_{\text{Mean}} = \frac{\eta_{\text{Hot}} + \eta_{\text{Cold}}}{2}$$

Apparatus

Fig. 6.1 shows the extended concentric tube heat exchanger connected to the service unit.



Fig. 6.1: Extended concentric heat exchanger connected to the service unit.

Table 6.1: Extended concentric tube heat exchanger specifications

Inner Tube	
Material	Stainless steel
Outside Diameter	0.012m
Wall Thickness	0.001m
Outer Tube	
Material	Clear Acrylic
Inside Diameter	0.022m
Wall Thickness	0.003m
Active Heat Transfer Section	
Length	0.636m
Area (extended)	0.04396m

Procedure

- Connect the cold water circuit to give co-current flow.
- Turn on the 'MAIN SWITCH' and 'HEATER SWITCH'
- Set the hot water temperature controller to 60°C.
- Set the cold water flow rate V_{cold} to 12g/sec
- Set the hot water flow rate V_{hot} to 30g/sec.
- Monitor the stream temperatures and the hot and cold flow rates to ensure these too remain close to the original setting. Then record the following:
T1, T2, T3, T4,T5, T6, T7, T8, T9, T10, V_{hot} and V_{cold}
- Adjust the cold-water flow valve so that V_{cold} is approximately 12g/sec. Maintain the Hot water flow rate at approximately 30g/sec (the original setting).
- Allow the conditions to stabilize and repeat the above observations.
- Repeat the all above for **counter-current flow (same flowrates as co-current flow)**.
- Repeat the same procedure for the following hot and cold flows:

V_{hot} (g/sec)	V_{cold} (g/sec)
15	15
15	30
15	50
30	15
30	30
30	50
50	15
50	30
50	50

Question to be answered in lab. report:

- Sketch the temperatures (T_1, \dots, T_{10}) for co and counter-current flow as a function of time . (Vs. Time)
- Sketch the temperatures (T_1, \dots, T_{10}) for co and counter-current flow patterns. Vs. Position .Does it much with the expected pattern (expected temperature profile)?
- Calculate the thermal and the mean temperature efficiencies for each 1 Minute intervals and draw them on the same graph.
- Calculate the overall heat transfer coefficient and LMTD for each 1 Minute intervals and draw them on the same graph. Discuss your results
- Calculate \dot{Q}_e, \dot{Q}_a for each 1 Minute intervals and draw them on the same graph. Discuss your results
- Which is more efficient, co-current or counter- current flow pattern? Explain.
- Discuss the effect of flow rate variation on your experimental results.

Nomenclature

Cold stream flow rate	V_{cold}	gram s ⁻¹
Hot stream flow rate	V_{hot}	gram s ⁻¹
Hot fluid inlet temperature	T1	°C
Hot fluid outlet temperature	T2	°C
Cold fluid inlet temperature	T3	°C
Cold fluid outlet temperature	T4	°C
Decrease in hot fluid temperature	Δt_{hot}	K
Increase in cold fluid temperature	Δt_{Cold}	K
Decrease in hot fluid temperature	dT hot	K
Increase in cold fluid temperature	dT cold	K
Inside diameter of hot tube	d_i	m
Outside diameter of hot tube	d_o	m
Mean diameter	d_{mean}	m
Number of hot tubes	n	-
Effective length of hot tube	L	m
Mean temperature	T_{mean}	°C
Density of stream fluid	ρ	kg litre
Specific Heat of stream fluid	C_p	kJkg ⁻¹ K ⁻¹
Heat flow rate from hot stream	\dot{Q}_e	Watts
Heat flow rate to cold stream	\dot{Q}_a	Watts
Heat loss to surroundings	\dot{Q}_f	Watts
Logarithmic mean temperature difference	LMTD	K
Heat transfer surface area	A	m ²
Overall heat transfer coefficient	U	Wm ⁻² K ⁻¹
Thermal efficiency	η_{Thermal}	%
Temperature efficiency hot stream	η_{hot}	%
Temperature efficiency cold stream	η_{cold}	%
Mean temperature efficiency	η_{mean}	%
Hot tube effective length	L	m
Maximum temperature difference across heat exchanger	dTmax	K
Minimum temperature difference across heat exchanger	dTmin	K

SHELL AND TUBE HEAT EXCHANGER

Objective

- To calculate the overall efficiency at different fluid rates.
- To calculate the mean temperature efficiency.
- To recognize the difference between co-current and counter-current flows.
- To determine the overall heat transfer coefficient using logarithmic mean temperature difference for counter-current and co-current flows

Theory

The overall thermal efficiency

$$\eta_{\text{Thermal}} = \frac{\dot{Q}_a}{\dot{Q}_e} \times 100(\%)$$

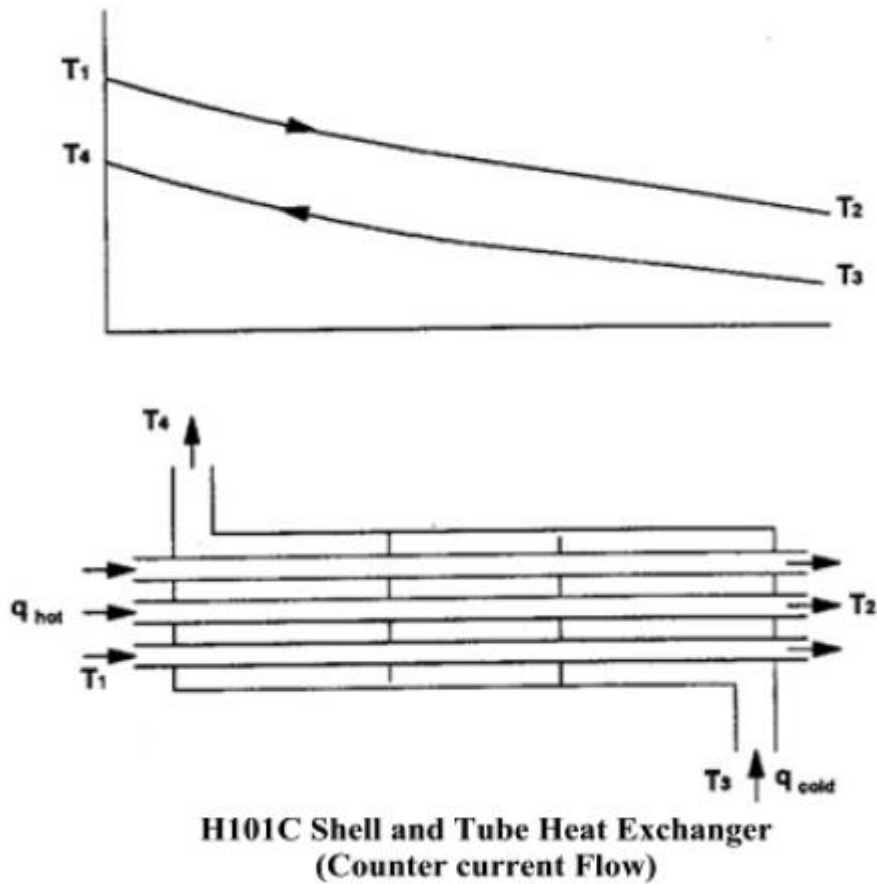
\dot{Q}_a (the power absorbed by the cold stream)=

$$\dot{Q}_a = V_{\text{cold}} \rho(\text{cold}) C_{p,\text{cold}} [T_4 - T_3]$$

\dot{Q}_e : (the power emitted by the hot stream)=

$$\dot{Q}_e = \dot{V}_{\text{Hot}} \rho(\text{hot}) C_{p,\text{hot}} [T_1 - T_2]$$

A useful measure of the heat exchanger performance is the temperature efficiency. The temperature change in each stream (hot and cold) is compared with the maximum temperature difference between the two streams. This could only occur in a perfect heat exchanger of infinite size with no external losses or gains.



The temperature efficiencies of the hot and cold streams for counter-current are given as:

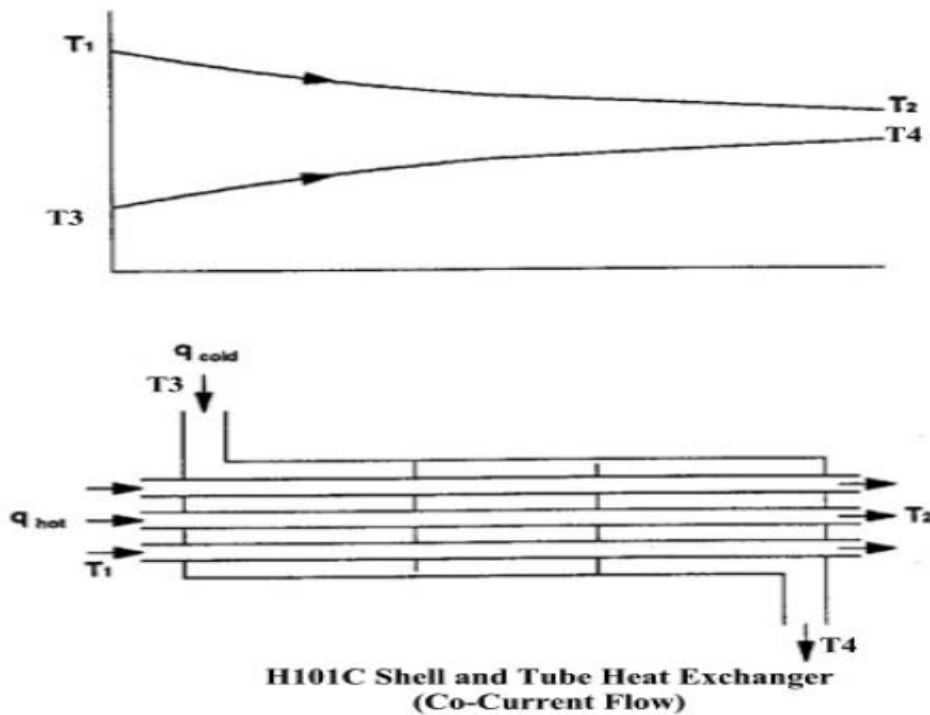
$$\eta_{\text{Hot}} = \frac{T_1 - T_2}{T_1 - T_3} \times 100\% \quad \eta_{\text{Cold}} = \frac{T_4 - T_3}{T_1 - T_3} \times 100\%$$

The mean temperature efficiency

$$\eta_{\text{Mean}} = \frac{\eta_{\text{Hot}} + \eta_{\text{Cold}}}{2}$$

Co-Current Flow

For the co-current flow system the calculation procedure is similar but the formulae are as follows



The power emitted from the hot stream \dot{Q}_e

$$\dot{Q}_e = \dot{V}_{Hot} \rho(hot) C_{p,hot} [T_1 - T_2]$$

The power absorbed by the cold stream \dot{Q}_a

$$\dot{Q}_a = \dot{V}_{cold} \rho(cold) C_{p,cold} [T_4 - T_3]$$

Reduction in Hot fluid temperature $\Delta T_{hot} = (T_1 - T_2) \text{ K}$

Increase in Cold fluid temperature $\Delta T_{cold} = (T_4 - T_3) \text{ K}$

The temperature efficiency of the hot stream from the above diagram

$$\eta_{Hot} = \frac{T_1 - T_2}{T_1 - T_3} \times 100\%$$

The temperature efficiency of the cold stream from the above diagram

$$\eta_{\text{Cold}} = \frac{T_4 - T_3}{T_1 - T_3} \times 100\%$$

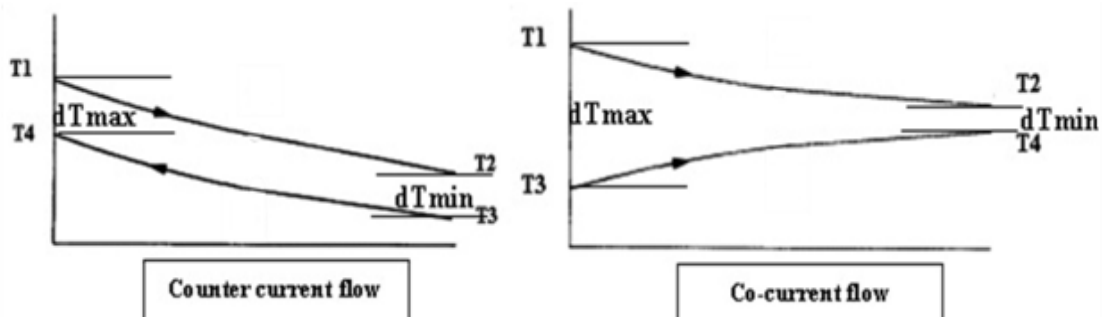
The mean temperature efficiency

$$\eta_{\text{Mean}} = \frac{\eta_{\text{Hot}} + \eta_{\text{Cold}}}{2}$$

As the temperature difference between the hot and cold fluids vary along the length of the heat exchanger, it is necessary to derive a suitable mean temperature difference that may be used in heat transfer calculations.

The LMTD is defined as:

$$\text{LMTD} = \frac{dT_{\text{max}} - dT_{\text{min}}}{\ln\left(\frac{dT_{\text{max}}}{dT_{\text{min}}}\right)}$$



$$\text{LMTD} = \frac{(T_1 - T_4) - (T_2 - T_3)}{\ln\left(\frac{(T_1 - T_4)}{(T_2 - T_3)}\right)}$$

$$\text{LMTD} = \frac{(T_1 - T_3) - (T_2 - T_4)}{\ln\left(\frac{(T_1 - T_3)}{(T_2 - T_4)}\right)}$$

In order to calculate the overall heat transfer coefficient the following parameters must be used with consistent units:

$$U = \frac{\dot{Q}_e}{A \times \text{LMTD}}$$

Where

\dot{Q}_e : Heat emitted from hot stream (Watts)

LMTD: Logarithmic mean temperature difference (K)

A: Heat transfer area of heat exchanger (m^2)

The heat transfer area may be calculated from:

$$d_m = \frac{d_o + d_i}{2}$$

And

$$A = \pi d_m L n$$

Where

d_o : Heat transfer tube outside diameter (m)

d_i : Heat transfer tube inside diameter (m)

d_m : Heat transfer tube mean diameter (m)

L: Heat transfer tube effective length (m)

n: Number of heat transfer tubes (Non dimensional)

Apparatus

Fig. 5.1 shows the shell and tube heat exchanger connected to the service unit, Fig. 5.2 shows co-current and counter-current flow patterns.



Fig. 5.1: Shell and tube heat exchanger connected to the service unit.

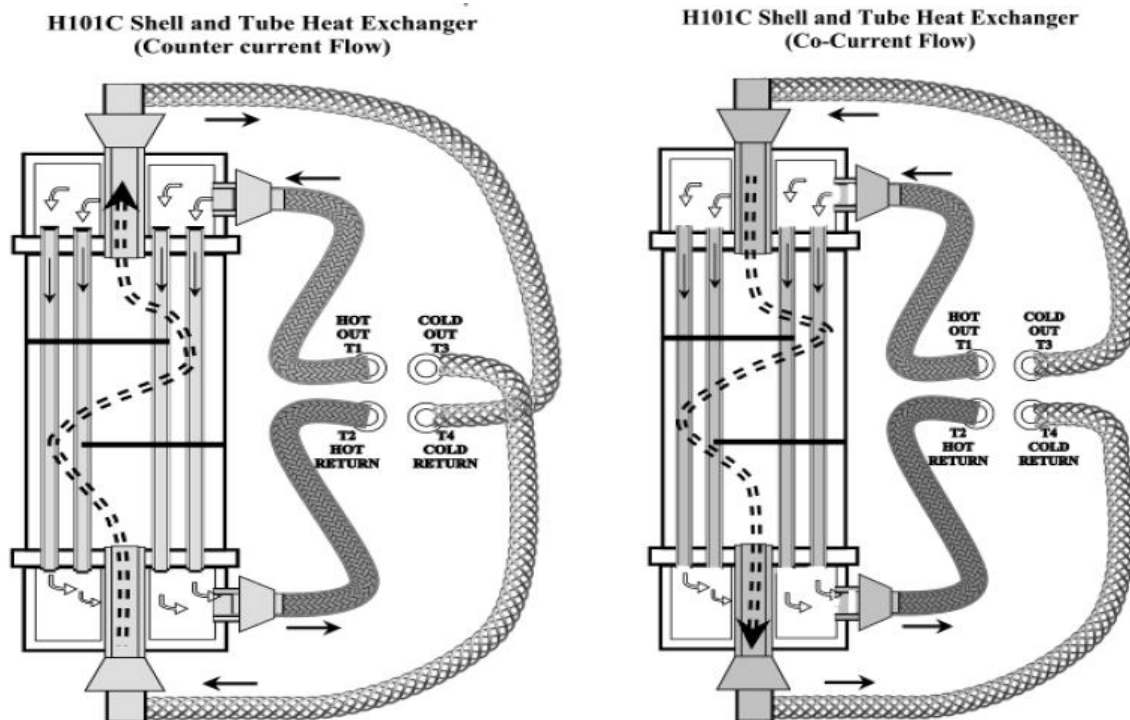


Fig. 5.2: Counter-current and co-current flow patterns.

Table 5.1: Shell and tube heat exchanger specifications

Tube Material	Stainless steel
Tube Outside Diameter	0.00476m
Tube Wall Thickness	0.0006m
Number of tubes in bundle	7
Effective length of tube in bundle	0.205m
Effective heat transfer area (Total)	0.0187m ²
Shell Material	Clear Borosilicate (Pyrex type glass)
Shell Inside Diameter	0.075m
Shell Wall Thickness	0.01m
Number of baffles	2

Procedure

- In **counter-current flow**, the hot and cold-water streams flow in essentially opposing directions through the heat exchanger. Connect the 'COLD RETURN' reinforced hose to the upper socket on the heat exchanger.
- Connect the 'COLD OUT' reinforced hose to the lower socket on the heat exchanger.
- Turn on the 'MAIN SWITCH' and 'HEATER SWITCH'
- Set the hot water temperature controller to 60°C.
- Set the cold water flow rate V_{cold} to 12g/sec
- Set the hot water flow rate V_{hot} to 30g/sec.
- Monitor the stream temperatures and the hot and cold flow rates to ensure these too remain close to the original setting. Then record the following:

$T_1, T_2, T_3, T_4, V_{\text{hot}}$ and V_{cold}

- Adjust the cold-water flow valve so that V_{cold} is approximately 30g/sec. Maintain the Hot water flow rate at approximately 30g/sec (the original setting).
- Allow the conditions to stabilize and repeat the above observations.
- Repeat the same procedure for the following hot and cold flows:

V_{hot} (g/sec)	V_{cold} (g/sec)
15	15
15	30
15	50
30	15
30	30
30	50
50	15
50	30
50	50

- Repeat the all above for **co-current flow**.

Question to be answered in lab. report:

- Sketch the temperatures (T_1, \dots, T_4) for co and counter-current flow as a function of time. (Vs. Time)
- Calculate the thermal and the mean temperature efficiencies for each 1 Minute intervals and draw them on the same graph.
- Calculate the overall heat transfer coefficient and LMTD for each 1 Minute intervals and draw them on the same graph. Discuss your results
- Calculate \dot{Q}_e , \dot{Q}_a for each 1 Minute intervals and draw them on the same graph. Discuss your results
- Which is more efficient, co-current or counter-current flow pattern? Explain.
- Discuss the effect of flow rate variation on your experimental results.

Nomenclature

Cold stream flow rate	V_{cold}	gram s ⁻¹
Hot stream flow rate	V_{hot}	gram s ⁻¹
Hot fluid inlet temperature	T1	°C
Hot fluid outlet temperature	T2	°C
Cold fluid inlet temperature	T3	°C
Cold fluid outlet temperature	T4	°C
Decrease in hot fluid temperature	Δt_{hot}	K
Increase in cold fluid temperature	Δt_{cold}	K
Decrease in hot fluid temperature	dT hot	K
Increase in cold fluid temperature	dT cold	K
Inside diameter of hot tube	d_i	m
Outside diameter of hot tube	d_o	m
Mean diameter	d_{mean}	m
Number of hot tubes	n	-
Effective length of hot tube	L	m
Mean temperature	T_{mean}	°C
Density of stream fluid	ρ	kg litre
Specific Heat of stream fluid	C_p	kJkg ⁻¹ K ⁻¹
Heat flow rate from hot stream	\dot{Q}_e	Watts
Heat flow rate to cold stream	\dot{Q}_a	Watts
Heat loss to surroundings	\dot{Q}_f	Watts
Logarithmic mean temperature difference	LMTD	K
Heat transfer surface area	A	m ²
Overall heat transfer coefficient	U	Wm ⁻² K ⁻¹
Thermal efficiency	η_{Thermal}	%
Temperature efficiency hot stream	η_{hot}	%
Temperature efficiency cold stream	η_{cold}	%
Mean temperature efficiency	η_{mean}	%
Hot tube effective length	L	m
Maximum temperature difference across heat exchanger	dTmax	K
Minimum temperature difference across heat exchanger	dTmin	K

EXTENDED PLATE HEAT EXCHANGER

Objective

- To calculate the overall efficiency at different fluid rates.
- To calculate the mean temperature efficiency.
- To recognize the difference between co-current and counter-current flows.
- To determine the overall heat transfer coefficient using logarithmic mean temperature difference for counter-current and co-current flows

Theory

The overall thermal efficiency:

$$\eta_{\text{Thermal}} = \frac{\dot{Q}_a}{\dot{Q}_e} \times 100(\%)$$

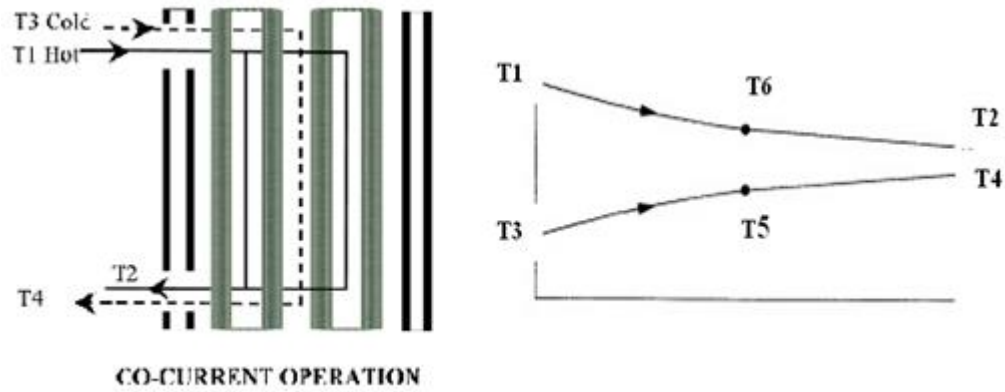
\dot{Q}_a (power absorbed by the cold stream)=

$$\dot{Q}_a = V_{\text{cold}} \rho(\text{cold}) C_{p,\text{cold}} [T_4 - T_3]$$

\dot{Q}_e : (the power emitted by the hot stream)=

$$\dot{Q}_e = V_{\text{Hot}} \rho(\text{hot}) C_{p,\text{hot}} [T_1 - T_2]$$

A useful measure of the heat exchanger performance is the temperature efficiency. The temperature change in each stream (hot and cold) is compared with the maximum temperature difference between the two streams. This could only occur in a perfect heat exchanger of infinite size with no external losses or gains.

Co-Current Flow

The temperature efficiencies of the hot and cold streams for counter-current are given as:

$$\eta_{\text{Hot}} = \frac{T1 - T2}{T1 - T3} \times 100\% \quad \eta_{\text{Cold}} = \frac{T4 - T3}{T1 - T3} \times 100\%$$

The mean temperature efficiency

$$\eta_{\text{Mean}} = \frac{\eta_{\text{Hot}} + \eta_{\text{Cold}}}{2}$$

The logarithmic mean temperature difference LMTD

$$\text{LMTD} = \frac{dT_{\text{max}} - dT_{\text{min}}}{\ln \left(\frac{dT_{\text{max}}}{dT_{\text{min}}} \right)} \quad \text{LMTD} = \frac{(T1 - T3) - (T2 - T4)}{\ln \left(\frac{(T1 - T3)}{(T2 - T4)} \right)}$$

The Overall heat transfer coefficient U

$$U = \frac{\dot{Q}_e}{A \times \text{LMTD}}$$

Where

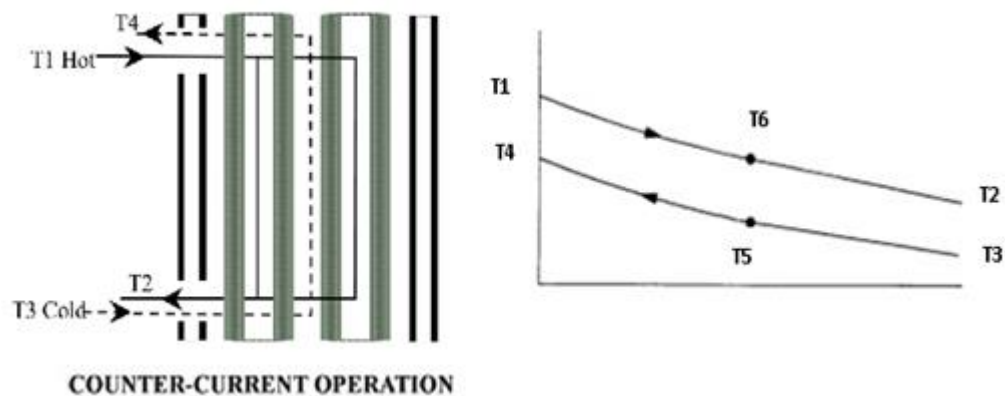
A: Heat transfer area of heat exchanger (m²)

\dot{Q}_e : Heat emitted from hot stream (Watts)

LMTD: Logarithmic mean temperature difference (K)

Counter-Current Flow

For the counter-current flow system, the calculation procedure is similar but the difference in LMTD formula as follow:



$$\text{LMTD} = \frac{(T1 - T4) - (T2 - T3)}{\ln \left(\frac{(T1 - T4)}{(T2 - T3)} \right)}$$

Apparatus

Fig. 7.1 shows the extended plate heat exchanger connected to the service unit.



Fig. 7.1: Extended plate exchanger connected to the service unit.

Table 7.1: Plate heat exchanger specifications

Plate Material	316 Stainless steel
Plate Overall Dimensions	0.072m*0.189m
Total Heat Transfer area (single)	0.048 m ²
Number of Plates	2*4

Procedure

- Connect the cold water circuit to give co-current flow.
- Turn on the 'MAIN SWITCH' and 'HEATER SWITCH'
- Set the hot water temperature controller to 60°C.

- Set the cold water flow rate V_{cold} to 12g/sec

- Set the hot water flow rate V_{hot} to 30g/sec.
- Monitor the stream temperatures and the hot and cold flow rates to ensure these too remain close to the original setting. Then record the following:

T1, T2, T3, T4, T5, T6, V_{hot} and V_{cold}

- Adjust the cold-water flow valve so that V_{cold} is approximately 12g/sec. Maintain the Hot water flow rate at approximately 30g/sec (the original setting).

- Allow the conditions to stabilize and repeat the above observations.

- Repeat the all above for **counter-current flow**.

- Repeat the above for **single plate** connection.
-

Question to be answered in lab. report:

- Sketch the temperatures (T1,..., T6) for co and counter-current flow patterns. Vs. Position .Does it much with the expected pattern (expected temperature profile)?

- Calculate the thermal and the mean temperature efficiencies for each 1 Minute intervals and draw them on the same graph.

- Calculate the overall heat transfer coefficient and LMTD for each 1 Minute intervals and draw them on the same graph. Discuss your results

- Calculate \dot{Q}_e , \dot{Q}_a for each 1 Minute intervals and draw them on the same graph. Discuss your results.

- Which is more efficient, co-current or counter- current flow pattern? Explain.

- Discuss the effect of using extended plate (increasing number of plates) on your experimental results.

Nomenclature

Cold stream flow rate	V_{cold}	gram s ⁻¹
Hot stream flow rate	V_{hot}	gram s ⁻¹
Hot fluid inlet temperature	T1	°C
Hot fluid outlet temperature	T2	°C
Cold fluid inlet temperature	T3	°C
Cold fluid outlet temperature	T4	°C
Decrease in hot fluid temperature	Δt_{hot}	K
Increase in cold fluid temperature	Δt_{cold}	K
Decrease in hot fluid temperature	dT hot	K
Increase in cold fluid temperature	dT cold	K
Inside diameter of hot tube	d_i	m
Outside diameter of hot tube	d_o	m
Mean diameter	d_{mean}	m
Number of hot tubes	n	-
Effective length of hot tube	L	m
Mean temperature	T_{mean}	°C
Density of stream fluid	ρ	kg litre
Specific Heat of stream fluid	C_p	kJkg ⁻¹ K ⁻¹
Heat flow rate from hot stream	\dot{Q}_e	Watts
Heat flow rate to cold stream	\dot{Q}_a	Watts
Heat loss to surroundings	\dot{Q}_f	Watts
Logarithmic mean temperature difference	LMTD	K
Heat transfer surface area	A	m ²
Overall heat transfer coefficient	U	Wm ⁻² K ⁻¹
Thermal efficiency	η_{Thermal}	%
Temperature efficiency hot stream	η_{hot}	%
Temperature efficiency cold stream	η_{cold}	%
Mean temperature efficiency	η_{mean}	%
Hot tube effective length	L	m
Maximum temperature difference across heat exchanger	dTmax	K
Minimum temperature difference across heat exchanger	dTmin	K

Best of luck