A SUMMER OVERSEAS EXPERIENCE AT THE IMPERIAL COLLEGE CO2 CAPTURE PILOT PLANT

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THE CHALLENGE

- While the University is very keen on overseas study and some of the other Engineering departments had in-semester programs,
    - The previous department chair (i.e., me) was not enthralled with the ND template:
        - ND courses taught by ND faculty — or people hired to teach a specific course — taught in the ND building in country X.
- The incoming chair (ejm) found out that Imperial College had just built a new fully-instrumented CO2 capture (into MEA) pilot plant and that they were offering summer session courses utilizing it. This could be paired with a standard CHE undergraduate lab course (they have a very extensive lab).
    - So he signed us up!

THE CHALLENGE

- So we recruited a group of students — who were all just finishing Sophomore year. Ideally, the Pilot Plant course would be a Senior elective and the lab is 2nd semester Junior year for us…..
  - It is obvious now, but at the time we didn't realize they would all be this "young".
- For the first time, I had no contact with the students or any aspect of the planned courses before going … One of our teaching faculty was going with them.
- However, in the first morning orientation session, within 15 minutes, I knew that we needed to have a plan for how to prepare the students for <u>next</u> year, to be able to maximize their learning in the Pilot Plant and to be able to run experiments and write lab reports.

MORE CHALLENGE

- Students "claim" to spend ~10+ hours per week outside of class for the undergraduate laboratory course taught on campus
- This is above a "safe" number for a lecture course to successfully translate to the 6 week, "distracting" location
  - e.g. "Mechanics" for Sophomore ME's didn't work at all.
- So we needed to devise a schedule of lab sessions, work periods and due dates to make the course work.
  - We also needed "on-call" faculty consulting to increase the efficiency of student effort.

IMPERIAL COLLEGE IS IN A REALLY NICE LOCATION!

THE STRATEGY

- Provide the maximal alignment between laboratory experiments and fundamental topics that govern the Pilot Plant processes.

- Conduct a semester long, one hour per week, series of lectures on these fundamental topics, but with continual threading of the pilot plant operations as examples.

  - We are limited in the amount of outside work — or its intensity, because students are taking *thermodynamics*, "*num-stats*", *Orgo II* and many also *linear algebra/differential equations*.

- We start each class with the CO2-MEA process diagram, review various operational aspects and then focus on a specific operation.

FUNDAMENTAL TOPICS: *UNIT OPERATIONS*

- Thermodynamics (energy/mass conservation)
  - We can trust the in-semester course to cover this.
- Fluid flow
- Heat transfer
- Mass transfer/gas absorption
- Process control

PROCESS DIAGRAM

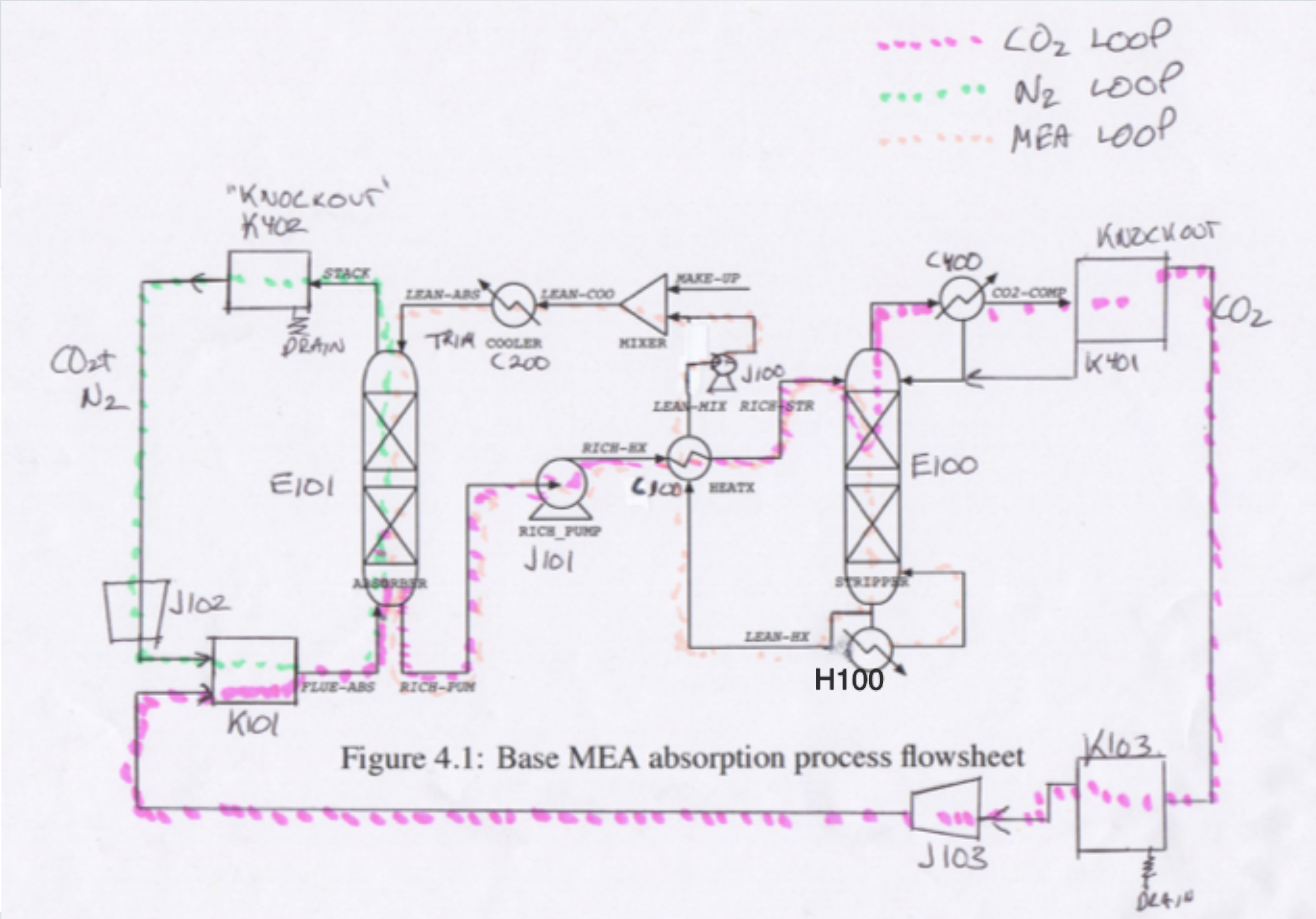

Figure 4.1: Base MEA absorption process flowsheet

IMPERIAL FLOWSHEET

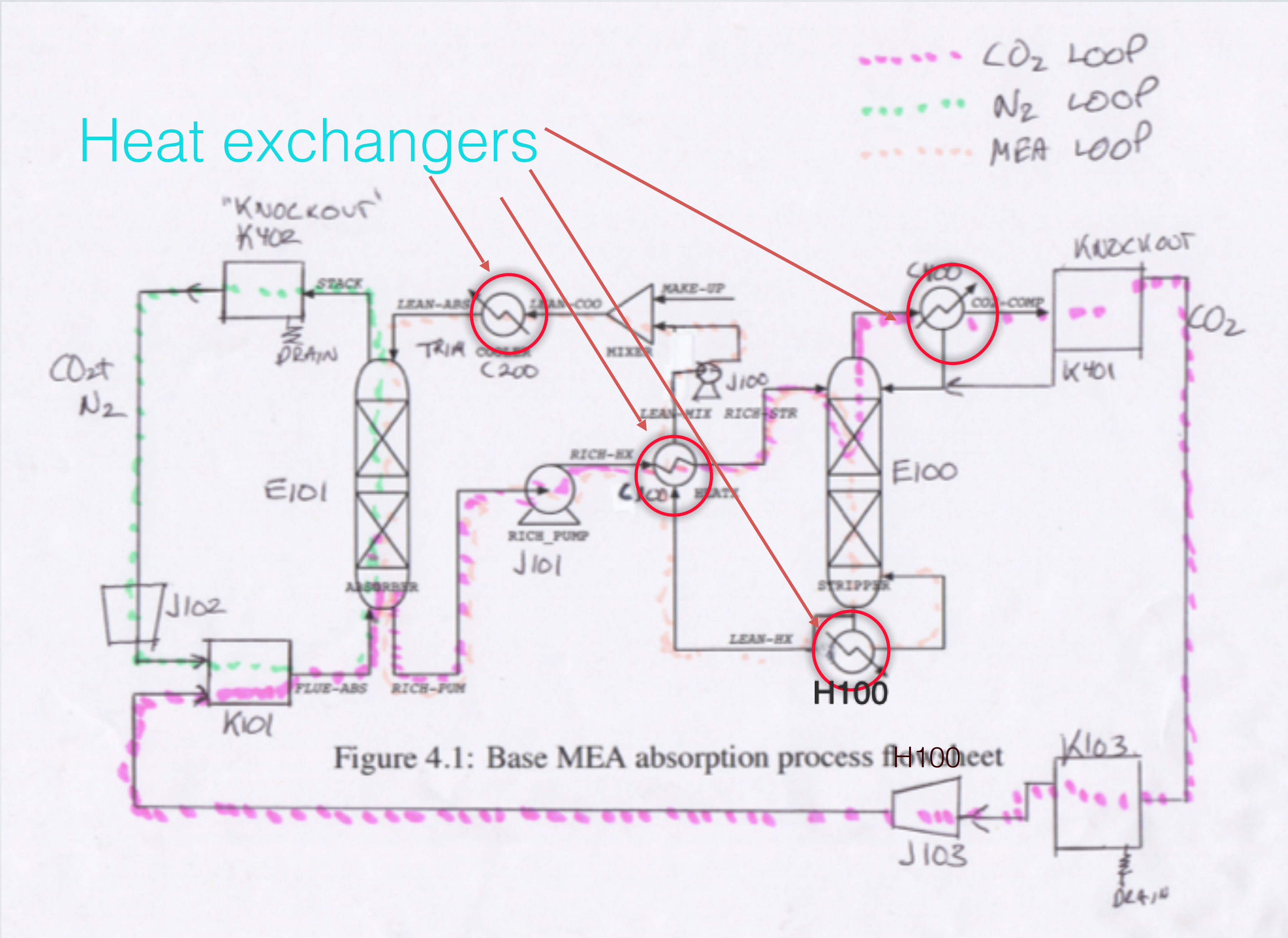

Figure 4.1: Base MEA absorption process flowsheet

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EXAMPLE TOPIC: HEAT EXCHANGE IN MEA PROCESS

- Students need to calculate heat loads on the various heat exchangers.
    - Check efficiencies and *effectiveness*
        - One of the plate heat exchangers would be better with more plates— the other has plenty
- They also get overall heat transfer coefficients and compare to predictions from correlations.

IMPERIAL HEAT EXCHANGERS

C200

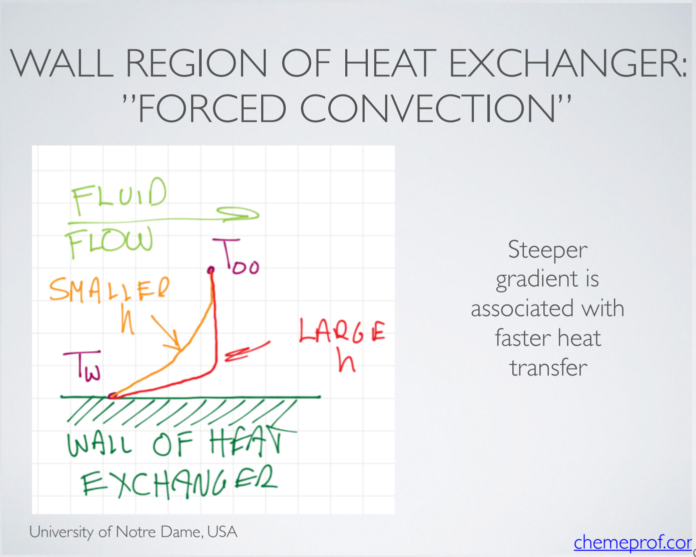
H100

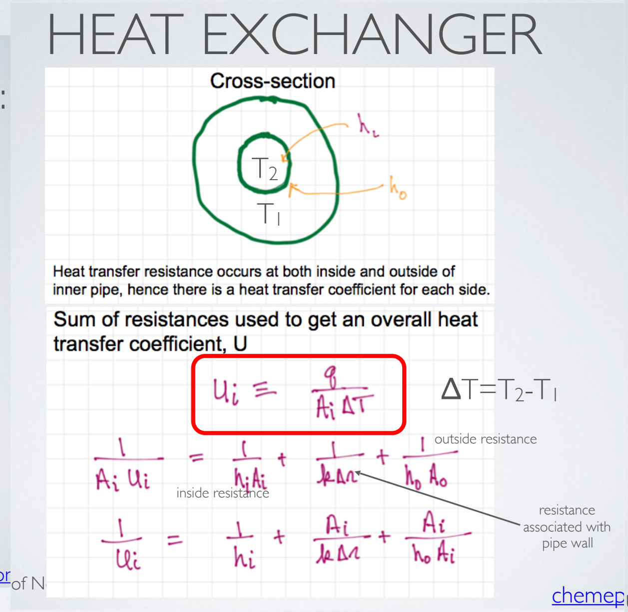
HEAT TRANSFER LAB EXPERIMENT

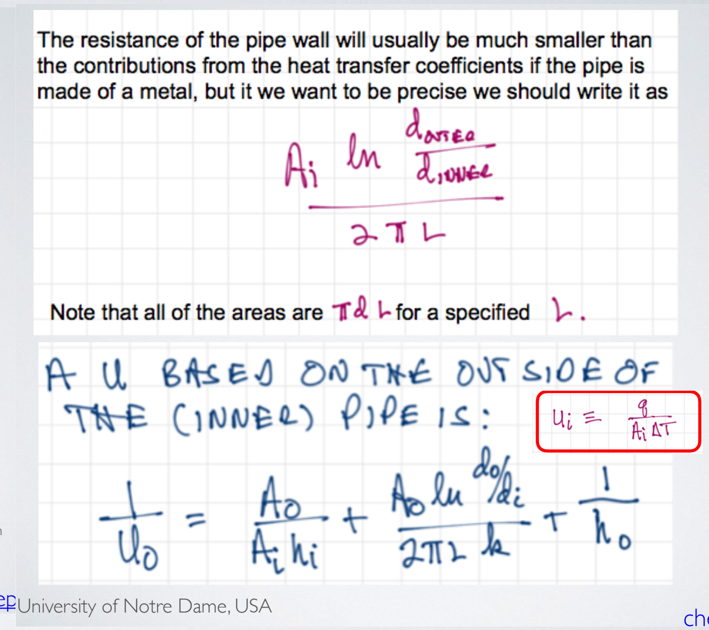
LAB HEAT TRANSFER EXPERIMENT

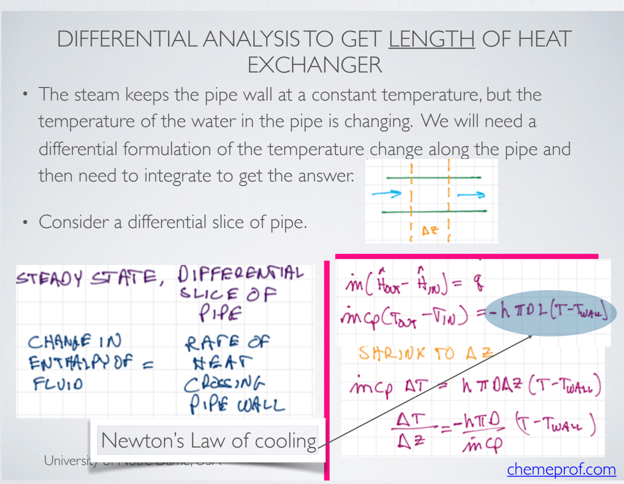
- Efficiencies, and effectiveness and heat transfer coefficients and comparisons for shell and tube, plate, double-pipe and air-water exchangers.
  - The log-mean temperature driving force is discussed in the lectures
    - The logarithmic driving force also arises in the gas absorption experiment.
  - Cocurrent versus Countercurrrent for the double-pipe heat exchanger
  - One data set to try to match with standard Nusselt number correlations.

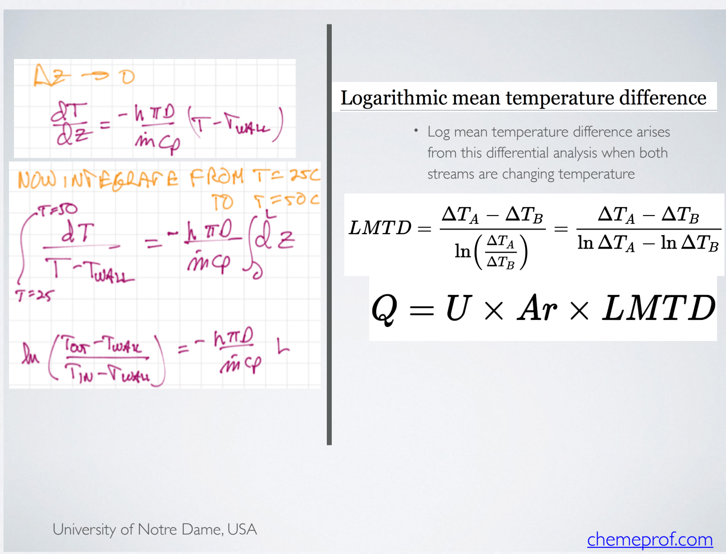
SOME EXAMPLE LECTURE SLIDES

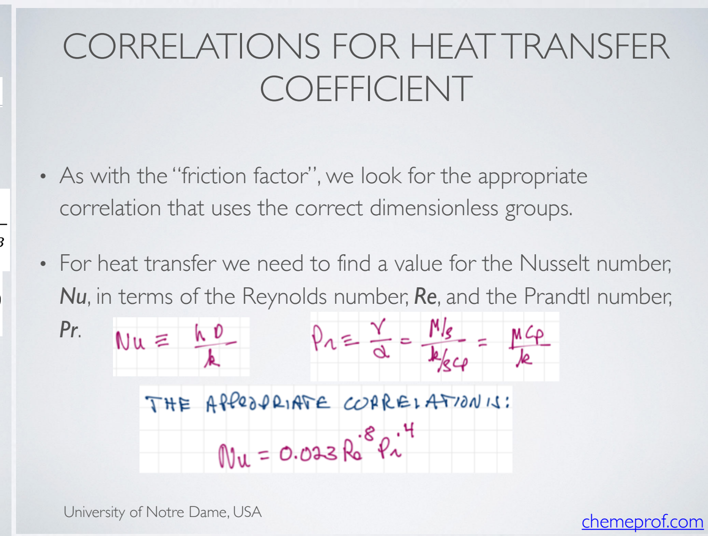












Imperial Flowsheet

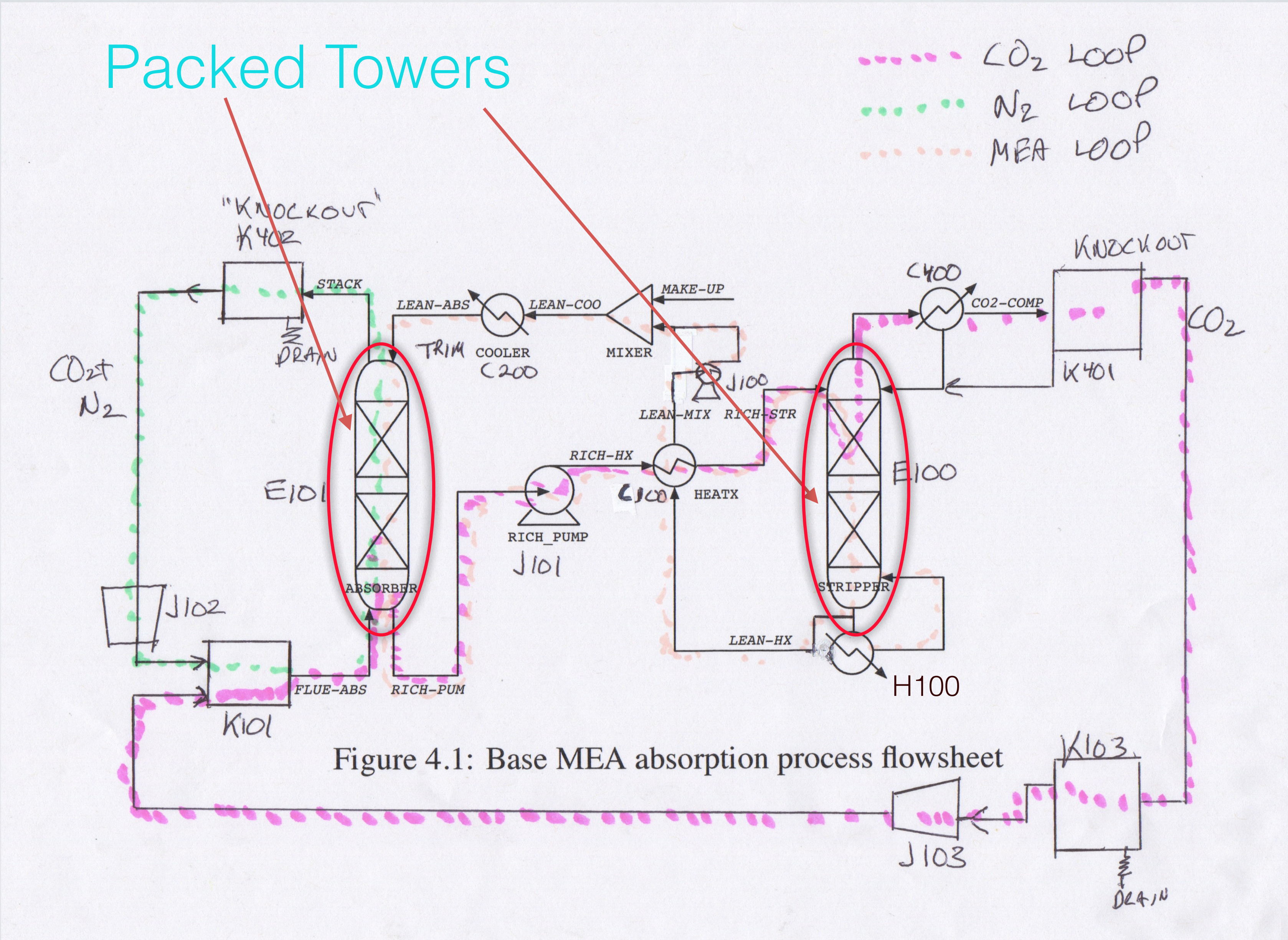


Figure 4.1: Base MEA absorption process flowsheet

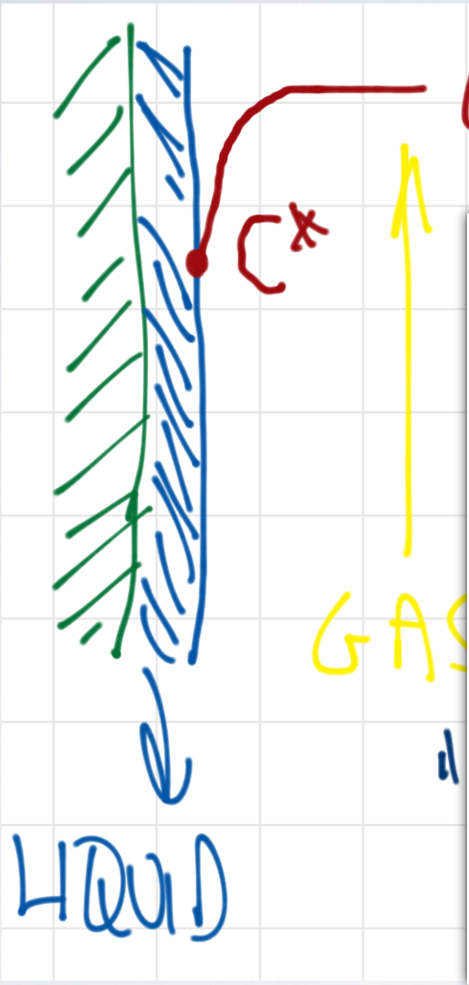
EXAMPLE TOPIC: MASS TRANSFER IN MEA PROCESS

- The gas composition can be sampled in the absorber at 6 locations.

- Students need to calculate the local mass transfer coefficient at each location.

    - They compare results to “claims” by the packing manufacturer (which are in height of transfer unit).

MASS TRANSFER RATE EQUATION



$$N_A = k\,A\left(C_{gas} - C^*\right)$$

k=> mass transfer coefficient

A=> area of contact

N_A=> moles across interface/time

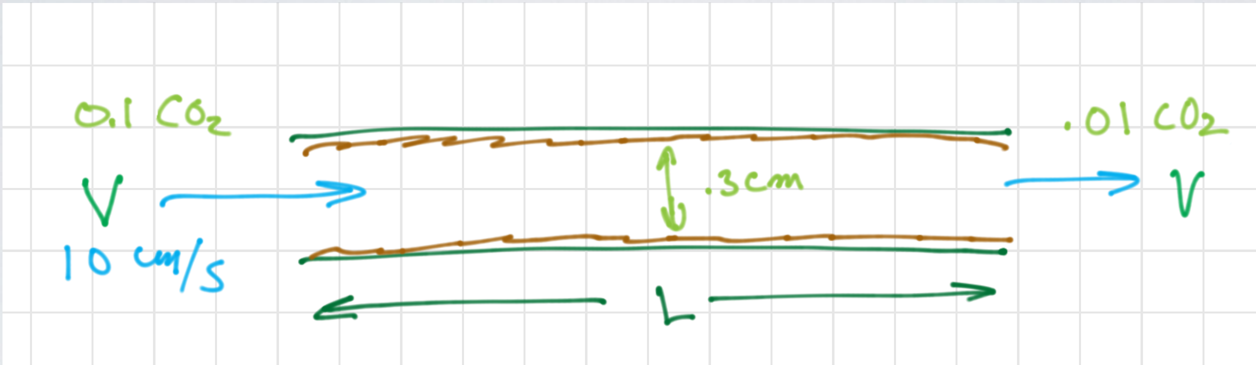
C=> molar concentration of CO_2 in gas

Flux = rate coefficient *(linear driving force)

SIMPLEST DIFFERENTIAL MASS TRANSFER PROBLEM

- A Gas mixture that contains CO2 is flowing in a circular tube. (Could do constant wall T for heat transfer.)
- The wall is made of a CO2 reactive absorbent.
- Thus, the CO2 will decrease along the way.
- We need to determine the length of the tube to allow the CO2 to reach the prescribed final value.

SCHEMATIC

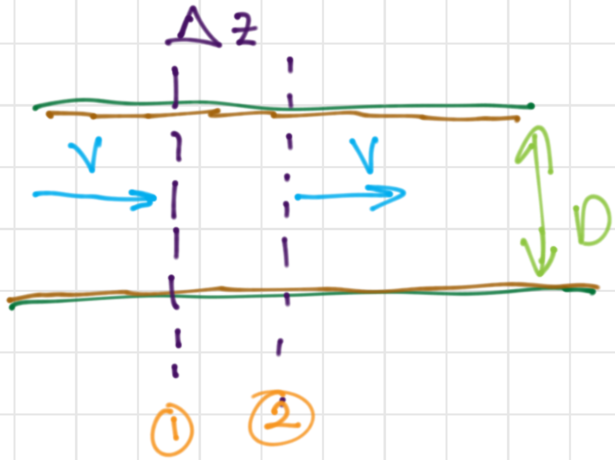


- "monolith" geometry

- CO2 concentration at wall is kept at 0

- For a given V, what is value of L required?

- To answer this, we need to formulate this as a differential problem.



"(MOLES)" MASS BALANCE ON A DIFFERENTIAL SLICE OF COLUMN

MOLES OF A CROSSING ① PER TIME − MOLES OF A CROSSING ② PER TIME = MOLES OF A THAT ADSORB PER TIME

WE NEED: $\frac{n}{V} = \frac{\text{MOLES}}{\text{VOLUME}}$ (IDEAL GAS)

(VOLUMETRIC FLOW × $\frac{\text{MOLES}}{\text{VOLUME}}$ × MOLE FRACTION)

v (AREA) $\quad \frac{n}{V} \quad$ "y"

RECALL:

$$\dot{Q} = hA(T_{WALL} - T_{FLUID})$$

MOLES OF A THAT ADSORB PER TIME

$$\dot{N}_A A_{WALL} = k \frac{n}{V}(y - y^*)\, \pi D \Delta z$$

SO OUR MOLE BALANCE ON DIFFERENTIAL SLICE:

$$\frac{\pi D^2}{4} V \frac{n}{V} y\Big|_1 - \frac{\pi D^2}{4} V \frac{n}{V} y\Big|_2$$

$$= k \frac{n}{V}(y - y^*)\, \pi D \Delta z$$

TAKE LIMIT AS $\Delta z \rightarrow 0$

$$\frac{\pi D^2}{4} V \frac{n}{V} dy = k \frac{n}{V}(y - y^*)\, \pi D\, dz$$

SIMPLIFY: $\dfrac{dy}{y - y^*} = \dfrac{4k}{VD} dz$

FOR OUR PROBLEM

$y^* = 0$

WE CAN EASILY INTEGRATE

$$\int_{y_{in}}^{y_{out}} \frac{dy}{y} = \frac{4k}{VD}\int_0^L dz$$

$$\ln\left(\frac{y_{out}}{y_{in}}\right) = \frac{4k}{VD}(-L)$$

Length of tube needed: $L = \frac{VD}{4k}\ln\left(\frac{y_{in}}{y_{out}}\right)$

For a packed bed, height of packing: $Z = -\left(\frac{G/A_T}{ka}\right)\ln\left(\frac{y_1}{y_2}\right)$

Exactly analogous formulae

Height of transfer unit

Number of transfer units

PREP-COURSE LAB EXPERIENCE

- We have students run one thermodynamics experiment (Rankine or Vapor Compression cycle) in our lab at some point in the spring semester
  - This facilitates the schedule at Imperial College.
  - We can "check them out" on the basics of experimental laboratory safety and performance.
  - With these results, they are free to do as much work (data analysis and writing) ahead of time….
- New this year: We will also show them the basic workings of the heat transfer and gas absorber experiments (with them free to video the events.)

SCHEDULE AND STUDENT WORK

- We have one written report due at 5 PM on the 2nd, 3rd and 4th Wednesdays
- The Pilot Plant reports are due on 5th Thursday.
- The oral presentations are on the 6th Wednesday.
- Quality of written reports is essentially as good as those produced in Junior Lab
- The oral reports are better!

WRITTEN REPORTS

- Full length (i.e., 20 pages of text and 5-7 figures + appendices
- For the Introduction, students must find some connection between the technology of interest and the location of Great Britain or Europe.
- Students are supported by "Program Assistants" (just- graduated seniors) who (are supposed to) know one of the 4 subject areas in extra depth, but all who know well how to divide the work to construct a good report.
- Faculty could be on-site or available by video-con (*Zoom* is great if you are stuck with Adobe!!)
- From both (mjm observations) and focus groups (interviewed by Kerry Meyers, one of our teaching faculty), we think that the highly focused effort over about ~60 hours (Sunday night to Wed afternoon), with support available, seems to be the "trick".

(MJM POINTS OF EMPHASIS)

- Understand the fundamentals to at least a reasonable degree
- Get the numbers correct!
- Learn to write an informative, clear Abstract
- Discuss the results with coherent, logical arguments supported by the underlying theory.

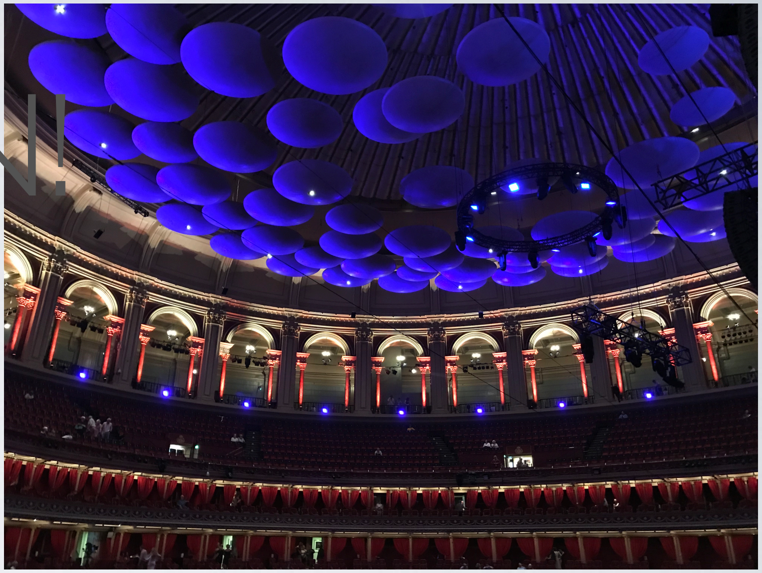
"CULTURAL ASPECTS"

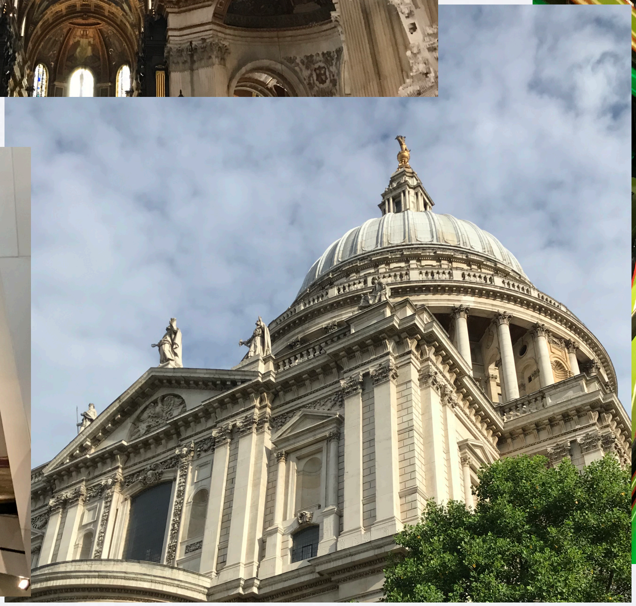
- Students have 3 of the 5 Fridays (+ all weekends) off for travel
  - They go all over Europe and around GB
- There are three fantastic Museums next to the Imperial Campus (no admission charge) that can visited for short time periods — say during lunch.
  - We have mjm (favorites) slides for every lecture!
- We have been doing 2 "popular"musicals and *The Mousetrap*, usually with a dinner together before, and couple of other evening social events together.
  - A surprising fraction of students have never seen "*Broadway level*" performances before.
  - This is primed in the spring lectures as well!
- Final Day around town to St. Paul's, Tower Bridge, Borough Market, Tower of London…

SUMMARY

- We have been successful at "teaching" our "Junior" laboratory course and a Unit Operations course, that uses an <u>exquisitely unique</u> pilot plant at Imperial College, to students who are 1 to 1.5 years too "young"
- This has been facilitated by ~complete alignment of the lab and pilot plant onto the unit operations topics of fluid flow, heat and mass transfer and process control.
- Also, there is a high level of faculty and TA support and the students are completely focused on the task at hand for critical time-periods before reports are due.
  - They also benefit from living "together".
- If there is any interest, a complete set of slides, with practice problems for four, 3-hour sessions done in 2017 for students from Dalian University is available.

LONDON!





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