CH EN 3453 – Heat Transfer

Intro to Heat Exchangers

plus

Experimental Design
and Data Analysis

Info…

• Homework #8 due Friday
  – Help session Wed at 4:30 in MEB 2325

• Experimental section of project report due Friday at 4:00 PM
  – Include description of equipment as one subsection
    • Reference any figures used!!
  – Include experimental procedure as another subsection

• Data from Friday’s lab day is posted on “project” page of web site

• SCI Scholars internship
  – For sophomores and juniors with 3.5 GPA or better
  – Deadline for application is Dec 19
  – See www.acs.org/sci for more info

• U.S. DOE Mickey Leland Energy Fellowship
  – For U.S. Citizens with minimum 3.0 GPA
  – See orise.orau.gov/mlef for more info
### Upcoming Schedule

<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
<th>Chapters/Sections</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 20-Oct</td>
<td>Forced convection: Introduction to internal flow</td>
<td>8.1 - 8.3</td>
<td>TA's teach</td>
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<tr>
<td>W 22-Oct</td>
<td>Forced convection: Internal flow correlations</td>
<td>8.4 - 8.5</td>
<td>TA's teach</td>
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<tr>
<td>F 24-Oct</td>
<td>LAB DAY - Heat Exchanger Experiments</td>
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<td>HW 7 Last day to withdraw</td>
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<tr>
<td>M 27-Oct</td>
<td>Intro to heat exchangers + Experiments &amp; data analysis</td>
<td>8.6 - 8.7, 8.10</td>
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<td>W 29-Oct</td>
<td>Heat exchangers, LMTD approach</td>
<td>11.1 - 11.3</td>
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<tr>
<td>F 31-Oct</td>
<td>Heat exchangers: Effectiveness-NTU</td>
<td>11.4</td>
<td>HW 8 Project experimental section due</td>
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<tr>
<td>M 03-Nov</td>
<td>Heat exchanger design</td>
<td>11.5 - 11.7</td>
<td>TA's teach</td>
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<tr>
<td>W 05-Nov</td>
<td>Heat exchangers: LMTD approach for complex systems</td>
<td>118.1</td>
<td>TA's teach</td>
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<tr>
<td>F 07-Nov</td>
<td>Natural (free) convection, boiling and condensation</td>
<td>Ch 9, (Ch 10)</td>
<td>HW 9 Project theory section due</td>
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<tr>
<td>M 10-Nov</td>
<td>Review of convection and heat exchangers</td>
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<tr>
<td>W 12-Nov</td>
<td>MIDTERM EXAM #2 - Convection and heat exchangers</td>
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<tr>
<td>F 14-Nov</td>
<td>Intro. to radiation: Heat flux, intensity and radiation</td>
<td>12.1 - 12.2</td>
<td>Project results section due</td>
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<td>M 17-Nov</td>
<td>Blackbody radiation</td>
<td>12.3</td>
<td>TA's teach</td>
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<tr>
<td>W 19-Nov</td>
<td>Radiation from real surfaces</td>
<td>12.4 - 12.7</td>
<td>TA's teach</td>
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<tr>
<td>F 21-Nov</td>
<td>Solar and environmental radiation</td>
<td>12.8 - 12.9</td>
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<tr>
<td>M 24-Nov</td>
<td>Radiation between surfaces - the view factor</td>
<td>13.1</td>
<td>Project peer reviews begin</td>
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<tr>
<td>W 26-Nov</td>
<td>Radiation in enclosures and radiation networks</td>
<td>13.2</td>
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<tr>
<td>F 28-Nov</td>
<td>HOLIDAY - Thanksgiving</td>
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<tr>
<td>M 01-Dec</td>
<td>Multimode heat transfer and network representations</td>
<td>13.3</td>
<td>HW 11 Peer-reviewed drafts returned</td>
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<td>W 03-Dec</td>
<td>Heat transfer networks, radiation with participating media</td>
<td>13.4</td>
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<tr>
<td>F 05-Dec</td>
<td>Radiation to and from high temperature gases</td>
<td>13.5</td>
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<td>M 08-Dec</td>
<td>Radiation summary and review</td>
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<td>HW 12 Project final reports due</td>
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<td>W 10-Dec</td>
<td>Review - Conduction</td>
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<tr>
<td>F 12-Dec</td>
<td>Review - Convection</td>
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<tr>
<td>W 17-Dec</td>
<td>FINAL EXAM (8:00 - 10:00 in WEB 1250)</td>
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### Heat Exchanger

![Diagram of a heat exchanger with labeled parts: Tube outlet, Shell inlet, Baffles, Shell outlet, Tube inlet.](#)
Shell-and-Tube Heat Exchanger

A Real Heat Exchanger
Simple Tubular Heat Exchanger

Outline

• Types of experimental studies
• Experimental objectives
• Limiting factors
• Experimental approaches
• Data analysis
• Examples
Types of Experimental Studies

• Controlled experiments
  – Variables can be controlled
  – Hypotheses can be tested
  – Examples: Fundamental phenomena, process studies, clinical trials

• Natural experiments
  – Observation of natural phenomena
  – Variables cannot be controlled
  – Examples: Astronomy, geology, meteorology, paleontology, economics, political science

Experimental Objectives

Why Do We Experiment?

• Determine correlations between phenomena
• Identify cause and effect
• Quantify influence of an independent variable on a dependent variable
• Acquire data for modeling of a process, population or system
Scope of an Experimental Study

- Number of variables to study
- Range of variables / number of levels
- Relative importance of variables
- Reliability of data
  - Uncertainty / accuracy / precision
  - Reproducibility

Example

- 4 variables (e.g., temperature, pressure, flow rate, concentration, reagent, residence time, flow pattern)
- 3 levels for each variable (e.g., “normal,” high and low)
- How many experiments?
  - Full matrix: $3 \times 3 \times 3 \times 3 = 81$ experiments
  - 5 variables at 3 levels gives 243 experiments
  - 4 variables at 4 levels gives 256 experiments
Limiting Factors

• Time
• Money
• Manpower
• Experimental equipment
• Analytical capabilities
• Understanding / expertise
• Support

Too Many Variables with Too Few Resources

• What is the real goal of the study?
• How exact do the results need to be?
• Do all variables need to be studied?
• Which variables are most/least important?
• What is the simplest/fastest experiment that will give satisfactory results?
• Has anyone performed similar experiments in the past?
RESEARCH…

• Just because it is called RE-search doesn’t mean that you are expected to repeat what someone has done before

• Quick survey of previous work
  – Internal studies of the same or similar problem
  – Published results (try Google Scholar)

• Think hard about what affects the variable(s) you are studying
  – Drag out your old textbooks
  – Anecdotal evidence

Experimental Approaches

• Screening studies
• Binary testing
• Hypothesis testing
• Focus on key variables
• Factorial experimental design
• Statistical experimental design
Screening Studies

• Quick experiments at extremes of the experimental conditions
• Identify the most significant factors
• Identify factors that can be safely ignored
• Help design experimental matrix

Binary Testing

• Used to decrease the number of variables under consideration
• Complement to screening tests
• Involves “on” or “off” testing of independent variables
• Step change
  – Is there any effect?
  – If so, is it worth pursuing further?
Hypothesis Testing

• Avoid blindly executing a vast matrix of experiments

• Use intuition, modeling and/or anecdotal evidence to prepare educated guesses of how the system will behave

• Also useful for identifying appropriate ranges of study for variables under consideration

Focus on Key Variables

• One approach to experimentation is to adjust one variable at a time to determine its effect on the system

• Time consuming, but can be useful if one or two parameters have an overwhelming influence on the system

• Useful for fitting constants of mechanism-based models

• Ensure that the adjusted parameter doesn’t have secondary effects/undesired interactions
Factorial Design
(Yates Analysis)

- For each parameter to be tested, assign a “high” (+) and a “low” (-) value
- Experimental matrix covers all combinations of variables
  - For 2 levels of each parameter, the number of experiments = $2^k$ where $k$ is the number of parameters
- Appropriate for few parameters

Statistical Experimental Design

- If several variables need to be considered, and effect of each cannot be ignored, the number of experiments can be reduced through statistical experimental design
- Attempts to cover the “experimental space” with a limited number of experiments
Statistical Experimental Design
continued…

• Algorithms and software packages are available which can generate an experimental plan
  – Plackett-Burman algorithm
  – Box-Behnken designs
  – Taguchi methods

• Empirical modeling is typically the only appropriate method of interpreting data from statistically designed experimental campaigns

Conclusions – Experimental Design

• Experimental campaigns frequently limited by time, resources

• Important to think through experiments
  – What is truly important?
  – What can be ignored?
  – Has anyone done this before?

• With few variables, factorial design is useful

• With many variables, statistical experimental design may be necessary
Data Analysis

• Use data to make sense of system
  – Balances (overall and component)
  – Heat transfer
  – Mass transfer
  – Reaction rates

• Identify trends in the data
  – Use understanding of system and chemical engineering principles to guess what trends should exist and check these
  – Plot ‘x’ versus ‘y’
    • Identify linear vs. exponential, etc.
  – Look for gaps or upsets in the data
    • Phase change
    • Transition from laminar to turbulent flow

Data Analysis

• Desirable to develop mathematical model to describe observed behavior

• Mechanism-based model
  – Mass transfer
  – Heat transfer
  – Reaction kinetics

• Empirical model

• Fit to data through e.g., minimizing square of residuals
Data Analysis: Setup

- Collect all data into one database
- Convert raw signals into useful measurements
  - volt signal to pressure
  - pressure drop to flow rate
  - obscure units to useful ones
- Perform basic calcs to make sense of data
  - Velocity + geometry to volumetric flow rate
  - Volumetric flow + temperature + pressure to mass flow

Data Analysis: Uncertainty

- Uncertainty analysis (“error analysis”) is necessary for good scientific study
- Two approaches:
  - Identify uncertainty in each component of system and use these in combination with appropriate engineering equations to propagate the uncertainty to the final measurement
  - Perform multiple (> 6) experiments at the same set of conditions and statistically evaluate the uncertainty
    - Reproducibility experiments should be randomized throughout experimental matrix
    - Requires e.g. F-test and confidence interval
Data Presentation: Tables

- Useful for showing a lot of data in compact form
  - If just 2 or 3 values, simply include within text
- **Not** useful for presentation of relationships
- Indicate units in table
- Often all raw data is summarized in a table as an appendix to a report, with key data presented within the report

Data Presentation: Charts

- Bar charts
  - Useful for presenting relative magnitudes for data when trends among the data are not expected
  - Multiple data sets can be stacked or placed side-by-side (e.g., mass balance)
- X-Y charts
  - Useful for indicating trends (or lack thereof) in data
  - Multiple data sets can be placed in chart with different lines and symbols
  - Multiple measurements can be combined using different y-axes with different scales and units
Data Presentation: Other Figures

- 3-D charts
  - When dependent variables are a result of two independent variables
- Modeling results (Comsol, Fluent, etc.)
  - Useful visualization
  - Don’t get too fancy!
- Other
  - Photographs
  - Sankey diagrams

Sankey Diagram

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*Notes: Data are preliminary. Values are derived from source data prior to rounding for publication. *Table may not equal sum of components due to independent rounding.
Sources: Tables 1.1, 1.2, 1.3, 1.4, and 2.1a.
Heat Exchanger Analysis

• What should we consider?
  How should we analyze the data?

• Remember heat balance
  – Can we confirm this?

• Compare to theory/model
  – Will learn during coming lectures
  – Plot experimental data vs theory

Heat Exchanger Data

<table>
<thead>
<tr>
<th>Data point</th>
<th>TUBE SIDE (HOT)</th>
<th>SHELL SIDE (COLD)</th>
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<tbody>
<tr>
<td></td>
<td>Flowrate (gal/min)</td>
<td>Inlet temp. (°C)</td>
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<tr>
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<td>26.0</td>
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