EngrD 2190 – Lecture 40

Course Summary and Review – Part 2
Graphical Modeling
and Dimensional Analysis/Dynamic Scaling

Final Exam

Friday, December 12, 7:00 - 9:30 p.m., 128 and 245 Olin Hall.

- Comprehensive - covers chapters 2 through 5, with emphasis on chapter 5: dimensional analysis and dynamic scaling.
- Open notes and open exercise solutions.
- Bring a calculator and a ruler/straightedge.
- Graphing calculators are okay.

December 2025

Sun	Mon	Tue	Wed	Thu	Fri	Sat
	1	2	3	4	5 We are here	6
Le… D… C…	TMD Office Hours Noon – 2 p.m.	9	10 TA Office Hours 2-4 p.m.	11 TA Office Hours 2-4 p.m.	12 EngrD 2190 7 p.m.	13
14	15 Math 2930 2 p.m.	16 Phys 2213 9 a.m.	17 Math 2940 9 a.m.	18	19 Chem 3890 7 p.m.	20
21	22	23	24	25	26	27
28	29	30	31			

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8 Dec, 2025

04:00 PM - 08:00 PM

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Atkinson Hall

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Lecture Monday 12/8 is cancelled

Applications for Affiliation are due Saturday December 20

Cornell Engineering

Application For Major Affiliation

Student Completes This Section

Last Name: ____________ First Name: ____________ Expected Degree Date: ____________

NetID: ____________ ID# (7-digit): ____________ Cell Phone: ____________

Major: ____

(to which you are applying)

Concentration/Interest within major: ____

(Optional, and if known)

Current Advisor Name & Dept.: ____

Student Signature: ____________________________ Date: ____________

After completing the top section, please submit to the Undergraduate Coordinator's office of the appropriate Major listed below:

Biological Engineering (207 Riley-Robb Hall)
Biomedical Engineering (121 Weill Hall)*
Chemical Engineering (158B Olin Hall)
Civil Engineering (221 Hollister Hall)
Computer Science (110 Gates Hall)*
Earth and Atmospheric Sciences (2124 Snee Hall)
Electrical and Computer Engineering (222 Phillips Hall)
Environmental Engineering (221 Hollister Hall)
Engineering Physics (261 Clark Hall)
Information Science, System, and Tech (110H Gates Hall)*
Materials Science and Engineering (210A Bard Hall)
Mechanical Engineering (125 Upson Hall)
Operations Research and Engineering (203 Rhodes Hall)

*An additional application beyond this form is needed. Please see appropriate major for more information.

Undergraduate Coordinator Completes This Section

Date Received: ____________________________

Affiliation Approved ☐ Affiliation Conditional ☐ Affiliation Denied ☐

Conditions/Comments: ____

____

____

Update Class/Term *(if needed)*: New Class (2,3,4): ____________ New Term (1,2): ____________

New Advisor: ____________ EMPL ID: ____________ E-mail: ____________

Authorizing Signature: ____________________________ Date: ____________

Affiliation

Typically ~65% of freshmen in EngrI 1120 choose to affiliate with ChemE.

~65% of those who earn an A in EngrI 1120 choose to affiliate with ChemE.

~65% of those who earn a B in EngrI 1120 choose to affiliate with ChemE.

~65% of those who earn a C in EngrI 1120 choose to affiliate with ChemE.

Choose your major.

Don't let a major choose you.

From the advice to sophomores in Fall 2026:

It will be tempting to just do the homework to completion, just "getting it done." I PROMISE you will forever grateful to yourself If you do each problem with the goal of *understanding*, not completion. This class is about the *journey*, not the destination.

Do as many practice problems as possible when preparing for an exam. Even though this class may have open-note exams, you don't have much time to go through your notes during the exam. Sufficient practice is much more helpful for finishing the exam on time.

Make a short study guide to use on the open-note exams and practice the problems *WITH YOUR NOTES*. It helps a lot.

EngrD 2190 – Chemical Process Design & Analysis

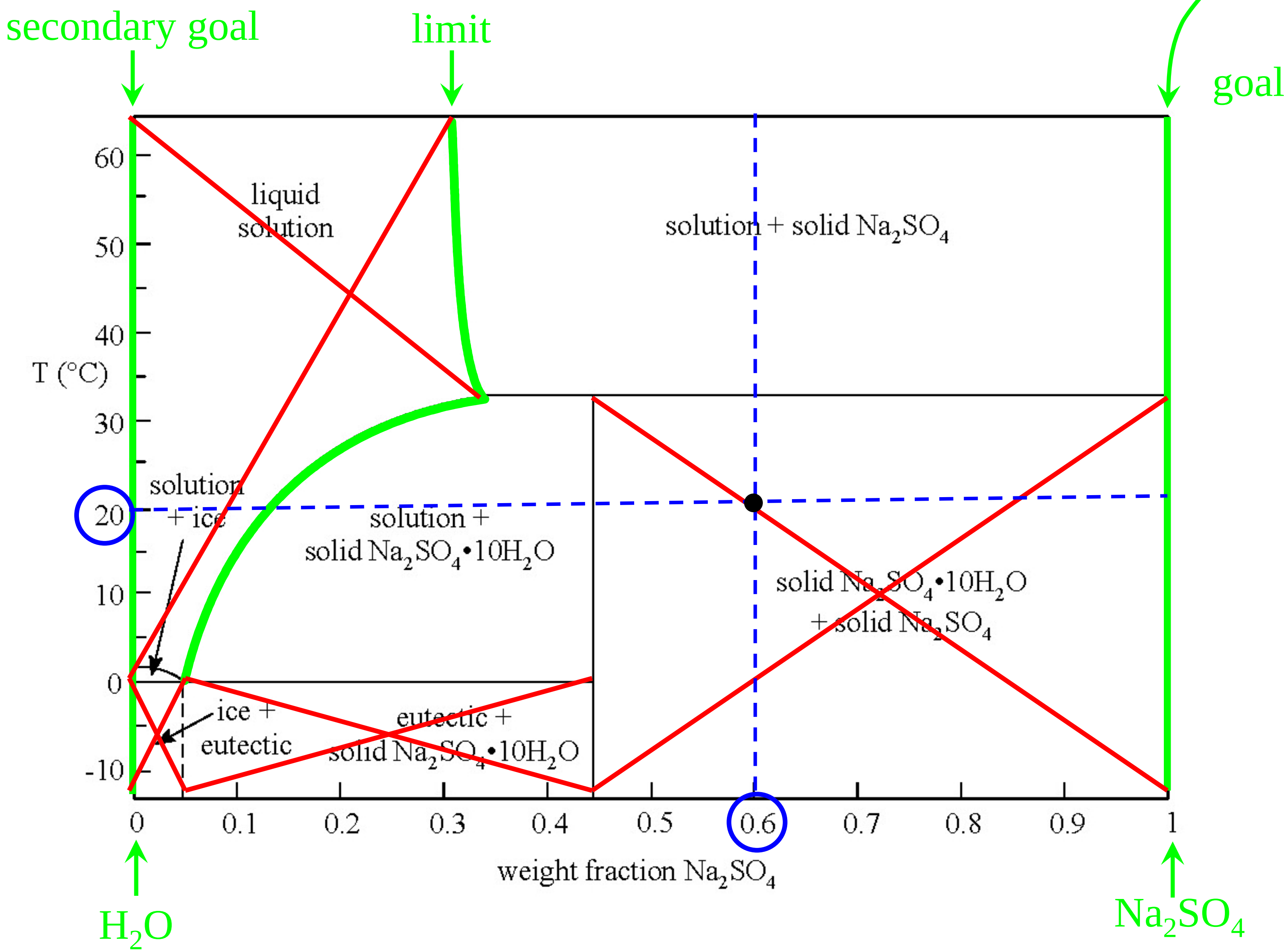
Course Summary and Review – Part 2

Graphical Modeling
Dimensional Analysis & Dynamic Scaling

Two graphical methods:
Tie lines and the lever rule
Operating lines

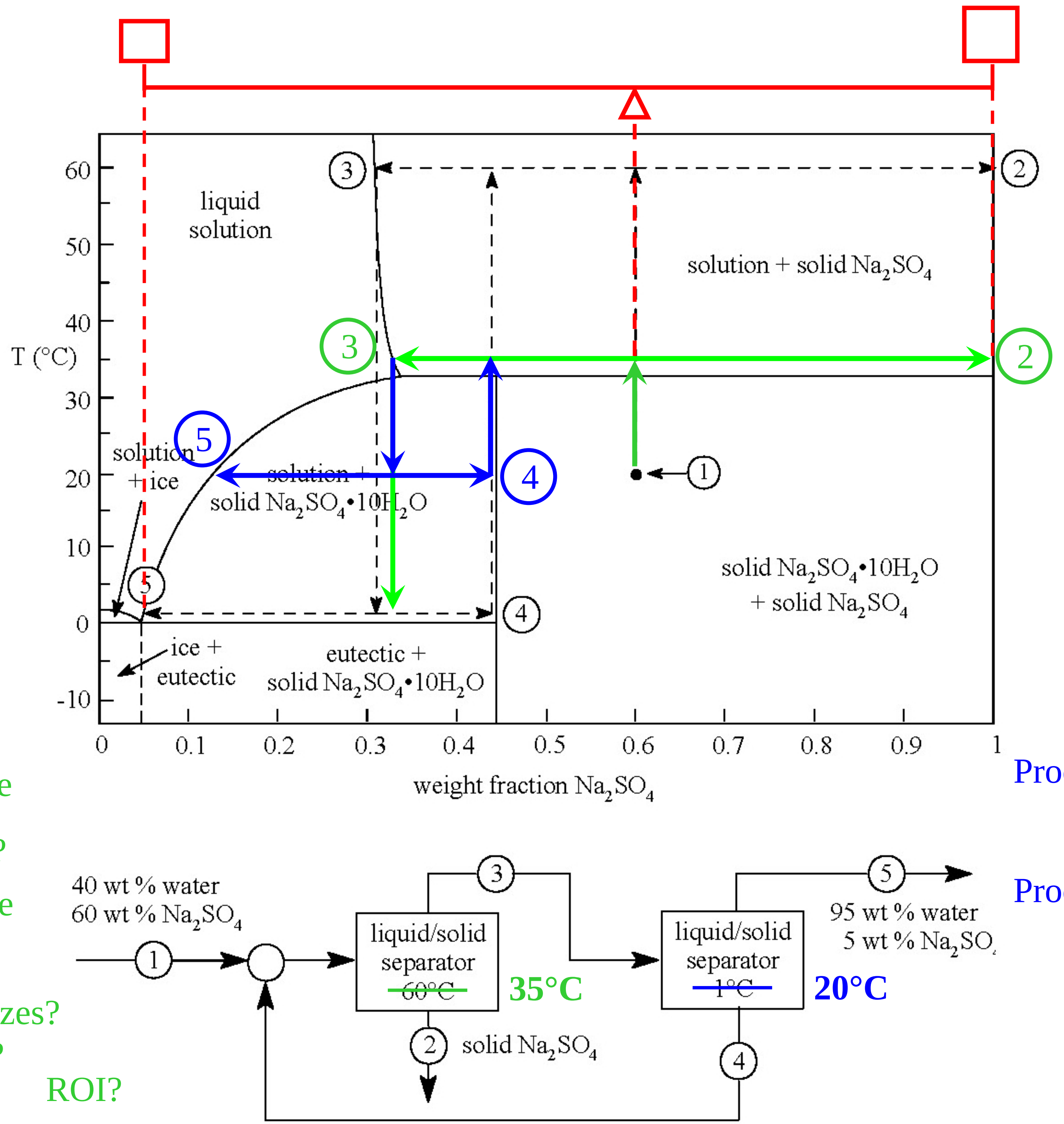
Exercise 4.94

Design a process to produce solid Na_2SO_4 from a mixture of 60 wt% Na_2SO_4 and 40 wt% water at 20°C.



Exercise 4.94

Solution



Product purity?

No change

Product flowrate?

No change

Capital costs?

Equipment sizes?

Operating costs?

Heating?

ROI?

Product purity?

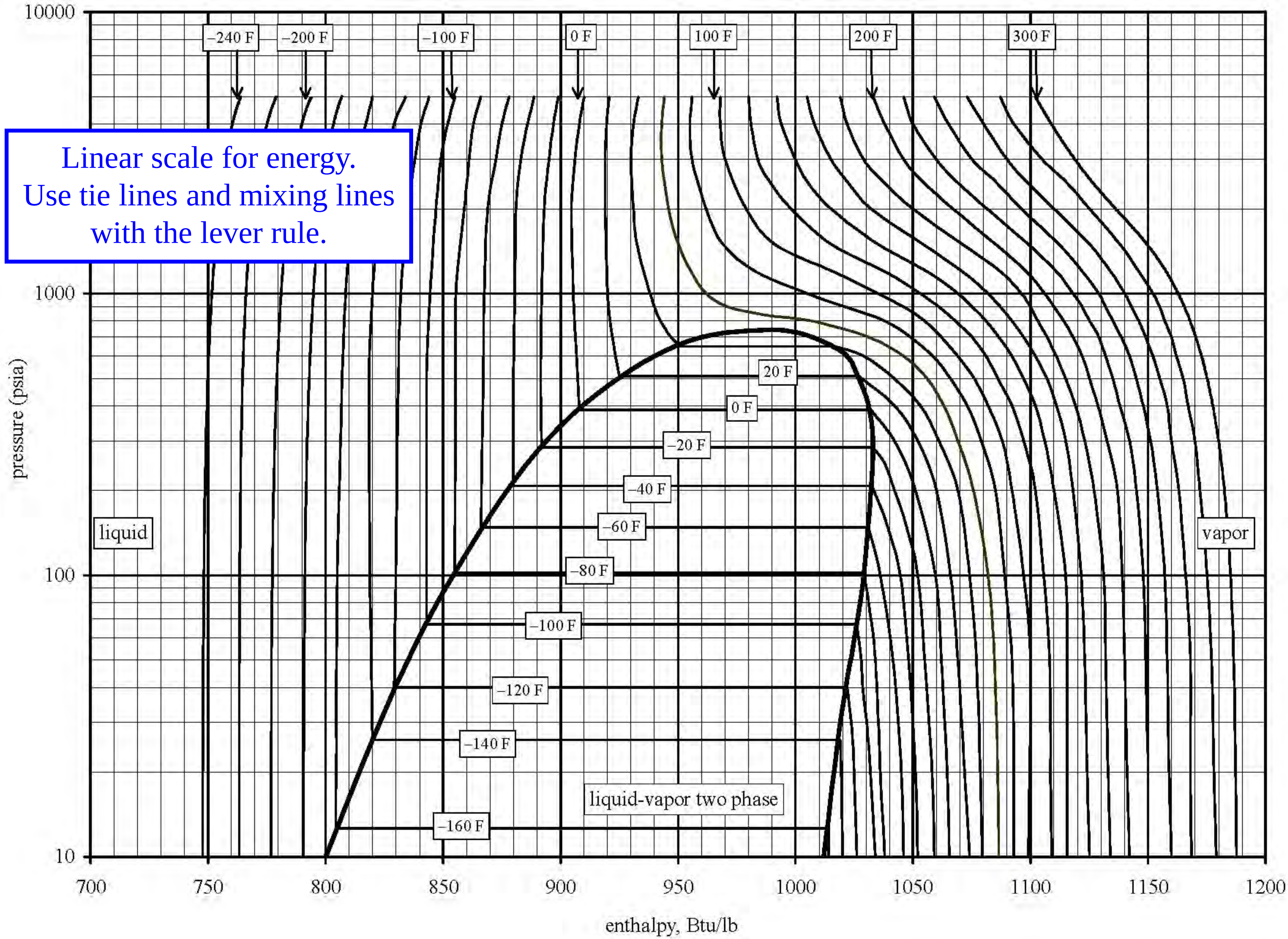
No change

Product flowrate?

Decreases.

ROI?

pressure-enthalpy diagram for ethylene



4.88 In section 4.1.2 we used a linear energy scale for energy balances on a pure substance, such as H_2O. A second dimension may be added, for example, for energy balances on systems in which the pressure changes. Use the pressure-enthalpy diagram for ethylene to answer the following questions.

(A) What is the heat of vaporization of ethylene at 300 psia (in Btu/lb)?

(B) What is the heat of vaporization of ethylene at −120°F (in Btu/lb)?

(C) What is the boiling point (in °F) at 500 psia?

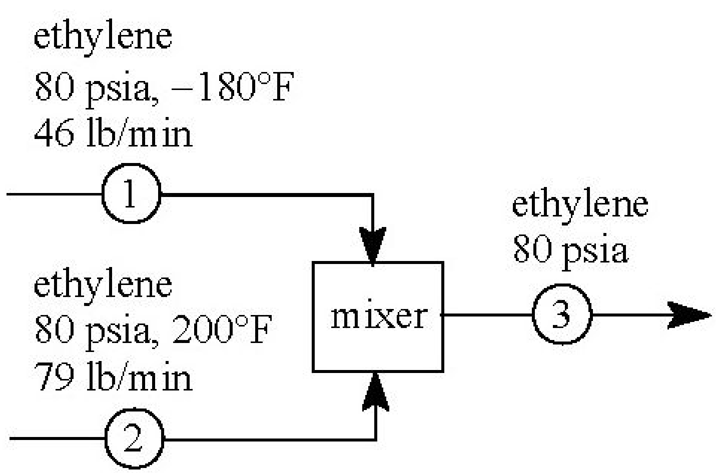
(D) What is the critical pressure (in psia) of ethylene?

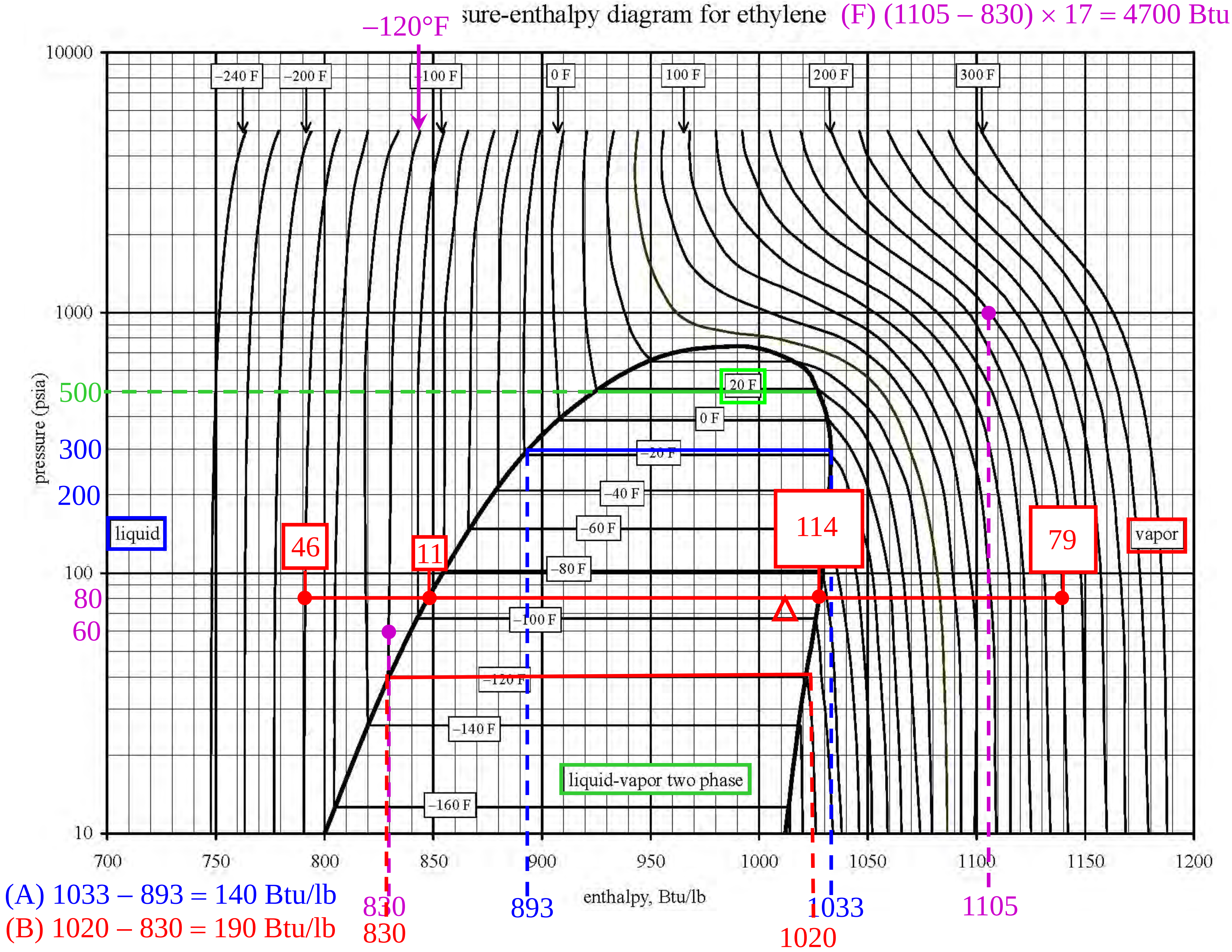
(E) What is the critical temperature (in °F) of ethylene?

(F) What is the enthalpy change (in Btu) for 17 lb of ethylene initially at 60 psia and −120°F compressed to 1000 psia and heated to 200°F?

(G) What is the approximate heat capacity of ethylene at 200 psia and −120°F (in Btu/(lb·°F))? Hint: to estimate the energy needed to increase the temperature of 1 lb by 1 °F, calculate the energy needed to increase the temperature of 1 lb by 20 °F and then divide by 20.

(H) Calculate the temperature and composition (liquid and vapor wt fractions) of stream 3 below.

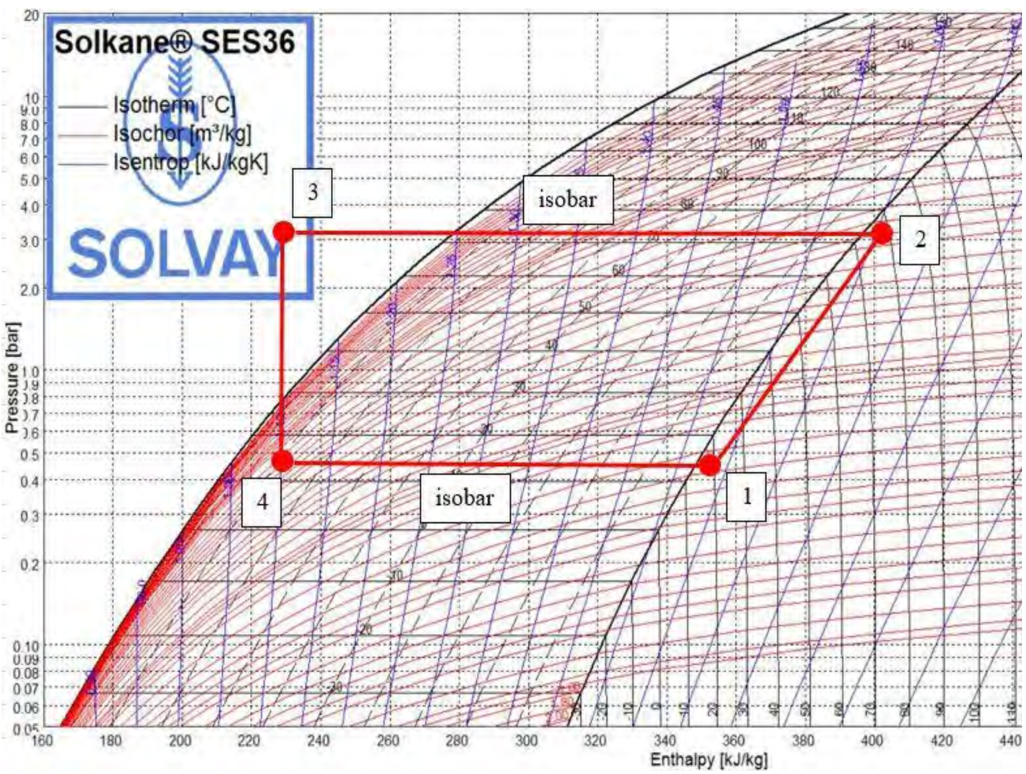


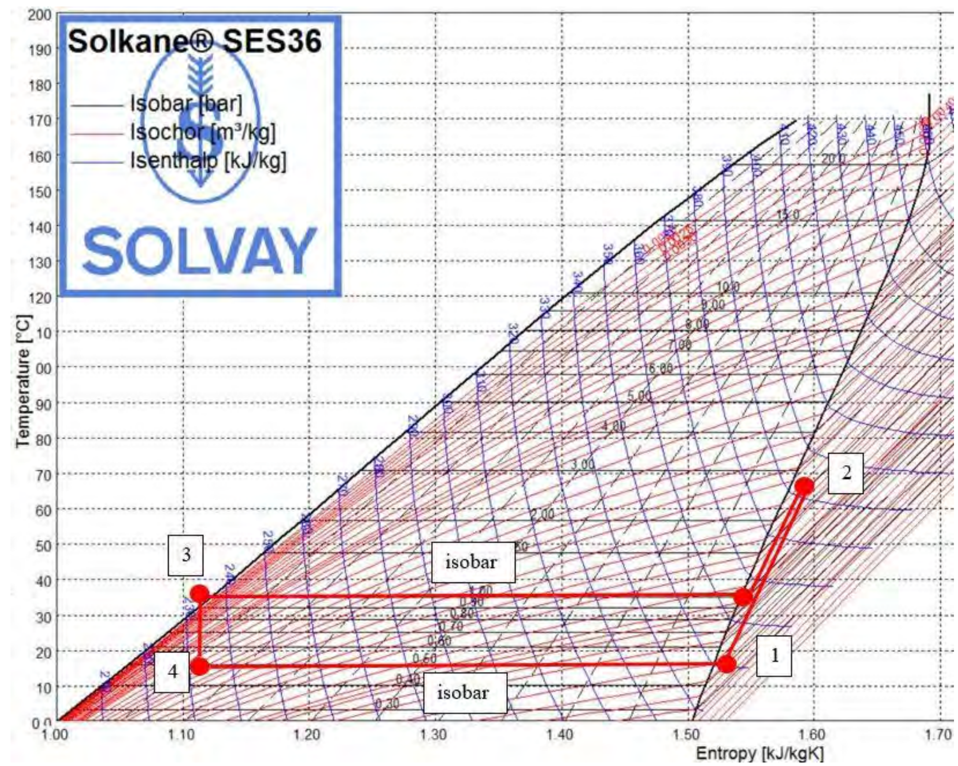


−120°F
sure-enthalpy diagram for ethylene
(F) (1105 − 830) × 17 = 4700 Btu
10000
1000
100
10
500
300
200
80
60
pressure (psia)
−240 F
−200 F
−100 F
0 F
100 F
200 F
300 F
20 F
0 F
−20 F
−40 F
−60 F
−80 F
−100 F
−120 F
−140 F
−160 F
liquid
vapor
liquid-vapor two phase
46
11
114
79
700
750
800
850
900
950
1000
1050
1100
1150
1200
enthalpy, Btu/lb
830
830
893
1033
1020
1105
(A) 1033 − 893 = 140 Btu/lb
(B) 1020 − 830 = 190 Btu/lb

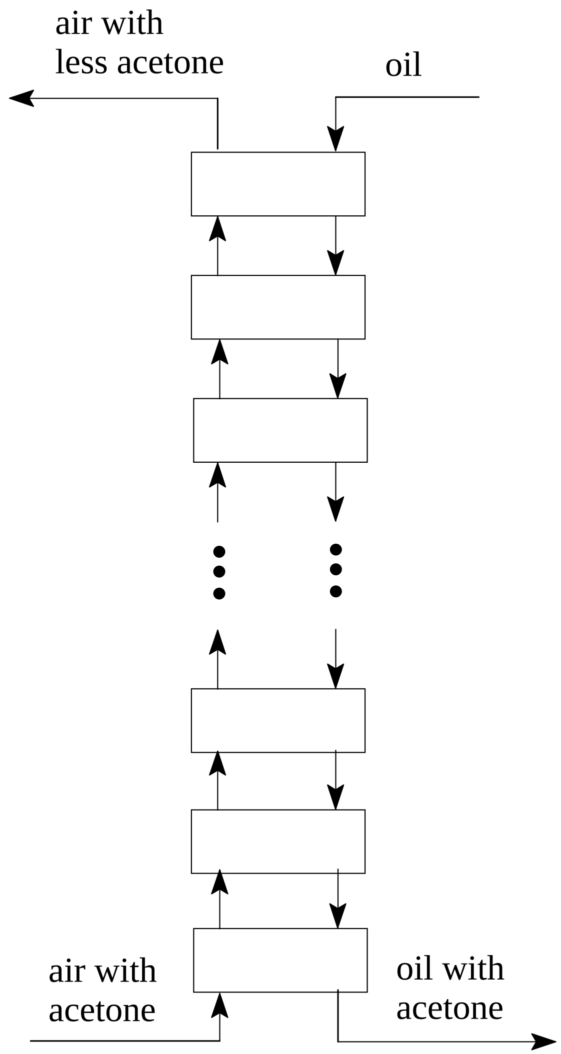
Refrigeration Cycle

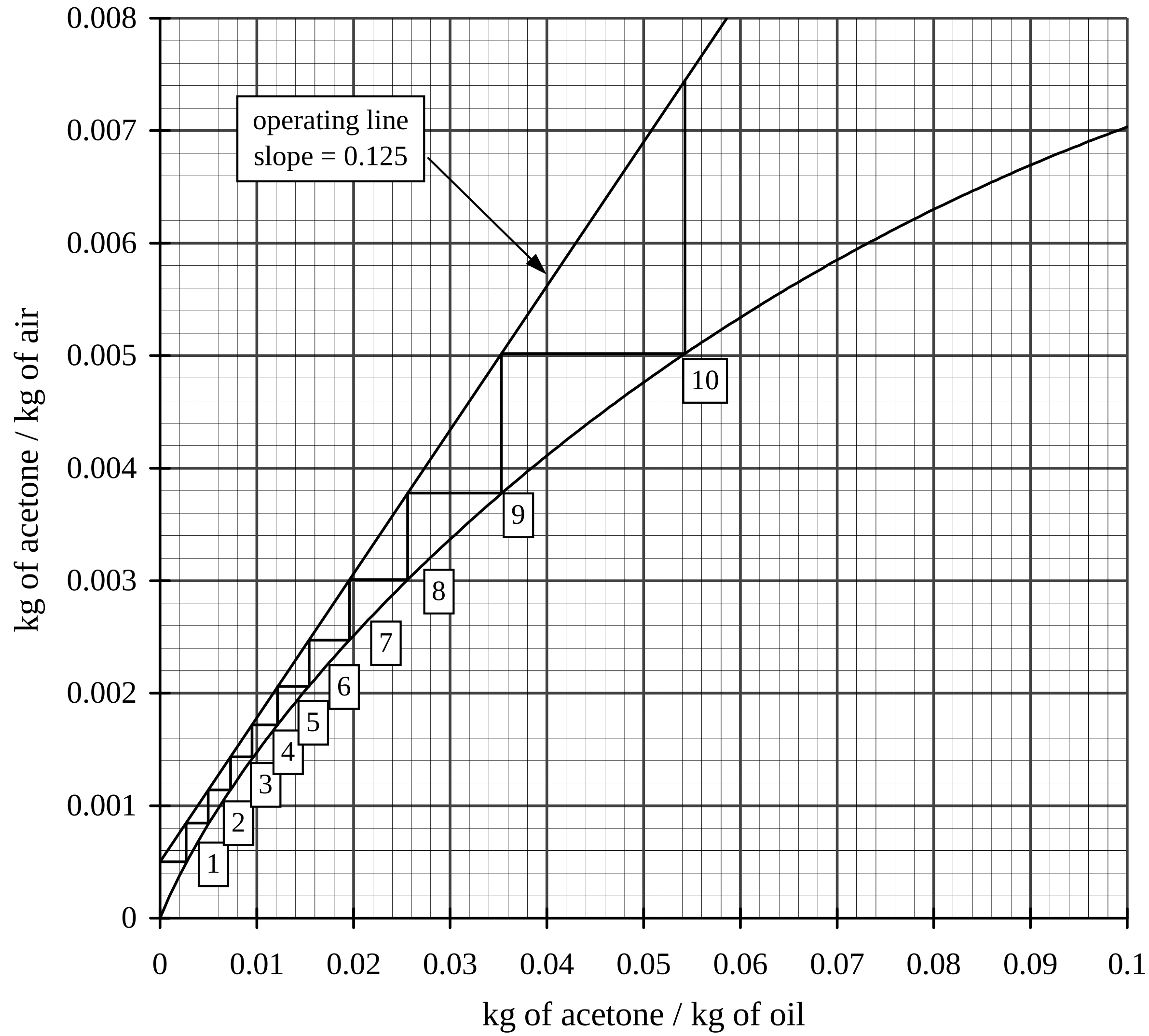
Shelley Yanosky & Olivia Young



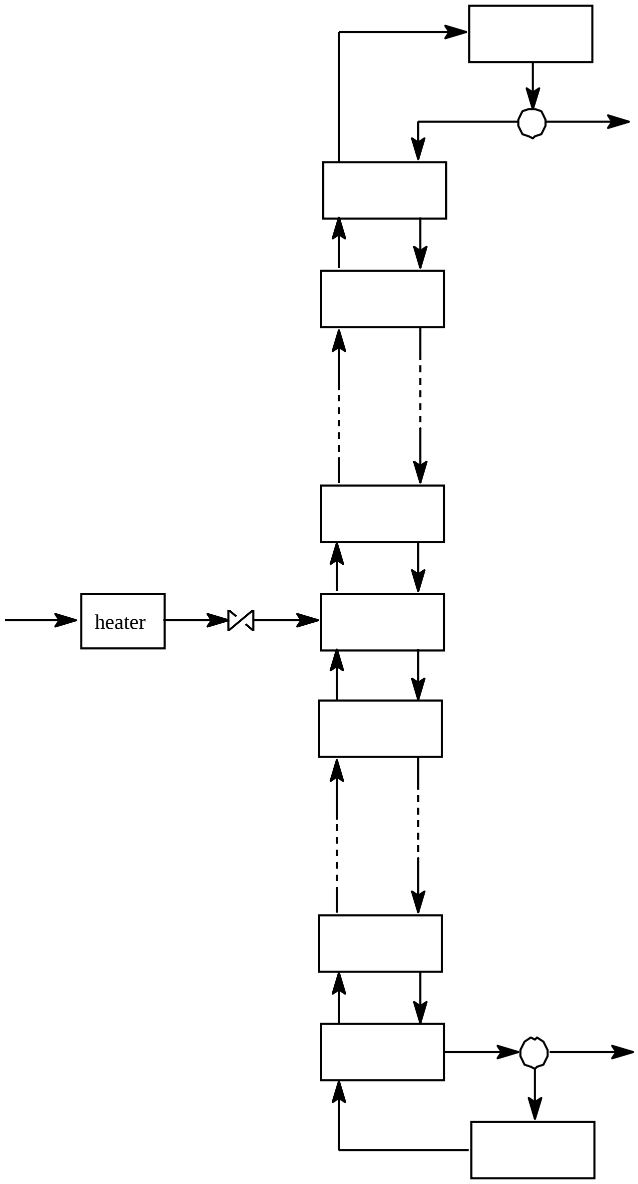


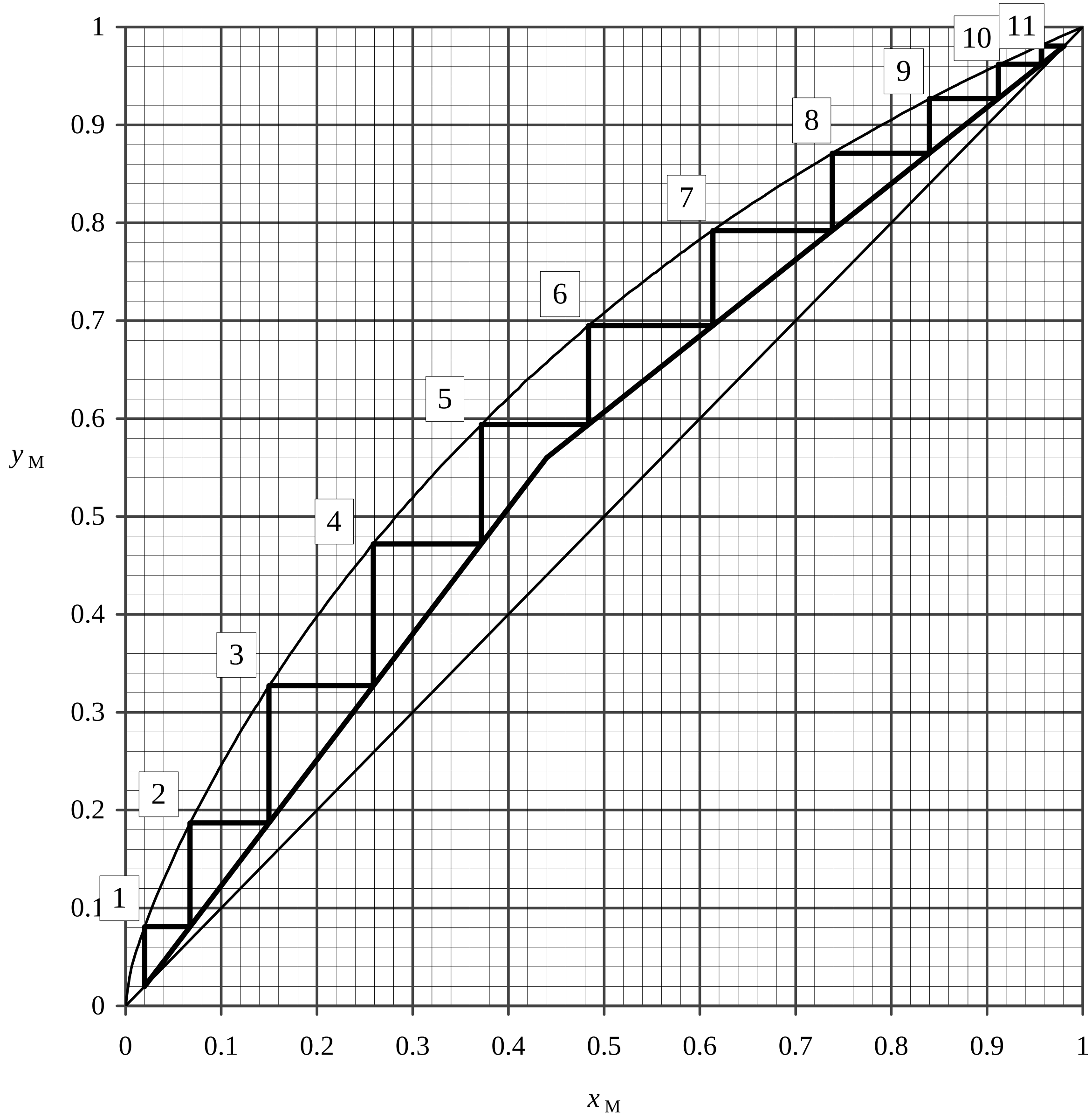
Multistage Countercurrent Absorbers



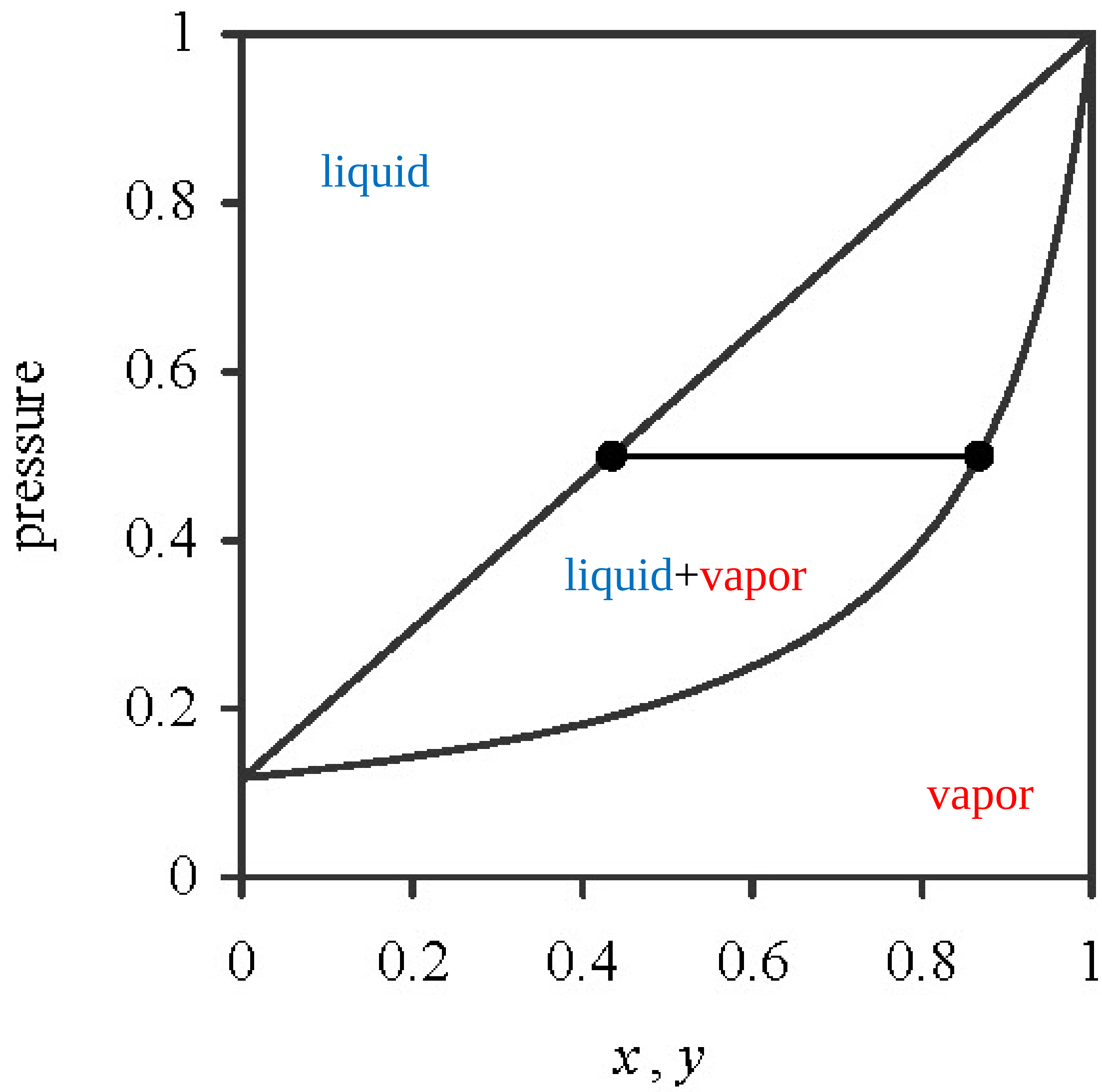


Multistage Countercurrent Distillation



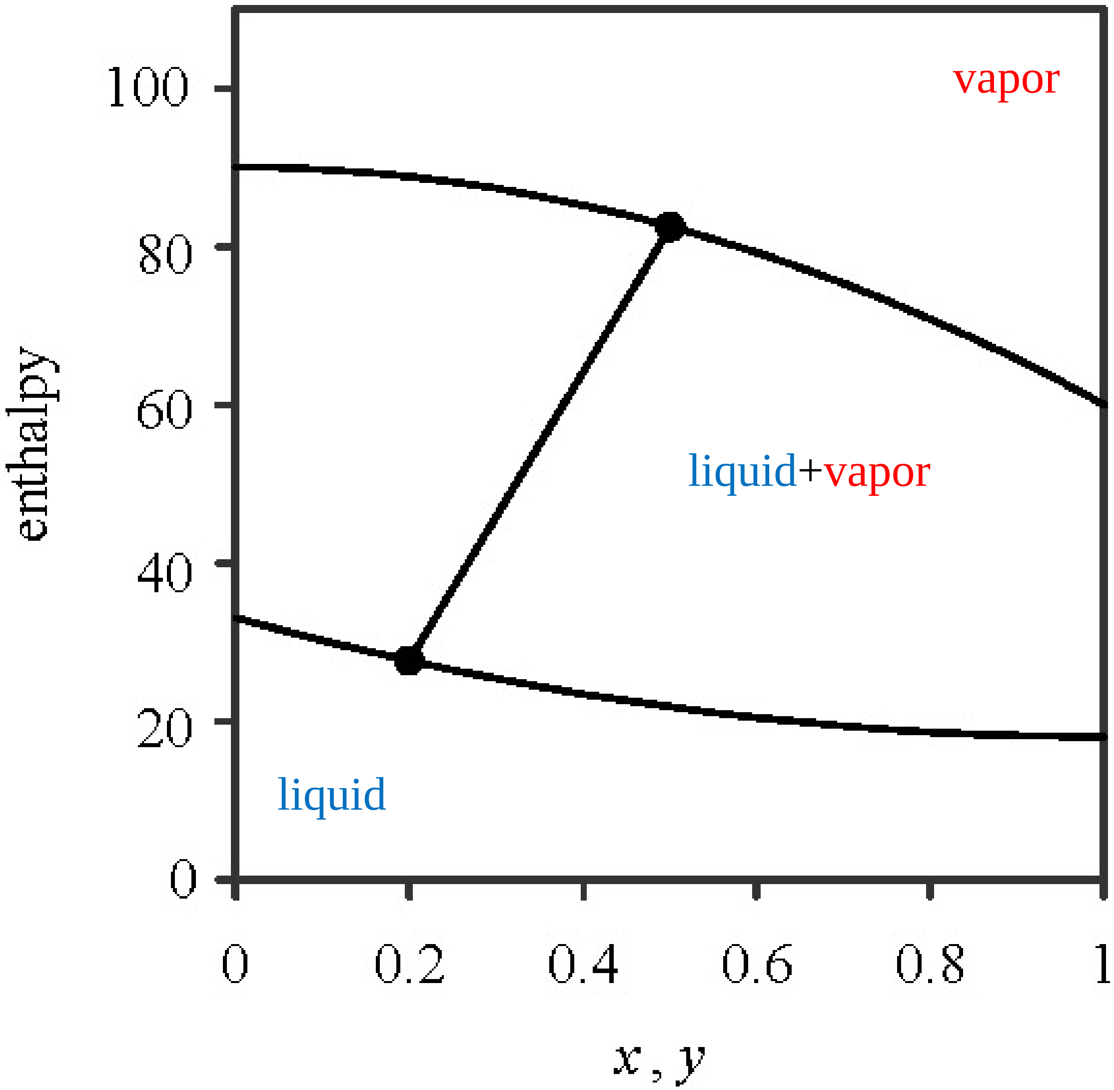


Is this a meaningful graphical model of a binary mixture in either a single-stage separator or a multi-stage, counter-current separator?



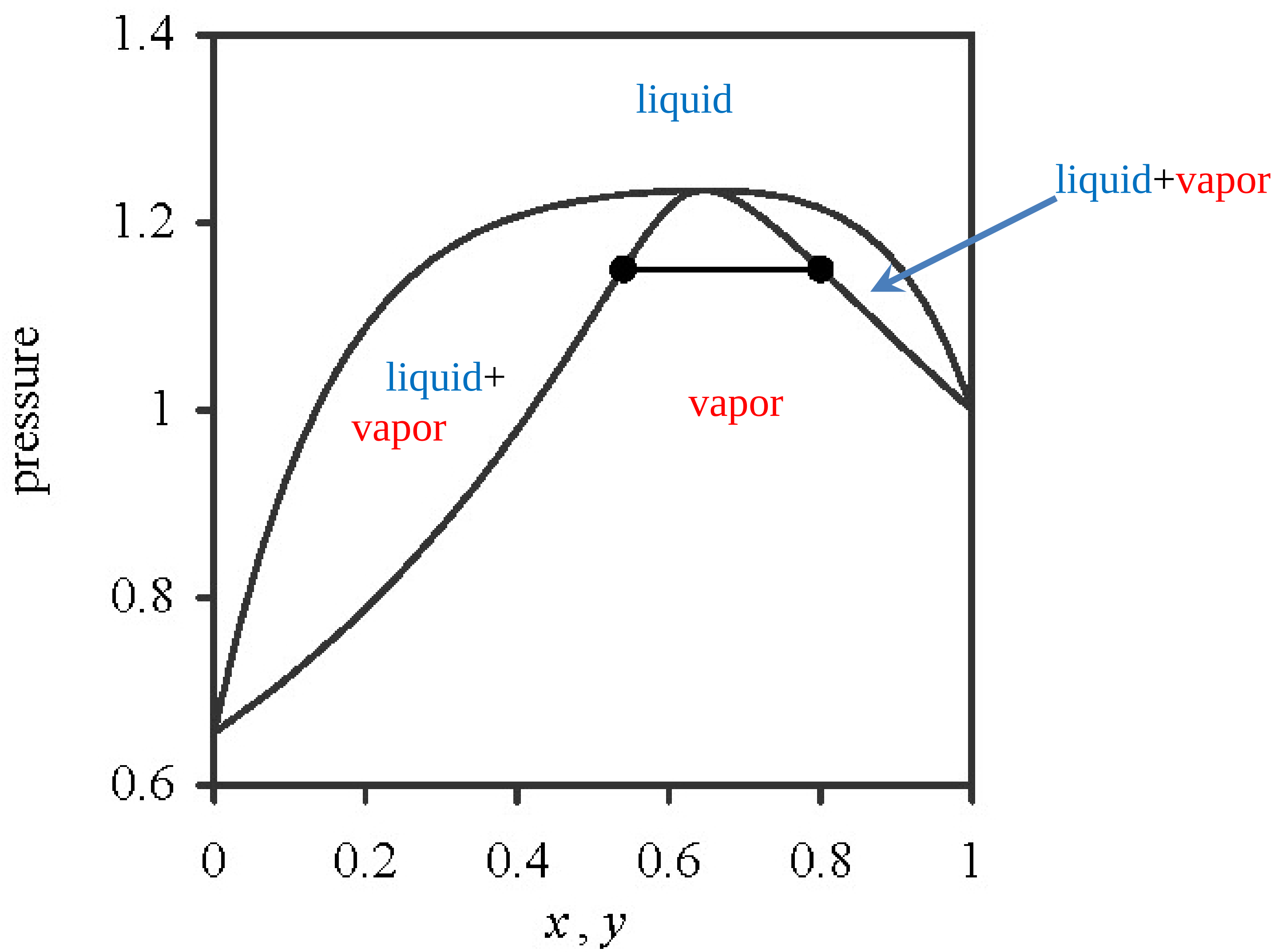
(A) meaningful or meaningless?

Is this a meaningful graphical model of a binary mixture in either a single-stage separator or a multi-stage, counter-current separator?



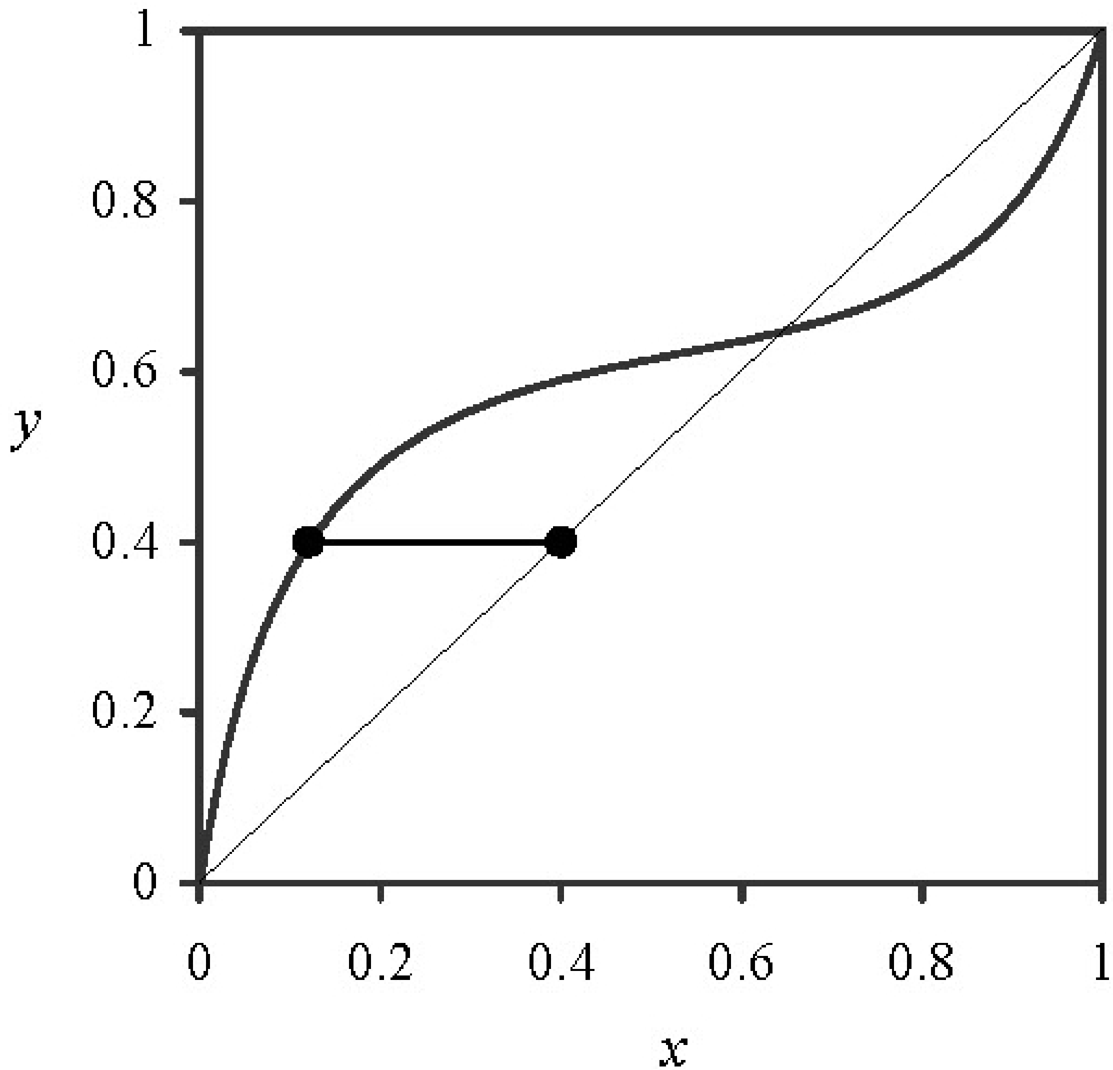
(B) meaningful or meaningless?

Is this a meaningful graphical model of a binary mixture in either a single-stage separator or a multi-stage, counter-current separator?



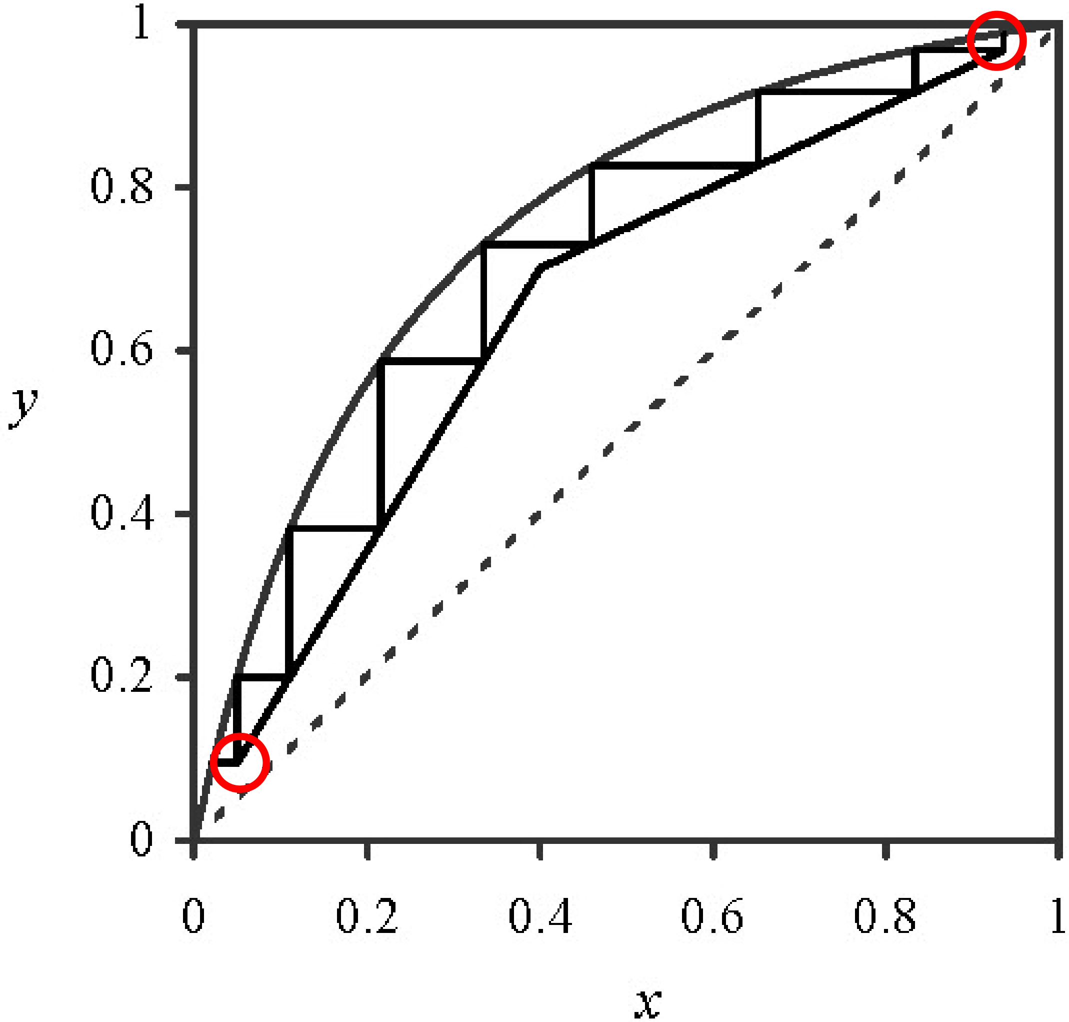
(C) meaningful or meaningless?

Is this a meaningful graphical model of a binary mixture in either a single-stage separator or a multi-stage, counter-current separator?



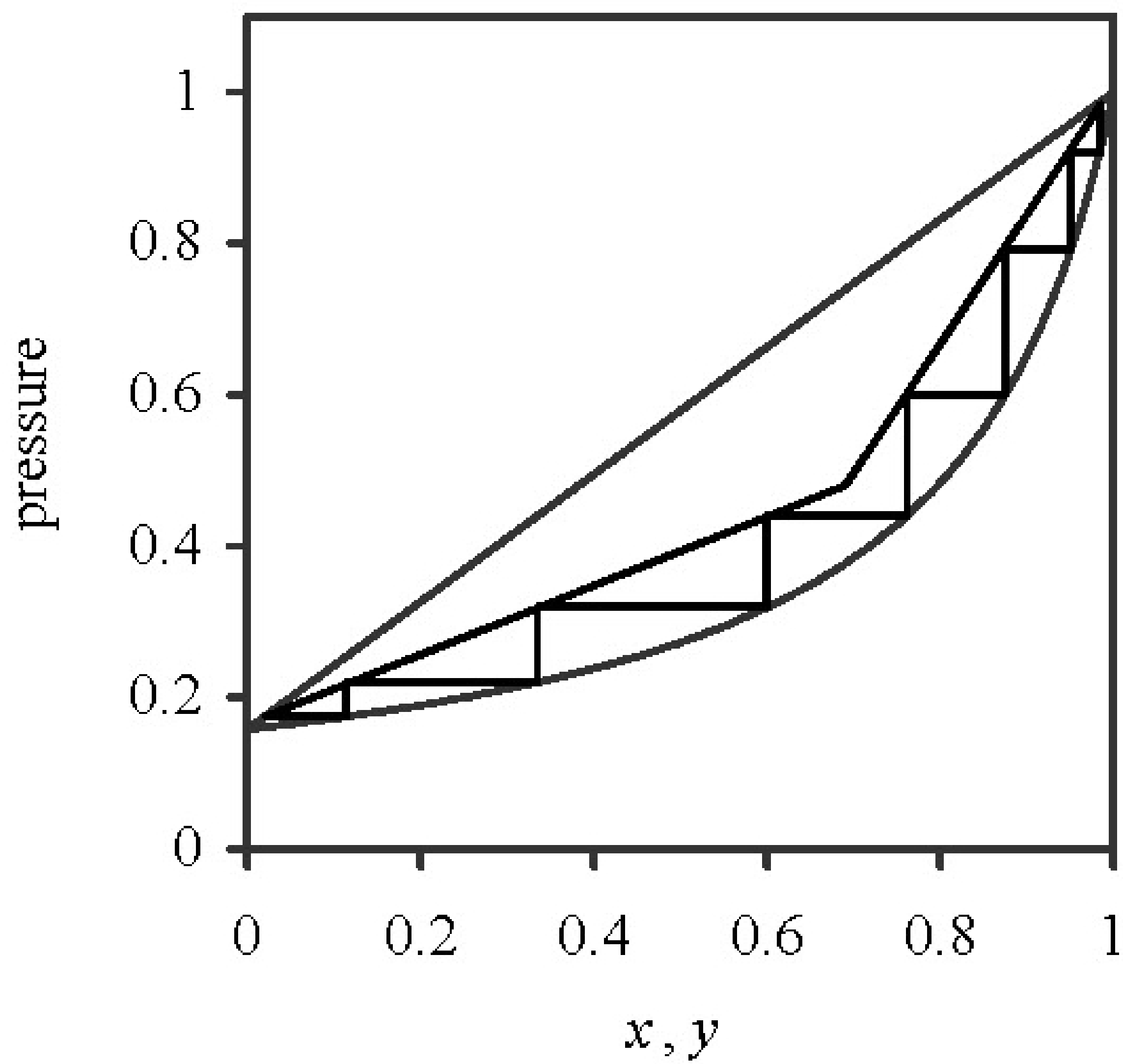
(D) meaningful or meaningless?

Is this a meaningful graphical model of a binary mixture in either a single-stage separator or a multi-stage, counter-current separator?



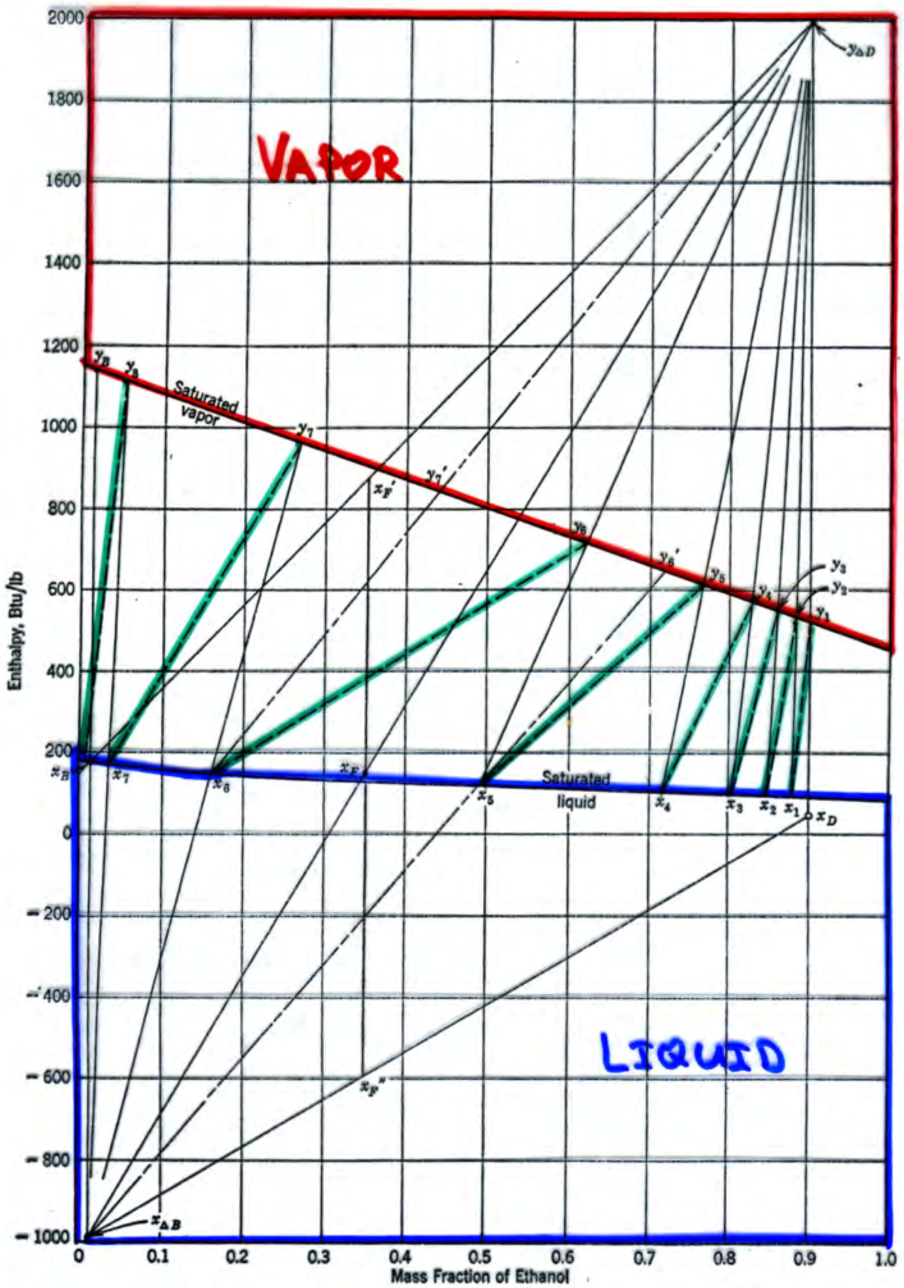
(E) meaningful or meaningless?

Is this a meaningful graphical model of a binary mixture in either a single-stage separator or a multi-stage, counter-current separator?

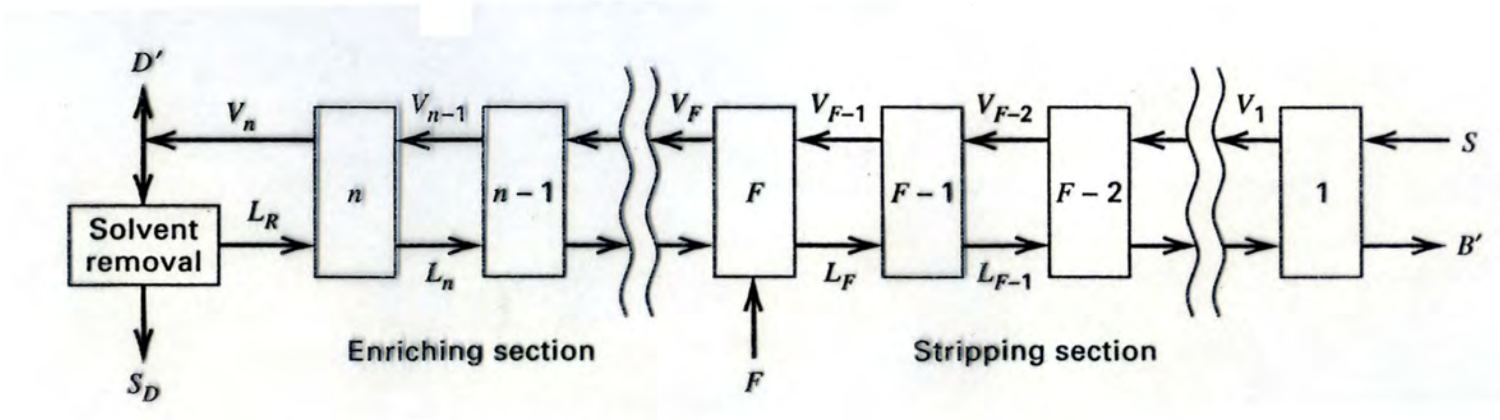


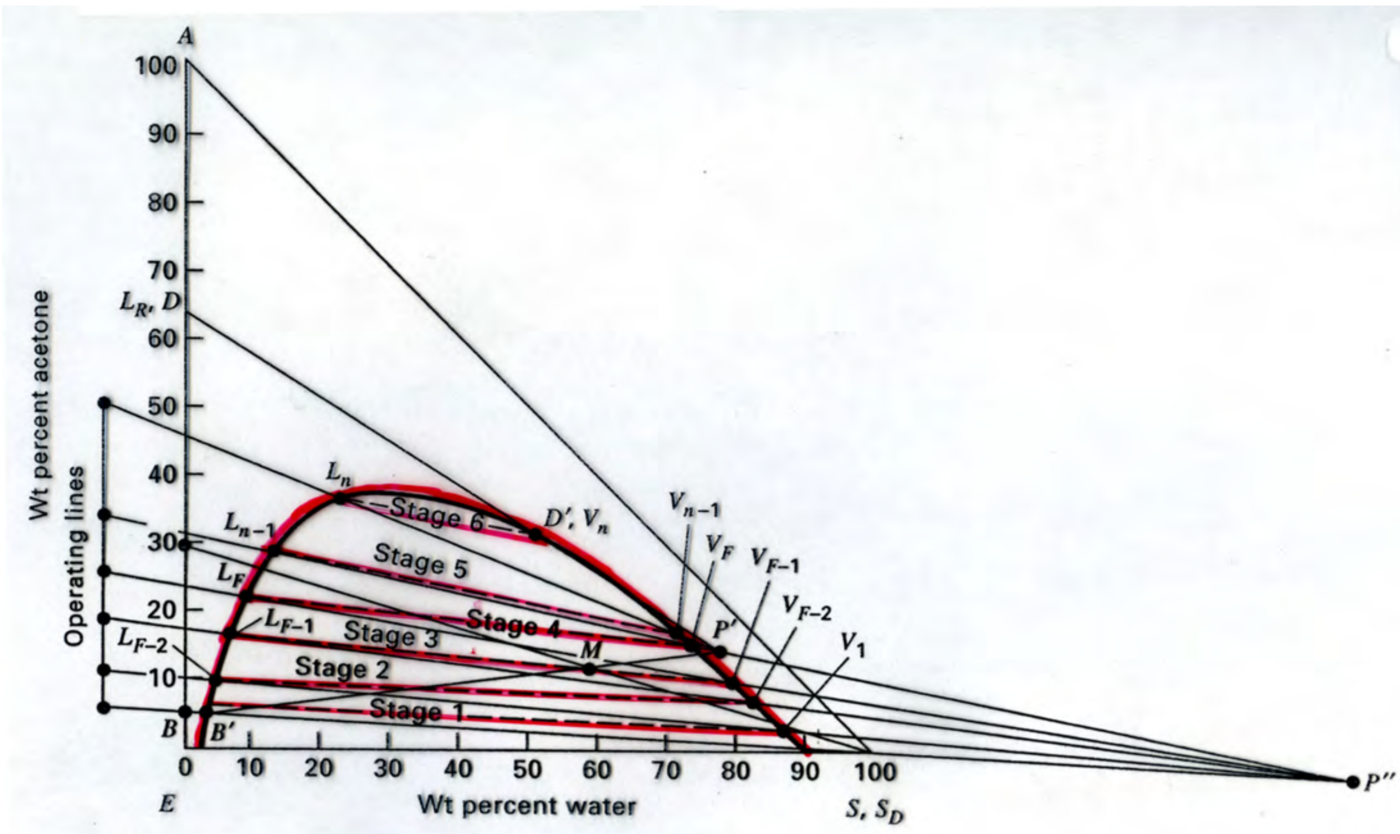
(F) meaningful or meaningless?

Multistage Countercurrent Distillation



Multistage Countercurrent Liquid-Liquid Absorber





The Stages of Separations Development

- Invent a new separation technique.
- Devise a graphical analysis.
- Write a song or poem.

Professor Harriott's Ode to McCabe-Thiele:

"… *Then one cried out* - *It's simple, don't you see?*

The key to this problem is L over V."

Three Skills in Dimensional Analysis / Dynamic Scaling

1. Derive a set of dimensionless groups given a list of parameters.

    Lectures 28, 29, and 30:

        Pendulums Swinging, People Walking, and Spheres Falling.

    Practice Exercises: 5.8, 5.13, 5.15, 5.20, and 5.22.

2. Use a Universal Correlation of Dimensionless Groups.

    Lecture 31.

    Practice Exercises: 5.28, 5.29, and 5.30.

3. Design a Dynamically Similar Model by Scaling.

    Lectures 32 and 33.

    Practice Exercises: 5.33, 5.34, and 5.39.

Solutions to practice exercises are posted at the EngrD 2190 homepage.

Method of Dimensional Analysis

1. List parameters will always be given in this course.
2. Find dimensions of each parameter
3. Write equation for generic Π group
4. Choose core variables
5. Derive Π groups
6. Measure Data
7. Plot universal correlation

Two Rules for Core Variables

1. The set of core variables must represent all dimensions. Easy to check.
2. The core variables must not form a dimensionless group. Not easy to check.

   It is often easier to derive the Π groups.
   If a problem arises, this rule was likely violated.

Methods of Using Dimensionless Correlations

If unknown variable uniquely appears in abscissca or ordinate – simple.

If unknown variable appears in both abscissca or ordinate – four methods.

1. Guess ‘n’ Check.
2. Eliminate the unknown parameter from the two dimensionless groups.
3. Convert the dimensionless correlation to an equation.
4. Recast the dimensionless correlation with the unknown variable as a core variable.

Designing a Dynamically Similar Model

Assume the system is described by n Π groups: $\Pi_1, \Pi_2, \ldots, \Pi_n$

1. Set $(\Pi_i)_{\text{model}} = (\Pi_i)_{\text{actual}}$ for $i = 1$ to $n-1$.
2. Use the model to measure Π_n.
3. Use Π_n to calculate parameters for the actual system.

If your model has a different length and/or mass dimension - your model is smaller or less massive - your model must also change something so there is a different time dimension.

Usually, use a different fluid for the model.

Fluid parameters: viscosity: $[\mu] = \dfrac{\text{M}}{\text{LT}}$

surface tension: $[\gamma] = \dfrac{\text{M}}{\text{T}^2}$

heat capacity: $[C_\text{P}] = \dfrac{\text{L}^2}{\text{T}^2\Theta}$

thermal conductivity: $[k] = \dfrac{\text{ML}}{\text{T}^3\Theta}$

Dimensional Analysis and Dynamic Scaling

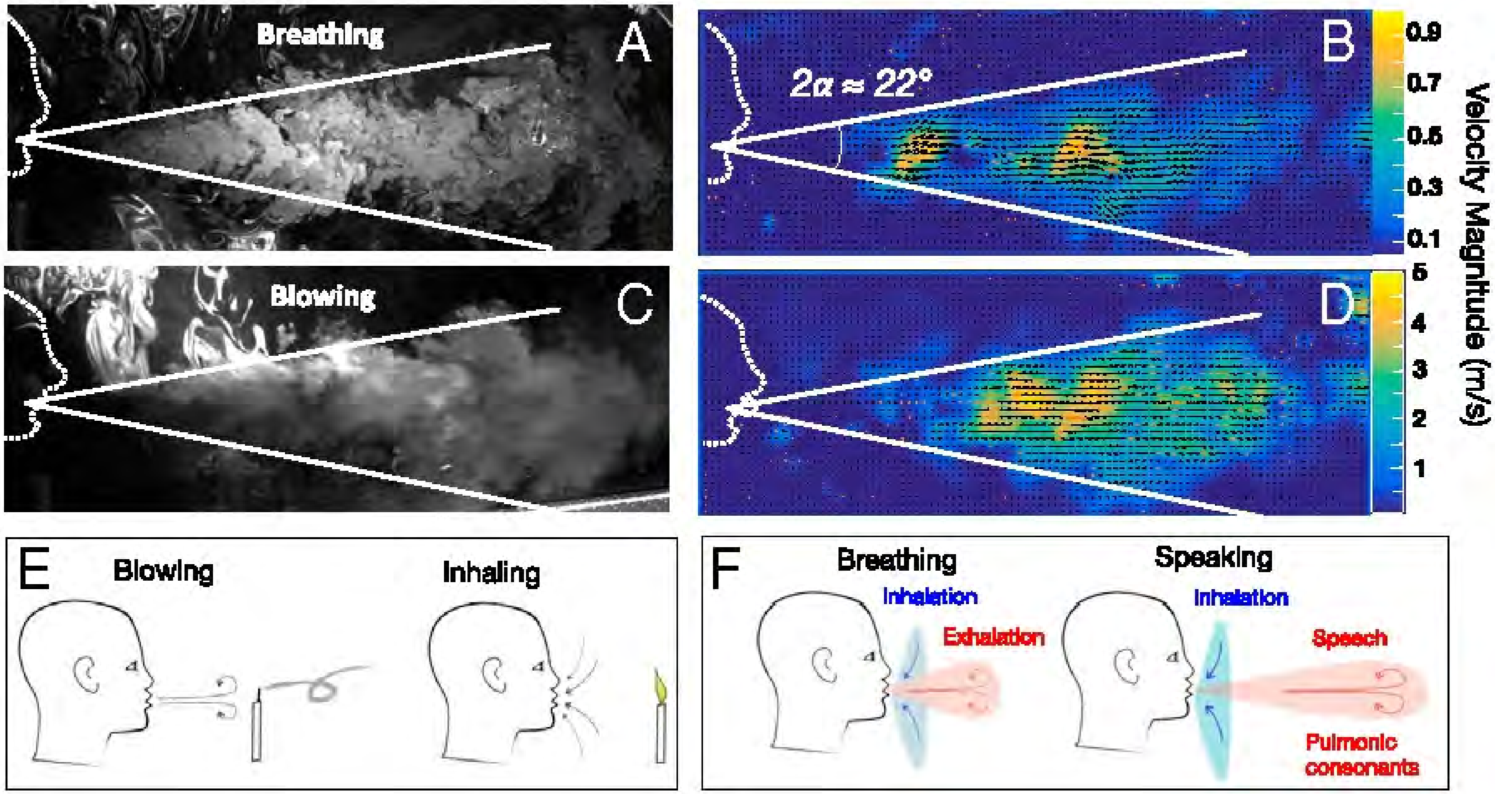
Dynamics of Aerosols Transmitted by Speech

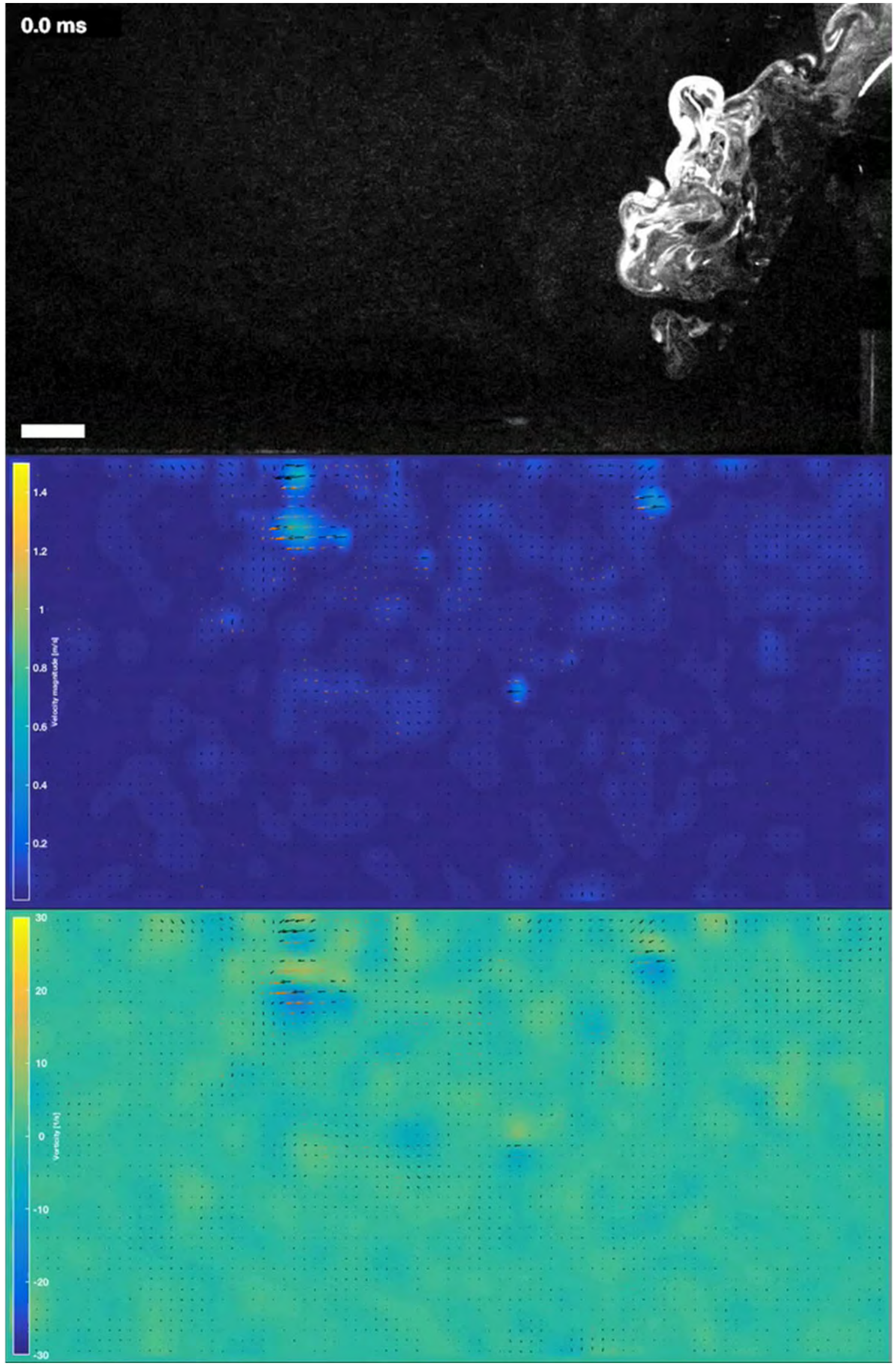
Dimensional Analysis:
Viral Transmission by Speech-Driven Aerosol Transport

Speech can produce jet-like transport relevant to asymptomatic spreading of virus

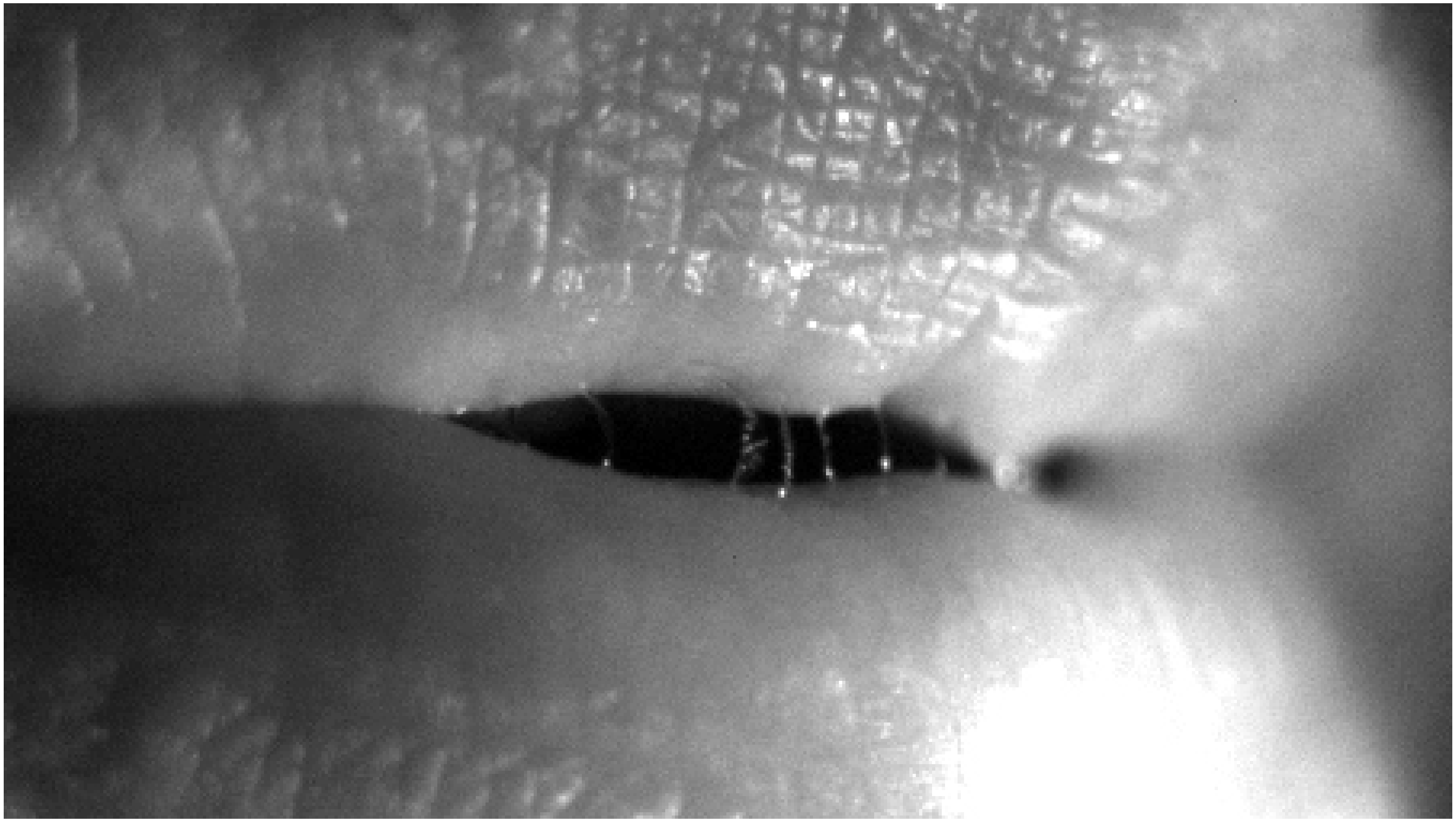
Manouk Abkarian[a,1], Simon Mendez[b,1], Nan Xue[c], Fan Yang[c], and Howard A. Stone[c,2]

[a]Centre de Biochimie Structurale, CNRS UMR 5048—INSERM UMR 1054, University of Montpellier, 34090 Montpellier, France; [b]Institut Montpelliérain Alexander Grothendieck, CNRS, University of Montpellier, 34095 Montpellier, France; and [c]Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544



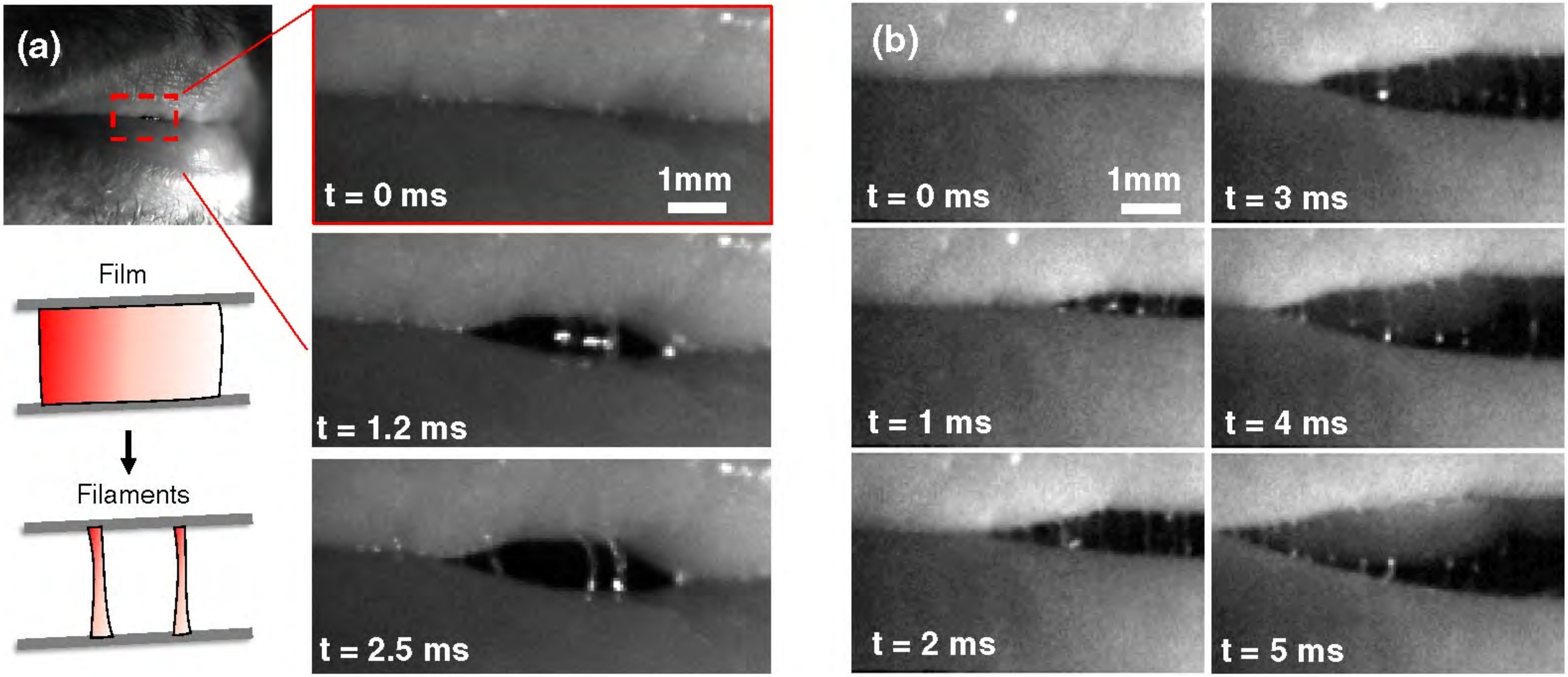

0.0 ms
1.4
1.2
1
0.8
0.6
0.4
0.2
Velocity magnitude [m/s]
30
20
10
0
-10
-20
-30
Vorticity [1/s]

Aerosol Droplets Form from Filaments on Lips



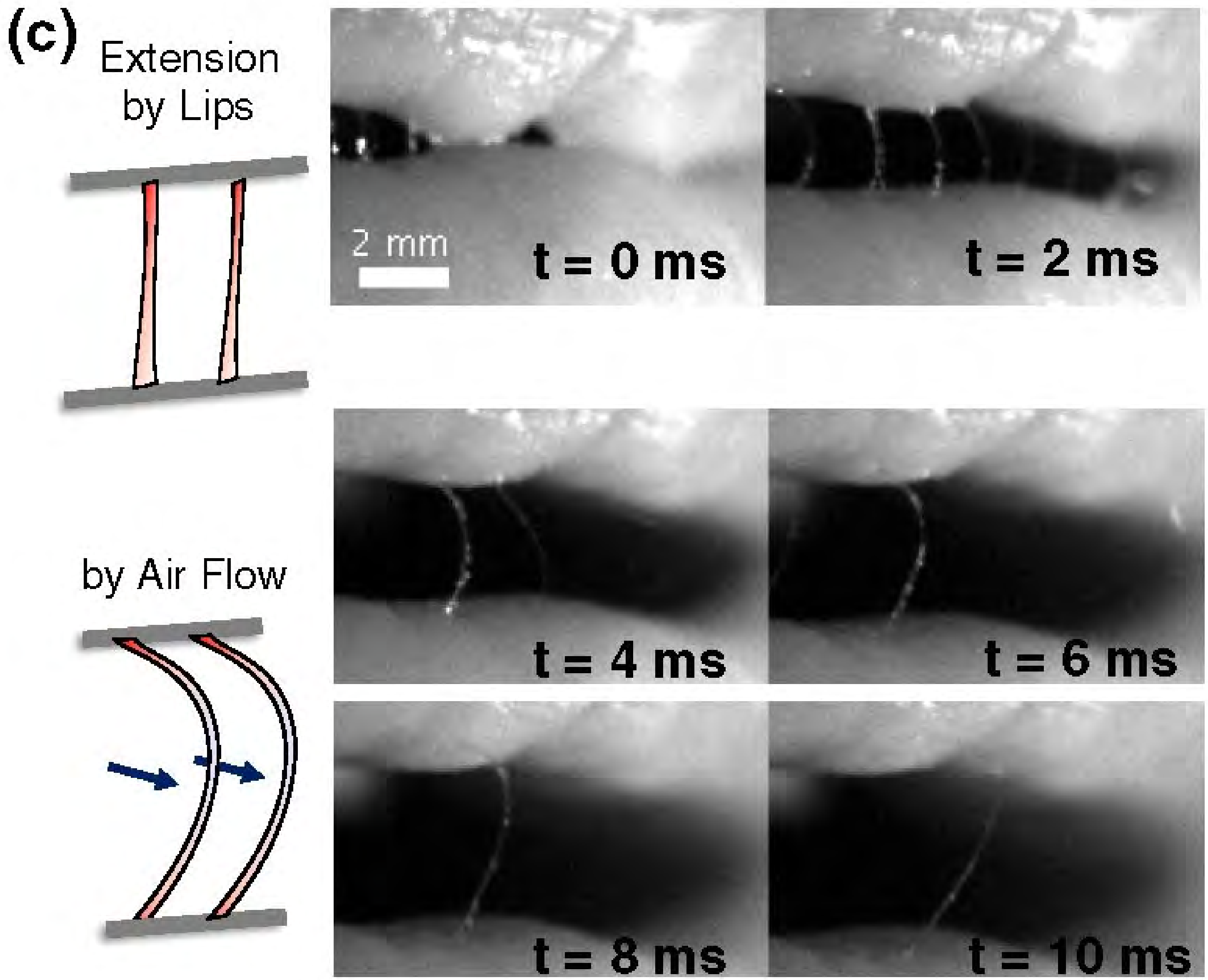
Howard Stone et al.:
engineering.princeton.edu/news/2020/10/06/speaking-creates-droplets-linked-disease-transmission

Aerosol Droplets Form from Saliva Filaments on Lips



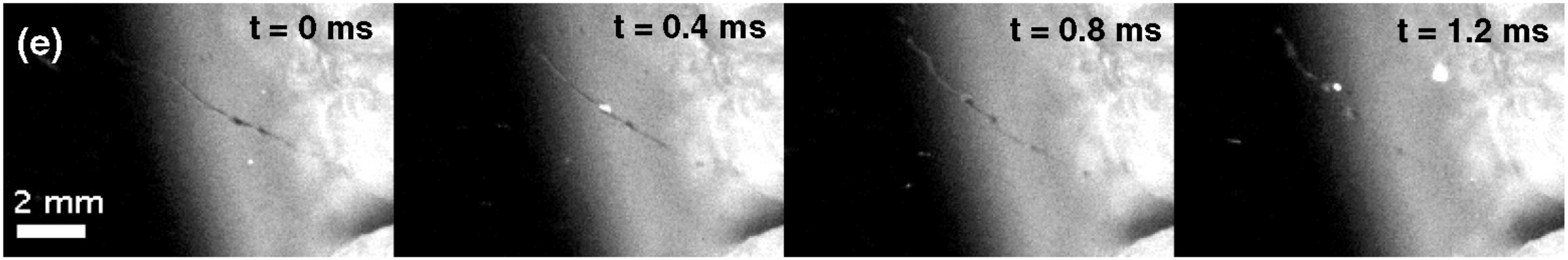
Manouk Abkarian and Howard Stone, "Stretching and break-up of saliva filaments during speech: A route for pathogen aerosolization and its potential mitigation," *Physical Review Fluids* **5**, 102301(R) (2020)

Aerosol Droplets Form from Saliva Filaments on Lips



Manouk Abkarian and Howard Stone, *Physical Review Fluids* **5**, 102301(R) (2020)

Aerosol Droplets Form from Saliva Filaments on Lips



System described by -

Reynolds Number – inertia/viscosity ratio in fluid flow

Stokes's Number – behavior of droplets suspended in fluid flow

Weber Number – inertia/surface tension of droplets suspended in air

Ohnesorge Number – surface tension/viscosity of droplets suspended in air

OON-neh-sah-geh (German)

see exercise 5.23

Time Scaling of Speech-Driven Aerosol Plume

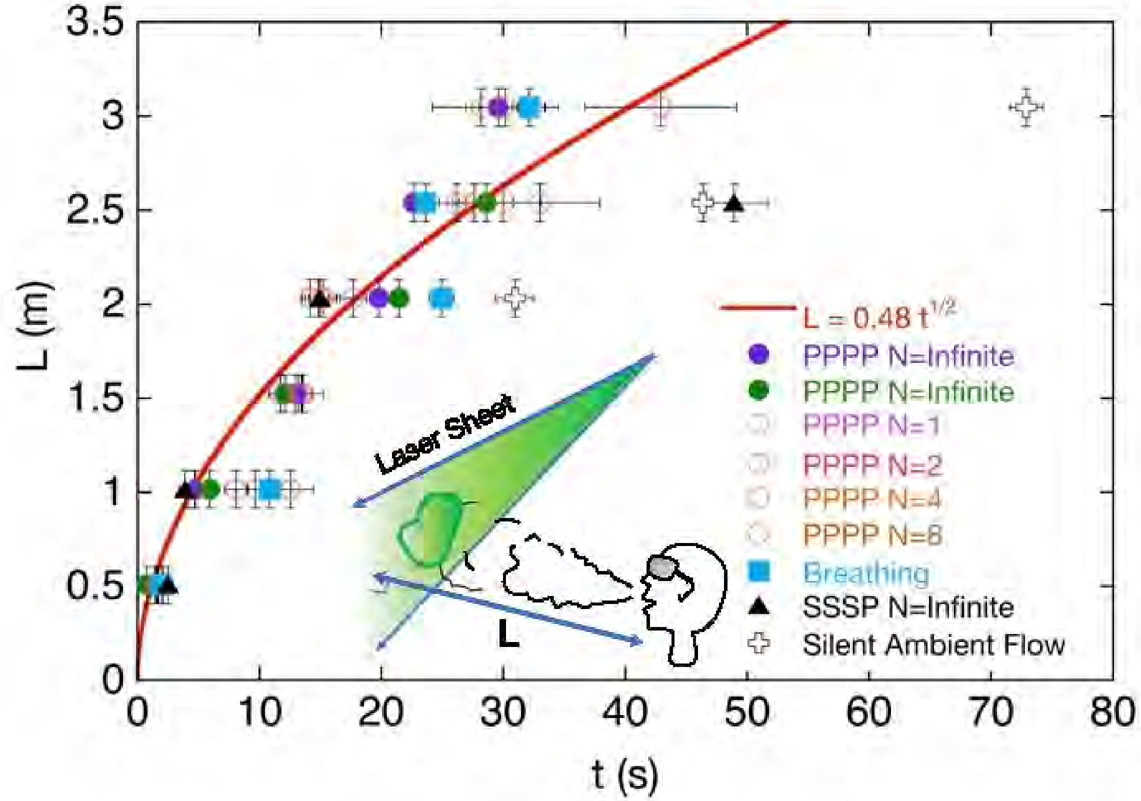


Fig. 6. Speech propagation distance L to a laser sheet versus time t while saying "Peter Piper picked a peck" (PPPP) and "Sing a song of six pence" (SSSP). N indicates the number of times the sentence has been repeated (with 1 s inhalation in between) before total silence and $N =$ Infinite means the sentence has been pronounced until the sheet was reached. The solid line represents a fit with a $t^{1/2}$ power law. "Silent ambient flow" (crosses) refers to the control case where the fog is convected by the ambient flow alone.

Manouk Abkarian, Simon Mendez, Nan Xue, Fan Yang , and Howard A. Stone, "Speech can produce jet-like transport relevant to asymptomatic spreading of virus," *Proceedings of the National Academy of Science* **117**, 25237 (2020)

EngrD 2190 Course Objectives

Learning Skills

To know your natural learning style, to recognize the learning style of a presentation or document, and to translate into your preferred learning style.

To gain teamwork skills for design, analysis, and learning.

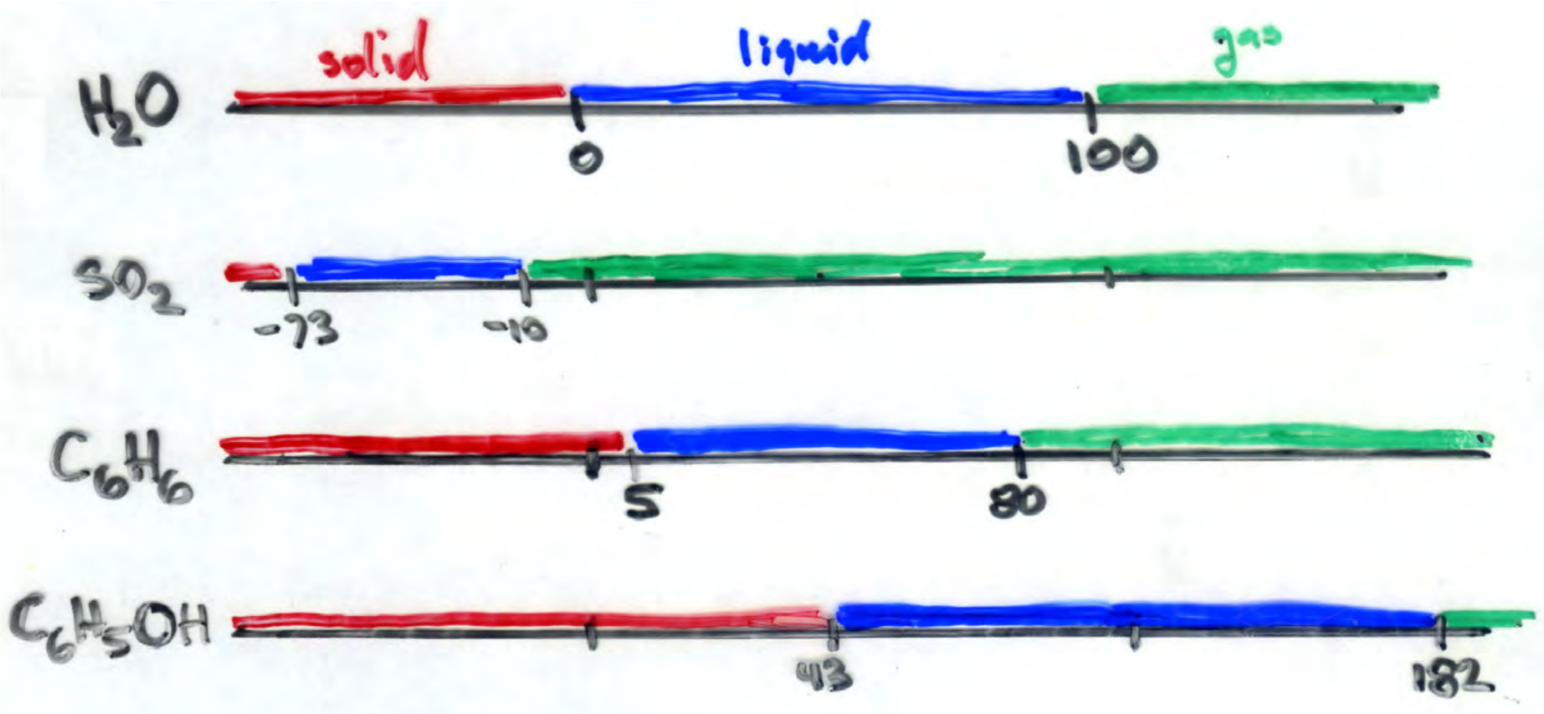
Stages and Styles of Learning

Stage	Style
Perception	Sensory Intuitive
Assimilation	Visual Verbal
Organization	Inductive Deductive
Processing	Active Reflective
Understanding	Sequential Global

Visual vs. Verbal Assimilation

	melting pt (°C)	boiling pt (°C)
H_2O	0	100
SO_2	–73	–10
C_6H_6	5	80
C_6H_5OH	43	182
H_2SO_4	10	338

Verbal



Visual

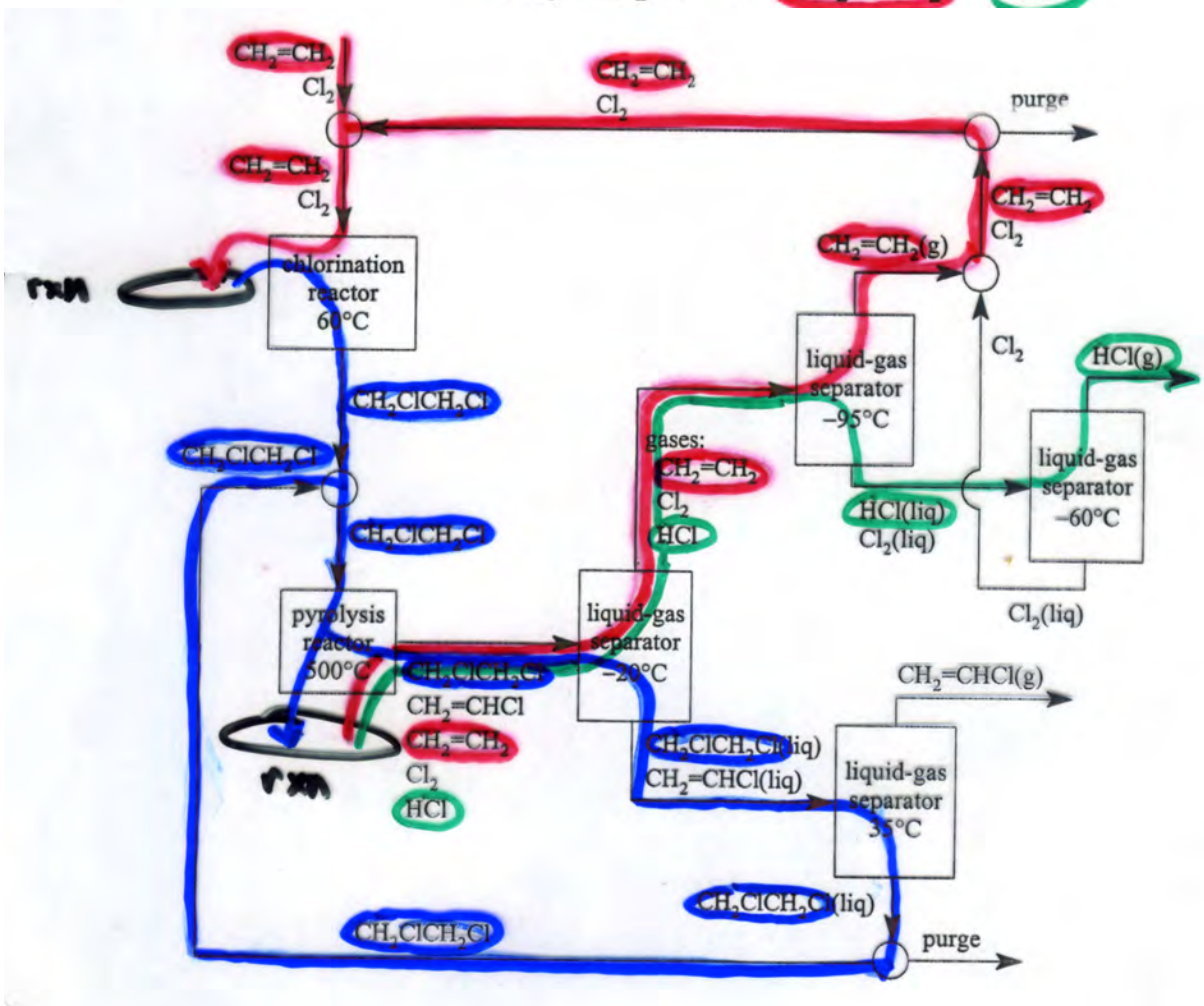
Active Processing and Visual Assimilation

chlorination (60°C) $CH_2{=}CH_2 + Cl_2 \rightarrow CH_2Cl{-}CH_2Cl$

pyrolysis (500°C) $CH_2Cl{-}CH_2Cl \rightarrow CH_2{=}CHCl + HCl$

$CH_2Cl{-}CH_2Cl \rightarrow CH_2{=}CH_2 + Cl_2$

$CH_3{-}CH_2Cl \rightarrow CH_2{=}CH_2 + HCl$



Deductive vs. Inductive Organization

If you prefer to organize inductively
and your textbook has a deductive style,
annotate your textbook with inductive translations.

Deductive: "Solid-solid separators produce
solid-free liquids and wet solids."

Inductive: "Dirty water separates into clean water and mud,
not clean water and dust."

Deductive: "If a solid is soluble in a liquid,
the liquid and solid cannot be separated
into pure liquid and pure solids."

Inductive: "Salt water fed to a solid-liquid separator
will not separate into pure water and dry salt,
even though NaCl is a solid at 20°C."

Dimensionless Groups

Euler	“Oiler”	
Froude	“Frood”	Not “Froud”
Thiele	“TEE-leh”	Not “THEE-lee”
Péclet	“pay-CLAY”	
Poiseuille	“pwah-zø-YAH”	see p. 469.