Unit Five – First Law for Steady, Open Systems

Mechanical Engineering 370

Thermodynamics

Larry Caretto

September 23, 2010

California State University Northridge

Outline

- Quiz four results
- Unit five – steady open systems
  - View first law as a rate equation
  - Have mass crossing system boundaries
  - Flows across boundaries have several energy forms including internal (u) , kinetic and potential energy plus flow work (Pv)
  - Internal energy plus flow work is h = u + Pv

California State University Northridge 2

Future Quizzes

- Use equation summary from course web site
  - Presently in "What's New' section
  - Always available from link to course notes
- Only the ten highest quiz grades (of twelve) are counted in final grade
- Total quiz grade based on quizzes taken
  - Students who take N quizzes with N < 10 will receive zeros on 10 – N quizzes

California State University Northridge 3

Unit Five Goals

- Topic is first law for open systems, i.e., systems in which mass flows across the boundary
- Will look at general results and focus on steady-state systems.
- As a result of studying this unit you should be able to
  - understand all the terms (and dimensions) in the first law for open systems:

California State University Northridge 4

Open System Concepts

Use rate terms mass/time, energy/time = power

$\dot{W}_u$ the useful work rate or mechanical power (kW)

$\dot{m}$ the mass flow rate (kg/s)

$\frac{\vec{V}^2}{2}$ the kinetic energy per unit mass (kJ/kg)

gz the potential energy per unit mass (kJ/kg)

$E_{system} = m(u + \frac{\vec{V}^2}{2} + gz)_{system}$ total energy (kJ)

$\dot{Q}$ heat transfer rate (kW)

$\frac{dE_{system}}{dt}$ rate of energy change (kW)

Engineering units use Btu/hr

California State University Northridge 5

Unit Five Goals Continued

- use the equation relating velocity, mass flow rate, flow area, A, and specific volume

$$\dot{m} = \frac{\vec{V}A}{v}$$

- use the mass balance equation

$$\frac{dm_{system}}{dt} = \sum_{inlet} \dot{m}_i - \sum_{outlet} \dot{m}_i$$

California State University Northridge 6

Flow Work

- For open systems work is done on (or by) mass entering and leaving the system
- Flow work is Pv times mass flow rate
- Add this flow work to internal energy (times mass flow rate)
- First law for mass flows has h = u + Pv (sum of internal energy plus flow work)

California State University Northridge 7

Unit Five Goals Continued

– use the first law for open systems

$$\frac{dE_{system}}{dt} = +\sum_{inlet}\dot{m}_i\left(h_i + \frac{\vec{V}_i^2}{2} + gz_i\right) + \dot{Q} - \dot{W}_u - \sum_{outlet}\dot{m}_o\left(h_o + \frac{\vec{V}_o^2}{2} + gz_o\right)$$

– use the steady-state assumptions and equations

$$\frac{dm_{system}}{dt} = \frac{dE_{system}}{dt} = 0$$

California State University Northridge 8

Steady-state equations

– Steady-state first law for open systems

$$\dot{Q} = \dot{W}_u + \sum_{outlet}\dot{m}_o\left(h_o + \frac{\vec{V}_o^2}{2} + gz_o\right) - \sum_{inlet}\dot{m}_i\left(h_i + \frac{\vec{V}_i^2}{2} + gz_i\right)$$

– Steady-state mass balance for open systems

$$\sum_{inlet}\dot{m}_i = \sum_{outlet}\dot{m}_o$$

California State University Northridge 9

Unit Five Goals Continued

– recognize that kinetic and potential energies are usually negligible
  - A 1°C temperature change in air (ideal gas with c_p = 1.005 kJ/(kg·K) has Δh = 1005 J/kg
  - The same kinetic energy change requires a velocity increase from zero to 45 m/s (~100 mph)
  - The same potential energy change requires an elevation of 102 m (336 ft)

California State University Northridge 10

Unit Five Goals Concluded

– handle simplest case: steady-state, one inlet, one outlet (one mass flow rate), negligible changes in kinetic and potential energies

$$\dot{W}_u = \dot{Q} - \dot{m}(h_{out} - h_{in})$$

– work with ratios q and w

– Use the general definition of these ratios and the first law, which are (in simplest case)

$$q = \frac{\dot{Q}}{\dot{m}} \qquad w_u = \frac{\dot{W}_u}{\dot{m}} \qquad w_u = q - (h_{out} - h_{in})$$

California State University Northridge 11

Example Calculation

- **Given:** 10 kg/s of H_2O at 10 MPa and 700°C enters a steam turbine; the outlet is at 500 kPa and 300°C. There is a heat loss of 400 kW.
- **Find:** Useful work rate (power output)
- **Assumptions:** Steady-state, negligible changes in kinetic and potential energies
- **Configuration:** one inlet and one outlet

California State University Northridge 12

Example Continued

- First Law for this case
  - Steady-state open system
  - One inlet and one outlet
  - Assume kinetic and potential energy changes are negligible

Steady

$$\frac{dE_{system}}{dt} = \dot{Q} - \dot{W}_u + \sum_{inlet} \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + g z_i \right) - \sum_{outlet} \dot{m}_o \left(h_o + \frac{\vec{V}_o^2}{2} + g z_o \right)$$

One Inlet One Outlet

$$\dot{W}_u = \dot{Q} + \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out}$$

First Law and Mass Balance

- Simplify mass balance equation for this problem

Steady One Inlet One Outlet

$$\frac{dm_{system}}{dt} = \sum_{inlet} \dot{m}_i - \sum_{outlet} \dot{m}_o$$

- Combine result, $\dot{m}_{out} = \dot{m}_{in} = \dot{m}$ with first law for problem from previous chart

$$\dot{W}_u = \dot{Q} + \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out}$$

$$\dot{W}_u = \dot{Q} + \dot{m}(h_{in} - h_{out}) = \dot{Q} - \dot{m}(h_{out} - h_{in})$$

Getting the Answer

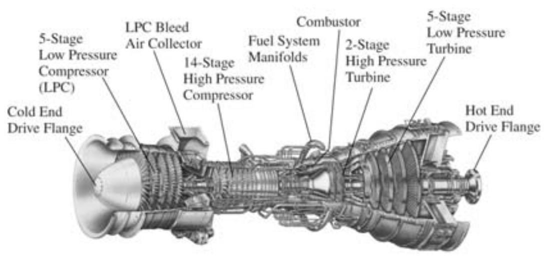
- First law in this case $\dot{W}_u = \dot{Q} - \dot{m}(h_{out} - h_{in})$
- At T_{in} = 700ºC and P_{in} = 10 MPa, h_{in} = 3870.0 kJ/kg (p. 920)
- At T_{out} = 300ºC and P_{out} = 500 kPa, h_{out} = 3064.6 kJ/kg
- Sign convention is that heat loss is negative: $\dot{Q} = \dot{Q}_{in} - \dot{Q}_{out}$
- Set $\dot{Q}$ = –400 kW in first law

The Answer

$$\dot{W}_u = (-400\ kW) - \frac{10\ kg}{s}\left(3064.6\frac{kJ}{kg} - 3870.0\frac{kJ}{kg}\right)\frac{kW \cdot s}{1\ kJ} = 7{,}654\ kW$$

- Positive work denotes a power output
- Turbine is a work producing device
- See diagram from text on next chart

Compressor and Turbine

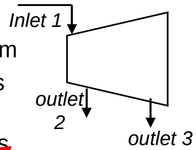


Another Example Calculation

- **Given:** 10 kg/s of H_2O at 10 MPa and 700ºC enters a steam turbine; one outlet (flow of 2 kg/s) is at 500 kPa and 300ºC. The other outlet is at 20 kPa and 90% quality. There is a heat loss of 400 kW.
- **Find:** Useful work rate (power output)
- **Assumptions:** Steady-state, negligible changes in kinetic and potential energies
- **Configuration:** one inlet and two outlets

Example Continued

- First Law for this case
  - Steady-state open system
  - One inlet and two outlets
  - Assume kinetic and potential energy changes are negligible



Steady

$$\frac{dE_{system}}{dt} = \dot{Q} - \dot{W}_u + \sum_{inlet} \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + gz_i \right) - \sum_{outlet} \dot{m}_o \left(h_o + \frac{\vec{V}_o^2}{2} + gz_o \right)$$

One Inlet

$$\dot{W}_u = \dot{Q} + \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3$$

California State University Northridge 19

First Law and Mass Balance

- Simplify mass balance equation for this problem

Steady One Inlet

$$\frac{dm_{system}}{dt} = \sum_{inlet} \dot{m}_i - \sum_{outlet} \dot{m}_o$$

$$0 = \dot{m}_1 - \dot{m}_2 - \dot{m}_3 \qquad \dot{m}_3 = \dot{m}_1 - \dot{m}_2 = \frac{10\ kg}{s} - \frac{2\ kg}{s} = \frac{8\ kg}{s}$$

- Combination of mass balance and first law

$$\dot{W}_u = \dot{Q} + \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3 = \dot{Q} + \frac{10\ kg}{s} h_1 - \frac{2\ kg}{s} h_2 - \frac{8\ kg}{s} h_3$$

California State University Northridge 20

Get Enthalpy and Heat Flow

- At T_1 = 700ºC and P_1 = 10 MPa, h_1 = 3870.0 kJ/kg (p. 920)
- At T_2 = 300ºC and P_2 = 500 kPa, h_2 = 3064.6 kJ/kg
- At P_3 = 20 kPa and x_3 = .9, h_3 = 251.42 kJ/kg + .9(2357.5 kJ/kg) = 2373.2 kJ/kg
- Sign convention is that heat loss is negative: $\dot{Q} = \dot{Q}_{in} - \dot{Q}_{out}$
- Set $\dot{Q}$ = –400 kW in first law

California State University Northridge 21

Getting the Answer

$$\dot{W}_u = \dot{Q} + \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3$$

$$\dot{W}_u = -400\ kW + \left(\frac{10\ kg}{s} \frac{3870.0\ kJ}{kg} - \frac{2\ kg}{s} \frac{3064.6\ kJ}{kg} - \frac{8\ kg}{s} \frac{2373.2\ kJ}{kg} \right) \frac{kW \cdot s}{1\ kJ} = 13{,}185\ kW$$

- Work greater in this case because of lower output pressure
- Shows how to handle multiple outlets

California State University Northridge 22

Doing Open System Problems

- Which approach is best for you?
  - Remember general equation and treatment of terms for various assumptions
  - Remember results for specific situations
  - Use a combination of these two approaches
- Transient problems (next week) have additional results
- All future quizzes and exams will be at least an open equation sheet

California State University Northridge 23

Class Exercise

- The inlet to an R-134a compressor is a saturated vapor at 0ºF. It's outlet has a pressure and temperature of 160 psia and 140ºF, respectively. The flow rate is 100 lb_m/hr and the heat loss is 100 Btu/hr. Find the work rate (power).

California State University Northridge 24

Class Exercise II

- Substance: R-134a
- Inlet: T_{in} = 0°F, saturated vapor
- Outlet: P_{out} = 160 psia, T_{out} = 140°F
- Assumptions and observations
  - Steady flow
  - Negligible changes in kinetic and potential energy
  - One inlet and one outlet

California State University Northridge 25

Class Exercise III

- First Law for this case
  - Steady-state open system
  - One inlet and one outlet
  - Assume kinetic and potential energy changes are negligible

Steady

$$\frac{dE_{system}}{dt} = \dot{Q} - \dot{W}_u + \sum_{inlet} \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + g z_i \right) - \sum_{outlet} \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + g z_i \right)$$

One Inlet One Outlet

$$\dot{W}_u = \dot{Q} + \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out}$$

California State University Northridge 26

Class Exercise IV

- Simplify mass balance equation for this problem

Steady One Inlet

$$\frac{dm_{system}}{dt} = \sum_{inlet} \dot{m}_i - \sum_{outlet} \dot{m}_i$$

One Outlet

- Combine result, $\dot{m}_{out} = \dot{m}_{in} = \dot{m}$ with first law for problem from previous chart

$$\dot{W}_u = \dot{Q} + \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out}$$

$$\dot{W}_u = \dot{Q} + \dot{m}(h_{in} - h_{out}) = \dot{Q} - \dot{m}(h_{out} - h_{in})$$

California State University Northridge 27

Class Exercise V

- First law in this case $\dot{W}_u = \dot{Q} - \dot{m}(h_{out} - h_{in})$
- At T_{in} = 0°F and saturated vapor h_{in} = h_g(0°F) = 103.08 Btu/lb_m (p. 976)
- At P_{out} = 160 psia, T_{out} = 140°F, h_{out} = 125.32 Btu/lb_m (p. 979)
- Sign convention is that heat loss is negative: $\dot{Q} = \dot{Q}_{in} - \dot{Q}_{out}$
- Set $\dot{Q}$ = –100 Btu/hr in first law

California State University Northridge 28

Class Exercise VI

$$\dot{W}_u = \frac{-100\ Btu}{hr} - \frac{100\ lb_m}{hr}\left(125.32\frac{Btu}{lb_m} - 103.08\frac{Btu}{lb_m}\right)\frac{hp \cdot hr}{2544.5\ Btu} = -0.913\ hp$$

- Negative work denotes a power input
- Compressor is a work consuming device
- See diagram on slide 17

California State University Northridge 29