CEV4512 INDUSTRIAL AIR POLLUTION CONTROL

YTU
Environmental Engineering Department

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CHAPTER 2
Process Design Principles

CHAPTER OUTLINE

- Definitions (21)
- Flowsheets (5)
- Material and Energy Balances (19)
- Analysis of a Coal-Fired Power Plant (13)

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DEFINITIONS (1/21)

- Capability of process design makes a difference
  - Operating engineer vs. design engineer
- Design
  - Development of a plan to accomplish a specific goal
- Process design
  - The art of engineering a safe, environmentally sound system for a dollar which any fool can do for two
  - The action of choosing and describing the sequence of steps from the planning stage to equipment specification stage of an air pollution control system

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DEFINITIONS (2/21)

- Major steps of a process design
  - Preliminary definition of a problem
  - Final problem definition
  - A series of decision points
    - that consist of alternatives and their associated problems
    - at each of which the engineer must evaluate the alternatives and choose the one that is the most technically and economically feasible
    - Evaluation of alternatives requires solution of all of the subproblems associated with that alternative

DEFINITIONS (3/21)

- Example
  - A company produces laminates for the building industry. One operation involves the drying of a granular material that contains a significant fraction of very fine dust, which exerts adhesive and flammable properties. The exhaust from the dryer is *clearly visible* and may *exceed* allowable particulate emission limits
- The preliminary problem
  - Exhaust is visible
  - Concerns arise related with aesthetic and regulatory standpoints
  - Actions
    - Calculations of emissions in the dryer exhaust
    - Sampling and lab analysis of the exhaust gas

DEFINITIONS (4/21)

- The final problem
  - Lab analysis confirms that exhaust exceeds allowable emission limits
  - Actions
    - Steps to be taken for design
    - Collection of data from measurements
      - Exhaust flowrate,
      - Particulate concentration, properties and size distribution at the inlet and outlet of the dryer
      - Particulate loadings
      - Operating temperature and pressure
    - Making engineering guesses on expected variations in all operating parameters based on process logs and engineering intuition

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DEFINITIONS (5/21)

- Alternatives
  - Controlling the exhaust gas by an electrostatic precipitator
  - Controlling the exhaust gas by a fabric filter
  - Controlling the exhaust gas by a wet scrubber
- Decision point 1
  - Evaluate alternatives
  - Particles are flammable. Employing an ESP could be dangerous
    - Fire and explosion risks ➔ Eliminate this alternative
  - Particles exert adhesive property. Using a fabric filter is not feasible
    - Fast clogging of fabric, difficult cleaning ➔ Eliminate this alternative
  - Wet scrubber prevents particles catching fire and adhesive properties of particles do not pose any problems ➔ Choose this alternative

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DEFINITIONS (6/21)

- Subproblems associated with wet scrubbing
  - Cost of liquid and electricity ➔ keep in mind
  - Disposal or reuse of sludge ➔ keep in mind
- Decision point 2
  - Type of scrubber
    - Venturi type
    - Orifice type
    - Tray tower
  - Compare alternatives considering
    - Collection efficiency
    - Pressure drop
    - Liquid-to-air ratios
    - Materials & costs of construction
    - Power requirements

DEFINITIONS (7/21)

- Preliminary design
  - Preliminary estimates of dimensions, materials, liquid flowrates, pressure drop, the degree to which compliance of emission standards, etc.
  - Preliminary estimates of investment and operating costs, service life, maintenance frequency, requirement for skilled personnel, etc.
- Final Design
  - Final dimensioning of the scrubber and auxiliary units (pumps, motors, etc.)
  - Final decision on constuction materials, equipment specifications
  - Detailed construction manual
  - Detailed costs estimates for implementing the design

DEFINITIONS (8/21)

- Construction
  - Construction at site
  - Construction at another place (shipping and installation costs)
- Startup
  - Detailed Aand steps for system startup
- Evaluation – Optimization
  - Sampling and lab analysis of particulates at the inlet and exit of the scrubber
  - Evaluating performance
  - Optimizing the performance (pressure drop, collection efficiency, liquid-to-air ratios, etc.)
  - Delivery to the owner

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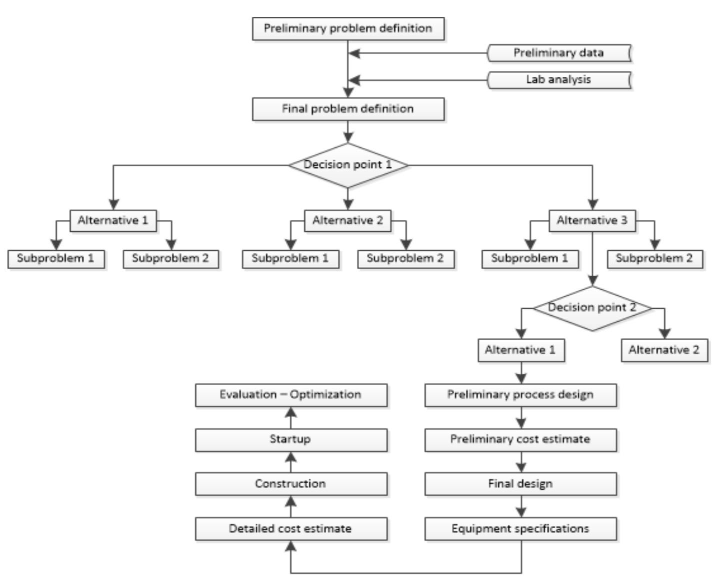
DEFINITIONS (9/21)



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DEFINITIONS (10/21)

- Process design principles applies to all kinds of engineered systems for production, pollution abatement, etc.
- You are all familiarized with wastewater treatment
  - Easier for you to understand the steps on a wastewater treatment problem
  - A major flaw in all environmental engineering departments not to include courses for air pollution control systems design

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DEFINITIONS (11/21)

- Example 1
  - A small metal finishing shop produces wastewater that is the center of complaints due to the fact that the wastewater contains hexavalent chromium (around 25 mg/L of Cr^{6+} as chromate ion). It is also highly acidic (pH is around 2) and they claim that the wastewater upsets the treatment processes when discharged to the common sewage collection system. The discharge limit is 1 mg/L of total chromium and pH 6-9.
  - The shop owner signs a contract with your employer to build a pretreatment system and you, as the design engineer, are assigned to the project.
  - What would be your action for solving this problem? Explain step by step.

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DEFINITIONS (12/21)

- Solution to Example 1
  - Preliminary definition of the problem
    - Total chromium (Cr^{6+} and Cr^{3+}) exceeds the discharge limit to the common collection system.
    - pH of wastewater is very low and it poses danger to common wastewater treatment system.
    - The solution is to reduce the pollutant load by taking necessary measures in the production line or by building a pretreatment system.
      - Steps to be taken for both solution alternatives
        - Collect samples and analyze them for at least chromium species, pH and acidity.
        - Inspect the production line: The sources of chromium and acidity, the sources of wastewater, and if it is possible to reduce the pollutant loads.
      - No way of reducing pollutant loads by taking measures on production line
      - And yes, the measurement results show that concentrations exceed discharge limits

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DEFINITIONS (13/21)

- Solution to Example 1
  - Final definition of the problem
    - A pretreatment system must be built. Concentrations must be reduced to allowable discharge limits.
    - Further steps to be taken for solving this engineering problem
      - Measure wastewater flowrate, temperature.
      - Check the facility's design and project files to understand at which points the wastewater is generated and how&where each stream mixes.
        - Always make visual inspection. Do not trust project files. See everything for yourself.
      - Collect & analyze samples (grab, 2-hour & 24-hour) for Cr^{6+}, Cr^{3+}, pH, and acidity.
    - Make a detailed research of «how-to»
      - What processes are used for Cr^{6+} removal?
      - What processes are used for neutralization, etc.?
    - Comment on your problem if it is similar to ones you found in your research

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DEFINITIONS (14/21)

- Solution to Example 1
  - Alternatives
    - Decision point: Adsorption or chemical settling?
    - Adsorption
      - No chemical sludge that can be classified as hazardous
      - Smaller space requirement (process is very fast)
      - Adsorbent cannot withstand the very low pH of wastewater
        - Neutralization unit is required
        - Already an objective of the treatment
      - Cheap, but higher amounts of waste adsorbent if natural adsorbent is used
      - Expensive, but small amounts of waste adsorbent if engineered adsorbent is used

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DEFINITIONS (15/21)

- Solution to Example 1
  - Alternatives
    - Decision point: Adsorption or chemical treatment?
    - Chemical treatment
      - Chemical sludge (hazardous)
      - Higher space requirement than adsorption
      - Chemical costs
        - For reducing Cr^{6+} into Cr^{3+}
        - For hydroxide settling
        - For neutralization
      - Storage tanks for chemicals
      - Dosage systems for chemicals
      - Mixers, etc.

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DEFINITIONS (16/21)

- Solution to Example 1
  - Design
    - Decision point: Adsorption or chemical treatment?
      - Let's select the adsorption alternative
    - Preliminary design & cost estimate
      - Neutralization unit
        - Chemical preparation and storage tanks
        - Chemical dosing systems (dosage pumps etc.)
        - Decision point: What chemical to use (lime, limestone, soda ash, caustic)?
          - Costs? Solubilities? Availability? Other requirements?
        - Decision point: Automation or manual operating? Costs? Risks?
      - Adsorber
        - Decision point: Upflow (pressurized if necessary) or downflow (open top)?
        - Decision point: Adsorbent (natural or synthetic)? Costs? Availability? Capacity? Kinetics (contact time, flow velocity, cross-sectional area, volume, etc.)? Temperature control?

DEFINITIONS (17/21)

- Solution to Example 1
  - Design
    - Decision point: Adsorption alternative selected
    - Preliminary design & cost estimate
      - Adsorber
        - Decision point: Cartouche-type or randomly packed bed?
        - Removal of used adsorbent?
        - Decision point: Regeneration or disposal?
        - How to regenerate?

        - Make a literature search for all decision points
        - Compare costs of investment and costs of operation
        - Consider availability of adsorbents and chemicals
        - Consider hauling of materials

DEFINITIONS (18/21)

- Solution to Example 1
  - Design
    - Decision point: Adsorption alternative selected
    - Final design & cost estimate
      - Neutralization
        - Chemical to be used
        - Dimensioning chemical preparation and storage tanks
          - Calculation of tank dimensions based on the amount of chemicals to be used
        - Preparing specifications of materials to be used (for tanks)
        - Selection of dosing system (pump specifications, piping specifications, valves, etc)
          - Based on maximum and minimum flowrates of chemical solutions
        - Automation system (pH meter and computers etc)
        - Mixing tank (dimensioning, materials, etc)
        - Mixers (motors, pedals, etc), calculation of level of turbulence, G values, etc.

DEFINITIONS (19/21)

- Solution to Example 1
  - Design
    - Decision point: Adsorption alternative selected
    - Final design
      - Adsorber
        - Exact specifications on the adsorbent, how to obtain it, and how much it costs
        - Dimensioning of the adsorber unit
          - Specifications of the materials
          - Directives on how to change the cartouches if cartouche-type is selected
          - Calculation of dimensions, contact time, etc
        - The inlet and outlet structures if a pressurized system is used, sampling ports
        - Calculation of how much is the service duration of a cartouche
        - Specifications of pumps, valves, and all fittings etc
        - Directives on how waste adsorbent disposal is achieved? How much does it cost?

DEFINITIONS (20/21)

- Solution to Example 1
  - Design
    - Decision point: Adsorption alternative selected
    - Final design
      - Other considerations
        - Skilled personnel?
        - Free-lance consulting?A
        - Control panels?
        - Etc.

DEFINITIONS (21/21)

- Solution to Example 1
  - Implementation
    - Total cost of installing the system.
    - Estimate of operating costs
    - Construction
    - Startup
    - Contracted operation by the designing party (you)
    - Continous monitoring, evaluation, and optimization for pre-stated period of time (based on the initial conract)
    - Delivery to the owner

FLOWSHEETS (1/5)

- A graphic description of a process
- Can vary in complexity
  - from a simple block diagram
  - to a detailed schematic showing instrumentation and stream operating conditions
- Degree of detail is determined by
  - the stage of development of the process
  - intended use of flowsheet
- At initial development stage
  - Simple qualitative flowsheet for developing connectivity of process
  - Connectivity
    - How individual components of the process are joined and how the overall process connects to the entire manufacturing facility

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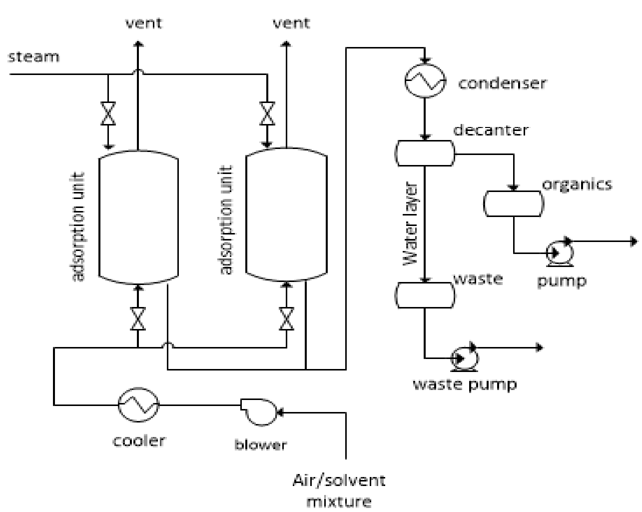
FLOWSHEETS (2/5)

- Preliminary flowsheet for a solvent recovery system



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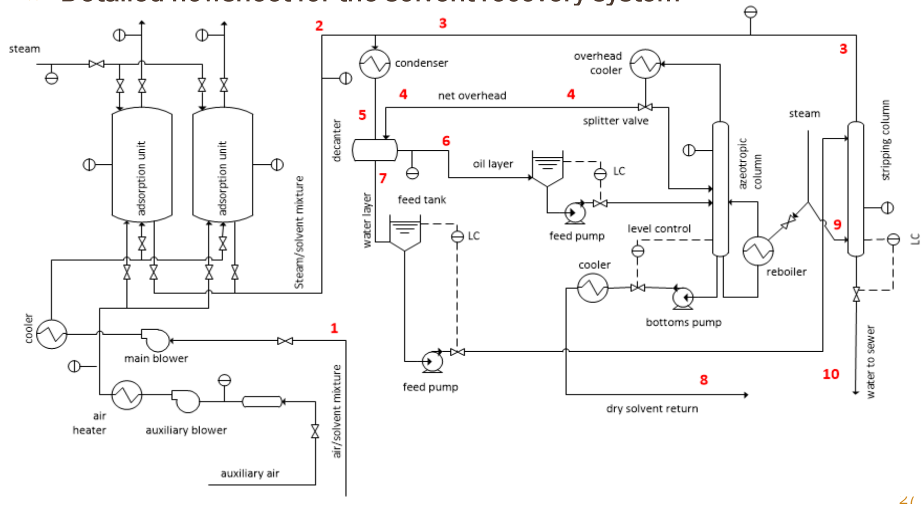
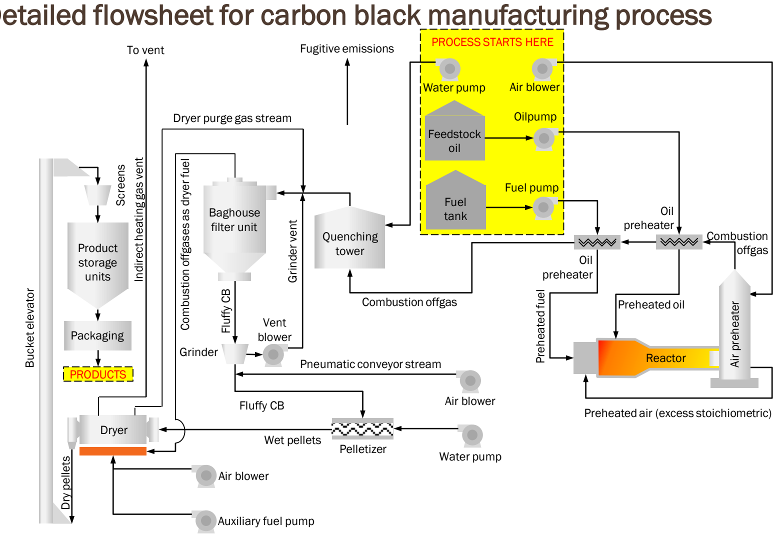
FLOWSHEETS (3/5)

- Detailed flowsheet for the solvent recovery system



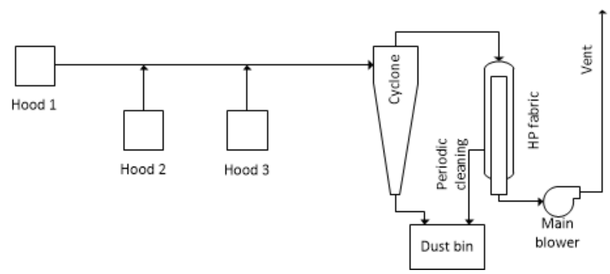
FLOWSHEETS (4/5)

- Detailed flowsheet for carbon black manufacturing process



FLOWSHEETS (5/5)

- Example 2
  - A carpenter house uses three different machines for cutting and shaping woods during production. The dust generated during the operations are collected by overhead hoods from each machine. The collected air stream will be passed through an air pollution control system to reduce dust emissions. The system consists of a cyclone and a high-performance fabric filter. Draw a preliminary flow sheet for air pollution control system design.



MATERIAL AND ENERGY BALANCES (1/19)

- Requirement of a complete knowledge of all material and energy flow
  - to and from each unit
  - for equipment selection and sizing
- Conservation of mass and energy
  - $Accumulation = Input - Output + Net\ generation$
- At steady-state
  - $0 = Input - Output + Net\ generation$
- Exceptions of steady-state approach
  - Incinerators, direct-fired dryers and adsorbers
  - Due to heat generation and/or pollutant accumulation in these units

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MATERIAL AND ENERGY BALANCES (2/19)

- Steps for performing energy and material balance calculations
  - Draw a sketch of the process
  - Identify and label all entering and exiting streams
  - Label all related data on the sketch
  - Draw a dashed envelope around that portion of the process involved in the balance
  - Select a suitable basis of materials and time frame for the calculation

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MATERIAL AND ENERGY BALANCES (3/19)

- Example 3
  - Exhausts from two storage bins at a fiberglass plant are combined and passed through a cyclone that provides 95% particulate removal on a weight basis. The following measurements were made.
    - Exhaust from bin A:
      - Flowrate: 85 m^3/min of dry air
      - Concentration: 34.3 g/sm^3 of SiO_2
      - Pressure: 8991 Pa (gage)
      - Temperature: 32 °C
    - Exhaust from bin B:
      - Flowrate: 71 m^3/min of dry air
      - Concentration: 22.9 g/sm^3 of SiO_2
      - Pressure: 15886 Pa (gage)
      - Temperature: 43 °C

Find the rate of solids discharge from cyclone, and the concentration of solids remaining in the air being exhausted from the cyclone.

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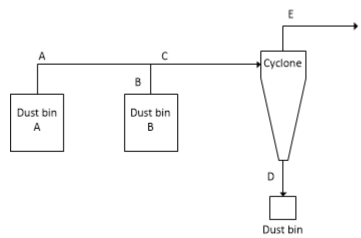
MATERIAL AND ENERGY BALANCES (4/19)

- Solution to Example 3
  - Flowsheet



  - Convert volumetric flowrates to standard conditions.
    - $Q_A = 85\frac{m^3}{min} * \frac{(101{,}325+8{,}991)Pa}{101{,}325\ Pa} * \frac{(273+25)K}{(273+32)K} = 90.4\frac{sm^3}{min}$
    - $Q_B = 71\frac{m^3}{min} * \frac{(101{,}325+15{,}886)Pa}{101{,}325\ Pa} * \frac{(273+25)K}{(273+43)K} = 77.5\frac{sm^3}{min}$

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MATERIAL AND ENERGY BALANCES (5/19)

- Solution to Example 3
  - Calculate total flowrate to cyclone
    - $Q_C = 90.4 + 77.5 = 167.9\frac{sm^3}{min}$
  - Calculate total dust loading to cyclone
    - $\dot{m}_C = Q_AC_A + Q_BC_B = 90.4\frac{sm^3}{min} * 34.3\frac{g}{sm^3} + 77.5\frac{sm^3}{min} * 22.9\frac{g}{sm^3} = 4875\frac{g}{min}$
  - Calculate dust concentration to cyclone
    - $C_C = \frac{4875\frac{g}{min}}{167.9\frac{sm^3}{min}} = 29\frac{g}{sm^3}$
  - Calculate solids discharge
    - $\dot{m}_D = 0.95\dot{m}_C = 0.95 * 4875\frac{g}{min} = 4631\frac{g}{min}$

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MATERIAL AND ENERGY BALANCES (6/19)

- Solution to Example 3
  - Calculate dust flow to exhaust
    - $\dot{m}_E = \dot{m}_C - \dot{m}_D = 4875 - 4631 = 244\frac{g}{min}$
  - Calculate dust concentration to exhaust
    - $C_E = \frac{\dot{m}_E}{Q_C} = \frac{244\frac{g}{min}}{167.9\frac{sm^3}{min}} = 1.45\frac{g}{sm^3}$

MATERIAL AND ENERGY BALANCES (7/19)

- Generalization
  - For a direct solution of simultaneous equations with *n* unknowns, *n* independent equations are required
  - The *n* required equations for a material balance can consist of one overall balance plus *C*–1 component balances, where *C* is the number of components
  - If an energy balance and material balance are considered simultaneously, an additional independent equation can be written for the overall enthalpy balance around the system

MATERIAL AND ENERGY BALANCES (8/19)

- What do we mean by generalizing?
  - There are three components in previous example: Bin A, Bin B, cyclone
    - Two balance equations can be written
    - $Q_A C_A + Q_B C_B = Q_C C_C$
    - $\dot{m}_D + \dot{m}_E = \dot{m}_D + Q_E C_E = \dot{m}_C = Q_C C_C$
  - There are five unknowns: $\dot{m}_D$, C_C, Q_C, Q_E, C_E
    - Some of them could be re-written
    - $Q_C = Q_A + Q_B$ ➔ known
    - $Q_E = Q_C = Q_A + Q_B$ ➔ known
    - $\dot{m}_D = \eta Q_C C_C$ ➔ can be described as a function of C_C
    - The number of unknowns are reduced to two: C_C and C_E
    - Value of $\dot{m}_D$ can be calculated after finding C_C

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MATERIAL AND ENERGY BALANCES (9/19)

- What do we mean by generalizing?
  - Writing the equations in matrix form, we get
    - $\begin{bmatrix} Q_C C_C & + & 0C_E \\ (1-\eta) Q_C C_C & - & Q_C C_E \end{bmatrix} = \begin{bmatrix} Q_A C_A + Q_B C_B \\ 0 \end{bmatrix}$
    - $Q_C = 90.4 + 77.5 = 167.9$
    - $\begin{bmatrix} 167.9 C_C & + & 0C_E \\ (1-0.95)167.9 C_C & - & 167.9 C_E \end{bmatrix} = \begin{bmatrix} 90.4 * 34.3 + 77.5 * 22.9 \\ 0 \end{bmatrix}$
    - $\begin{bmatrix} 167.9 & + & 0 \\ 8.395 & - & 167.9 \end{bmatrix} \begin{bmatrix} C_C \\ C_E \end{bmatrix} = \begin{bmatrix} 4875 \\ 0 \end{bmatrix}$
    - $\begin{bmatrix} C_C \\ C_E \end{bmatrix} = \begin{bmatrix} 29 \\ 1.45 \end{bmatrix} \frac{g}{sm^3}$
    - $\dot{m}_D = 0.95 * 167.9 * 29 = 4626 \frac{g}{min}$
  - Mass balance equation can be solved by solving linear system of eqn.s

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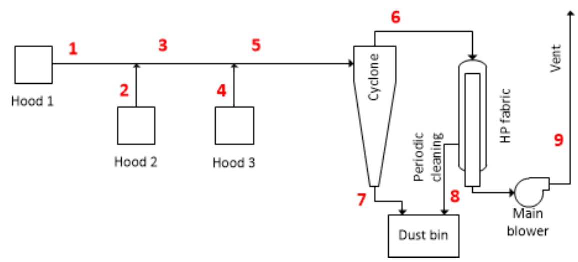
MATERIAL AND ENERGY BALANCES (10/19)

- Example 4
  - Remember previous example on air pollution control system in a carpenter house. Solve mass balance equations to calculate unknown values in the attachment. Also check whether the fan is suitable for the application or not. The fan capacity is 1500 m^3/h at a pressure of 75 cm H_2O.



MATERIAL AND ENERGY BALANCES (11/19)

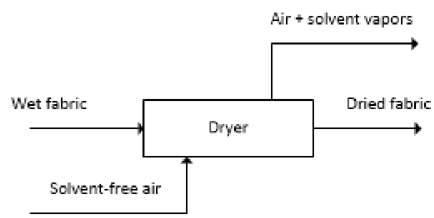
- Solution to Example 4

Stream no.	1	2	3	4	5	6	7	8	9
Stream name	Hood 1 suction	Hood 2 suction	Main line 3	Hood 3 suction	Main line 5	Cyclone exit	Cyclone dust	Filter dust	Vent
Flowrate (m^3/h)	468	216		720			–	–	
Diameter (mm)	100	70	130	100	180	180	–	–	180
Velocity (m/s)							–	–	
Length	7	5	8	5	10	1	–	–	30
Pressure loss (Pa)	831		316		308	56	–	–	1009
Particulate concentration (mg/m^3)	750	1500		1000			–	–	
Air mass flowrate (kg/h)							–	–	
Particulate mass flowrate (kg/h)									
Cyclone efficiency is 85%, filter efficiency is 100%. Air density is 1.20 kg/m^3									

Pipe pressure loss (Pa)	
Cyclone pressure loss (Pa)	1800
Filter pressure loss (Pa)	2950
Total pressure loss (Pa)	
Total pressure loss (cm H_2O)	
Fan flowrate (m^3/h)	

MATERIAL AND ENERGY BALANCES (12/19)

- Example 5
  - A textile finishing process involves drying a fabric that has been treated with a volatile solvent. The wet fabric entering the dryer contains 45% solvent, and 97% of the solvent entering the dryer volatilizes. Solvent-free air enters the dryer at a rate of 8 kilograms per kilogram of solvent-free fabric. The solvent has a molar mass of 60 g/mole.
    - Calculate the percentage of solvent in the dried fabric by weight.
    - Calculate the concentration of solvent in the dryer exhaust in mg/m^3 if the exhaust is at 70 °C and 1 atm.



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MATERIAL AND ENERGY BALANCES (13/19)

- Solution to Example 5
  - Assume a total mass of wet fabric of *m* enters to the dryer per hour
    - Mass flow of solvent-free fabric to the dryer is 0.55*m*
    - Mass flow of liquid solvent to the dryer is 0.45*m*
    - Mass flow of solvent-free air to the dryer is 8*0.55*m* = 4.40*m*
    - 97% of liquid solvent vaporizes in the dryer. Mass flow of gaseous solvent to the exhaust is 0.97*0.45*m* = 0.4365*m*
    - Mass flow of liquid solvent in the dried fabric is 0.45-0.4365 = 0.0135*m*
  - Percentage of solvent in the dried fabric is
    - $\frac{0.00135m}{0.55m+0.0135m} = 0.0240 = 2.4\%$ by weight
  - Mass fraction of solvent in the exhaust is
    - $\frac{0.4365m}{4.40m+0.4365m} = 0.09025 \frac{kg\ solvent}{kg\ mixture}$

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MATERIAL AND ENERGY BALANCES (14/19)

- Solution to Example 5
  - We need density of the mixture to find exhaust solvent concentration in mg/m^3.
    - Molar flowrate of air to the exhaust
      - $\dot{n}_{Air} = \frac{4.40m}{28.84\frac{g}{mole}} = 0.1526m\frac{moles}{h}$
    - Molar flowrate of solvent to the exhaust
      - $\dot{n}_{solvent} = \frac{0.4365m}{60\frac{g}{mol}} = 0.007275m\frac{moles}{h}$
    - Molar mass of exhaust mixture
      - $M_{mixture} = \frac{0.1526m*28.84+0.007275m*60}{0.1526m+0.007275m} = 30.26\frac{g}{mole}$
    - Density of exhaust mixture
      - $\rho_{mixture} = \frac{PM_A}{RT} = \frac{1\ atm*30.26\frac{g}{mole}}{0.082\frac{atm.L}{mole.K}*(273+70)K} = 1.076\frac{kg\ mixture}{m^3 mixture}$

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MATERIAL AND ENERGY BALANCES (15/19)

- Solution to Example 5
  - The exhaust solvent concentration in mg/m^3 is the product of exhaust density and mass fraction of solvent
  - $C = 0.9025\frac{kg\ solvent}{kg\ mixture} * 1.076\frac{kg\ mixture}{m^3 mixture} = 0.097109\frac{kg\ solvent}{m^3 mixture} = 97109\frac{mg}{m^3}solvent$

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MATERIAL AND ENERGY BALANCES (16/19)

- Enthalpy
  - Definition
    - *H = U + PV*
    - A physical property of the fluid
    - Very useful in making an energy balance on a flowing stream of gas
  - Point function
    - Function of the conditions at a given point
    - Independent of path to that particular point
  - Do not use absolute enthalpy
    - Use the change of enthalpy between a particular point and a datum
  - Enthalpy of air ➔ use psychrometric charts & tables

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MATERIAL AND ENERGY BALANCES (17/19)

- Enthalpy
  - Near atmospheric pressure, air behaves nearly ideally
    - Enthalpy is virtually independent of pressure
    - Change of enthalpy due to a change in temperature is
      - $\Delta H = H_2 - H_1 = \int_{T_1}^{T_2} C_p dT$
      - C_p is specific heat at constant pressure, kcal/kg.K
      - *T* is absolute temperature, K
    - For $T < 150°C$, following approach is sufficiently accurate
      - $\Delta H = C_{P,avg}(T_2 - T_1)$
      - $C_{P,avg}$ is average value of specific heat in temperature interval
  - Just a reminder of enthalpy. I've decided removing energy balance examples in this version

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MATERIAL AND ENERGY BALANCES (18/19)

Specific enthalpy of dry air (datum temperature is 15.5°)

T, °C	H, kJ/kg		T, °C	H, kJ/kg		T, °C	H, kJ/kg		T, °C	H, kJ/kg
30	14.5		200	186.5		750	782.8		1400	1558.1
35	19.6		225	212.1		800	840.3		1450	1619.5
40	24.6		250	237.9		850	898.3		1500	1681.1
45	29.6		275	263.9		900	1349.1		1550	1742.7
50	34.6		300	290.1		950	1452.6		1600	1804.5
60	44.6		350	342.8		1000	1558.8		1650	1866.4
70	54.7		400	397.5		1050	1667.7		1700	1928.4
80	64.8		450	451.8		1100	1779.4		1750	1990.5
90	74.8		500	505.9		1150	1252.5		1800	2052.7
100	84.9		550	559.7		1200	1313.4		1850	2115.0
125	110.2		600	613.3		1250	1374.4		1900	2177.4
150	135.6		650	669.3		1300	1435.5		1950	2240.0
175	161.1		700	725.8		1350	1496.7		2000	2302.6

MATERIAL AND ENERGY BALANCES (19/19)

Enthalpies of saturated steam and water, kJ/kg

T, °C	Sat. Liq.	Sat. Vapor		T, °C	Sat. Liq.	Sat. Vapor		T, °C	Sat. Liq.	Sat. Vapor		T, °C	Sat. Liq.	Sat. Vapor		T, °C	Sat. Liq.	Sat. Vapor		T, °C	Sat. Liq.	Sat. Vapor
0	0.00	2500.8		21	88.04	2538.6		42	175.72	2576.5		63	263.48	2614.0		84	351.50	2650.7		125	524.65	2713.0
1	4.23	2502.6		22	92.21	2540.4		43	179.89	2578.4		64	267.66	2615.8		85	355.70	2652.4		130	545.97	2719.8
2	8.44	2504.4		23	96.39	2542.2		44	184.07	2580.2		65	271.85	2617.5		86	359.91	2654.0		135	567.37	2726.5
3	12.64	2506.2		24	100.56	2544.0		45	188.24	2582.1		66	276.03	2619.3		87	364.11	2655.6		140	588.85	2732.9
4	16.85	2508.0		25	104.74	2545.8		46	192.42	2583.9		67	280.22	2621.0		88	368.31	2657.2		145	610.39	2739.1
5	21.05	2509.8		26	108.92	2547.6		47	196.59	2585.7		68	284.40	2622.8		89	372.52	2658.8		150	632.00	2745.1
6	25.25	2511.6		27	113.09	2549.4		48	200.77	2587.6		69	288.59	2624.5		90	376.73	2660.4		155	653.69	2750.8
7	29.45	2513.4		28	117.27	2551.2		49	204.95	2589.4		70	292.78	2626.2		91	380.93	2662.0		160	675.45	2756.2
8	33.65	2515.2		29	121.44	2553.0		50	209.13	2591.2		71	296.97	2628.0		92	385.14	2663.6		165	697.28	2761.5
9	37.84	2517.0		30	125.62	2554.8		51	213.30	2593.0		72	301.16	2629.7		93	389.35	2665.2		170	719.19	2766.5
10	42.03	2518.8		31	129.80	2556.6		52	217.48	2594.8		73	305.35	2631.5		94	393.56	2666.8		175	741.16	2771.3
11	46.22	2520.6		32	133.97	2558.4		53	221.66	2596.5		74	309.54	2633.2		95	397.77	2668.4		180	763.21	2775.8
12	50.41	2522.4		33	138.15	2560.2		54	225.84	2598.3		75	313.73	2634.9		96	401.98	2670.0		185	785.33	2780.1
13	54.60	2524.2		34	142.32	2562.0		55	230.02	2600.1		76	317.93	2636.6		97	406.20	2671.5		190	807.52	2784.2
14	58.78	2526.0		35	146.50	2563.8		56	234.20	2601.9		77	322.12	2638.4		98	410.41	2673.1		195	829.78	2788.0
15	62.97	2527.8		36	150.67	2565.6		57	238.38	2603.6		78	326.32	2640.1		99	414.63	2674.7		200	852.12	2791.6
16	67.15	2529.6		37	154.85	2567.4		58	242.56	2605.3		79	330.51	2641.8		100	418.85	2676.2				
17	71.32	2531.4		38	159.02	2569.2		59	246.74	2607.1		80	334.71	2643.5		105	440.05	2683.0				
18	75.50	2533.2		39	163.20	2571.0		60	250.93	2608.8		81	338.91	2645.8		110	461.09	2690.9				
19	79.68	2535.0		40	167.38	2572.8		61	255.12	2610.5		82	343.10	2647.5		115	482.21	2698.5				
20	83.85	2536.8		41	171.54	2574.7		62	259.30	2612.2		83	347.30	2649.1		120	503.39	2705.8				

ANALYSIS OF A PC POWER PLANT (1/13)

- Theory of producing electricity
  - Coal ➔ Heat energy ➔ Mechanical energy ➔ Electrical energy
  - PC means pulverized coal. Pulverized for
    - easy pneumatic carrying
    - fast and efficient burning

  - Efficiency depends on efficiency of
    - Converting mechanical work into electric energy
    - Converting heat energy to mechanical work
    - Converting chemical energy in coal into heat energy
      - That's why the coal is pulverized. To increase efficiency and speed of conversion

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ANALYSIS OF A PC POWER PLANT (2/13)

- PC Plants
  - Most significant emissions
    PM, SO_2, NO_x, Hg, and CO_2
- Steps of accomplishing main goal of producing electricity
  - Coal is crushed, conveyed and stored in bunkers
  - Bunkers feed coal to pulverizer
  - Pulverized coal is conveyed to furnace
    - Conveying is accomplished pneumatically by a large volume of air
    - Air stream contains atmospheric air, provides excess oxygen for combustion
  - PC is burned within furnace generating heat
  - Heat is transferred to high purity water generating superheated steam
  - Steam transfers its energy to mechanical work in turbines
  - Turbines rotate generators to produce electricity

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ANALYSIS OF A PC POWER PLANT (3/13)

- Notes
  - Pneumatic conveying air stream should have a flowrate that provides necessary oxygen for combustion (stoichiometric and excess oxygen)
  - Air stream should be preheated for fast and efficient combustion
  - Heating of air stream is accomplished through indirect contact of flue gases with air stream in a heat exchanger
  - Steam is produced by circulating high-purity water in tubes within furnace/boiler
  - Excess heat in flue gases is also used to superheat the steam in a second chamber within the furnace
  - In turbines, hot steam transfers its pressure and thermal energy into mechanical work

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ANALYSIS OF A PC POWER PLANT (4/13)

- Notes
  - Steam cools down and is transferred to a condenser
  - Another stream of low-purity water is used in cooler and steam is condensed
  - Condensed high-purity water is recirculated to furnace to produce more steam
  - Condensing water flow is sent to a cooler, usually a natural draft-type
    - Discussion on natural-draft type cooling towers
  - Cooled water is recirculated to condenser to condense more steam
  - Cooled flue gases are sent to air pollution control system
    - Particulate control
    - SO_2 control & NO_x control
    - Further

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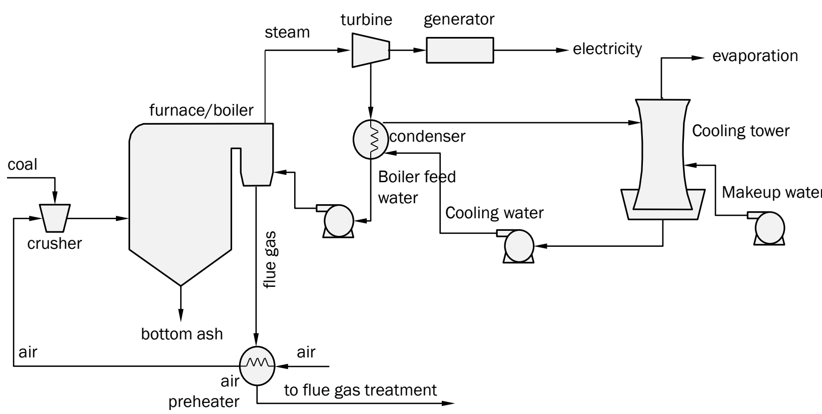
ANALYSIS OF A PC POWER PLANT (5/13)

- Simplified flow diagram for a PC plant



ANALYSIS OF A PC POWER PLANT (6/13)

- Classroom discussion
  - What do we mean by high-purity water? Which properties of water interferes with the process?
  - What about natural-draft type cooling towers
  - In what range of temperature is the hot steam and cooled steam? Why?
  - What about conversion efficiencies in each step?
    - Carnot cycle and Rankine cycle
  - Do we need any makeup water for high-purity and low-purity water streams?
  - How are these water streams treated? Any treatment system?
  - Other considerations…
  - Watch the video given in the attachment…

ANALYSIS OF A PC POWER PLANT (7/13)

- Example 6
  - A 750 MW power plant is burning coal that has the following properties: heating value = 23500 kJ/kg, carbon content = 60%, ash content = 9%, sulfur content = 2.2%, and mercury content o= 120 ppb. The plant has an overall thermal efficiency of 37.5%. Assume that 20% of the fly ash falls out in the bottom of the furnace and the rest goes out with the gases. An ESP collects the PM, and a wet scrubber controls SO_2. The required air pollution control device efficiencies are as follows: the ESP is 99.4% efficient; the wet scrubber is 92% efficient. Calculate
    - The rate of heat emissions to the environment in kJ/s
    - The coal feed rate to the furnace in ton/day
    - The rate of ash emissions to the atmosphere in kg/day
    - The rate of SO_2 emissions to the atmosphere in kg/day
    - The rate of mercury emissions to the atmosphere in g/day assuming 30% Hg removal in the wet scrubber
    - The rate of CO_2 emissions to the atmosphere in tons/day

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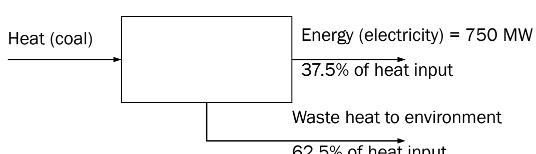
ANALYSIS OF A PC POWER PLANT (8/13)

- Solution to Example 6
  - Draw a simplified energy flow diagram and make calculations



  - Heat input is
    - 750 / 0.375 = 2000 MW
  - Waste heat to atmosphere is
    - 2000 – 750 = 1250 MW
  - In kilojoules per second
    - $Q_{waste} = 1250MW * \frac{1000kW}{1MW} * \frac{1\frac{kJ}{s}}{1kW} = 1.25 * 10^6 \frac{kJ}{s}$

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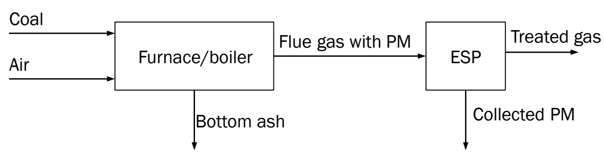
ANALYSIS OF A PC POWER PLANT (9/13)

- Solution to Example 6
  - The coal input rate is
    - $\dot{m}_{coal} = \frac{2000MW * \frac{1000kW}{1MW} * \frac{1\frac{kJ}{s}}{1kW}}{23500\frac{kJ}{kg}} * \frac{1\ ton}{1000kg}\frac{86400s}{1day} = 7353\frac{ton}{s}$
  - PM emissions



  - The rate of ash formation is
    - 0.09 * 7353 = 661.8 ton/day = 661800 kg/day

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ANALYSIS OF A PC POWER PLANT (10/13)

- Solution to Example 6
  - The mass flow of ash to bottom is
    - 661800 kg/day * 0.2 = 132360 kg/day
  - The mass flow of ash to ESP is
    - 661800 kg/day * 0.8 = 529440 kg/day
  - The emission rate of PM is
    - 529440 kg/day * (1 – 0.994) = 3177 kg/day

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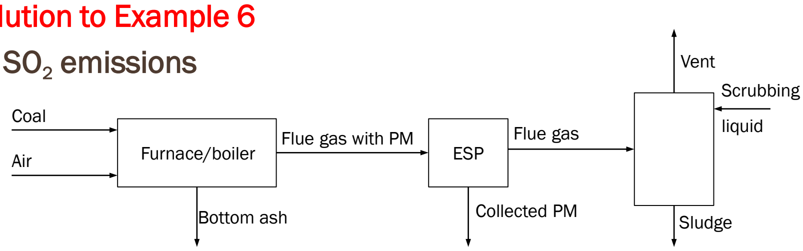
ANALYSIS OF A PC POWER PLANT (11/13)

- Solution to Example 6
  - SO_2 emissions



  - Sulfur that comes with coal is
    - 7353 ton/day * 0.022 = 161.8 ton/day
  - Sulfur dioxide formed in combustion is
    - 121.8*2 = 323.6 ton/day
  - Sulfur dioxide emitted is
    - 323.6* (1 – 0.92) = 25.88 ton/day = 25880 kg/day

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ANALYSIS OF A PC POWER PLANT (12/13)

- Solution to Example 6
  - The rate of mercury coming with coal is
    - 7353 ton/day * 0.120 g/ton = 882 g/day
  - 30% of this is removed in the scrubber. The emission rate is
    - 882 g/day * (1 – 0.30) = 617.4 g/day
  - Mass of carbon coming with coal is
    - 7353 ton/day * 0.6 = 4412 ton/day
  - The rate of CO_2 emission
    - 4412 ton C/day * 44 ton CO_2 / 12 ton C = 16177 ton CO_2/day

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ANALYSIS OF A PC POWER PLANT (13/13)

- Example 7
  - Derive the CO_2 emission factor for the coal in previous example
- Solution to Example 7

+ $$EF_{CO2} = \frac{16177\frac{kg}{day}*\frac{1\ day}{24\ h}}{750MW} = 0.899\frac{kg}{MWh}$$ of CO_2

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