SAULT COLLEGE OF APPLIED ARTS & TECHNOLOGY

SAULT STE. MARIE, ONTARIO

COURSE OUTLINE

Course Title:	APPLIED THERMODYNAMICS
Code No.:	MCH 305
Program:	MECHANICAL TECHNOLOGY
Semester:	5th
Date:	AUGUST 1983
Author:	W. J. ADOLPH

New: Revision

APPROVED

Chairperson <? Date

APPLIED THERMODYNAMICS — MCH 305
Course Name — Course Number

PHILOSOPHY/GOALS:

It is the goal of this course to succeed in providing the student of thermodynamics with the basic tools to be able, in subsequent courses, or on his own with a suitable text to apply the principles and techniques learned to the practical problems such as mixtures of vapours and gases, combustion, and steam plants. The discipline demanded by the course is transferrable to other endeavours.

METHOD OF ASSESSMENT:

Topical tests will provide the basis for subsequent grading. There are 5 topics, but proficience with topics 1 and 2 will likely be determined on the same test. Test numerical scores and letter grades are related as shown:

80 - 100%	A
66 - 79%	B
55 - 65%	C

TEXTBOOK(S):

Applied Thermodynamics for Engineering Technologists,
T.D. Eastop and A. McConkey
Longman

COMPETENCIES

General Competencies:

The student will be able to:

1. Apply the principles of thermodynamics to the analysis of and for an understanding of heat transfer devices, gas mixing, psychrometric devices, refrigeration and heat pumping devices, flow-through nozzles.

2. Exhibit a working knowledge of fundamentals of heat engine thermodynamics and the factors which account for efficiency improvement.

3. Produce *free* hand sketches and analysis in a professional manner.

4« Exhibit the evidence of his competence from his collection of problem lab assignments.

GENERAL OUTLINE

Topic 1 Review of Basic Thermodynamics

Reversibility, and reversible work, the first law, non-flow and steady flow equation, the working fluid - steam and perfect gas.

Topic 2 Reversible and Irreversible Processes

Reversible non-flow processes: constant volume, constant pressure, constant temperature, adiabatic and polytropic. Irreversible processes; flow and nonsteady flow.

Topic 3 The Second Law and Entropy

The heat engine, entropy, the T-s diagram for steam, and perfect gas, reversible process on a T-s diagram, entropy and irreversibility, availability.

Topic 4 The Heat engine cycles

The Carnot cycle, constant pressure cycle, air standard cycle, otto cycle, diesel cycle, dual combustion cycle, mean effective pressure, Stirling, Ericson and K-cyle, the practical Gasturbine, and the modified cycler.

SPECIFIC OBJECTIVES FOR REVIEW OF BASIC THERMODYNAMICS

The student will be able to:

Reversibility

1. List the three criteria of reversibility.

2. Explain why reversibility is impossible in practice.

3. Determine the reersible work done when a fluid at 3 bar and 0.18 m^/kg expands behind a piston to 0.6 bar according to the law p = $£^2$
   u

4. Define "reversible cycle".

5. Calculate the net work done by a kilogram of a fluid occupying 0.05-3 m at 20 bar when it expands reyersibly behind a piston according to pv^2 = c to a volume of 0.1 nr.

6. Explain, using a box with moveable partitions that irreversible work is not equal to pdu.

Conservation of Energy

7. Recall and write the first law of Thermodynamics.

8. Write the general energy equation and circle the terms which define the non flow energy equation. Write the non flow equation.

9. Calculate the change in internal energy of the working fluid when compressed during the compression stroke of an internal-combusion engine in which heat rejected to cooling water is 45 kj/kg and work input is 90 kj/kg.

10. Write the energy equation as it would be applied to a gas turbine unit.

11. Calculate the power required to drive a compressor and determine the inlet and outlet pipe corss-sectional areas. Air flows steadily of 0.4 kg/s entering at 6 m/s at 1 bar, specific volume of 0.85 m^2/kg, and leaves at 45 m/s at 6.0 bar and specific volume 0.16 nr/kg. Internal energy of air leaving is 88 kj/kg greater than the air entering. The colling water jacket absorbs heat from the air at 59 kj/s.

The Working Fluid

12. Draw a pressure volume diagram for steam, listing critical temperature and pressure, and showing several lines of the temperature family.

13. Define "saturated liquid line", "saturated vapour line" "drysaturated", "saturation temperature", "saturation pressure", "superheat", "degree of superheat"3"dryness fraction".

I-', a Using the differences in the shapes of the constant temperature curves close to, and far from the saturated vapour line of steam on a p-v diagram, explain the subtle difference - between vapours and gases.

15. Using tables, and the applicable formulae for determining dryness fraction of wet steam, determine the specific volume, enthalpy, internal energy of wet steam at 18 bar and 0.9 dryness fraction.

16. Using tables and appropriate formulae, determine the dryness fraction, specific volume, and internal energy of steam at 7 bar, and enthalpy 2600 kj/kg.

17. Determine the degree of superht, the enthalpy, and the internal energy. Show the condition on a p-v diagra1'. Steam is at 110 bar, and specific volume of 0.0196 m^/kg.

The Perfect Gas

18. Write the characteristic equation of state, using the pro per relationship for the amount of stuff as

(a) Kilograms-mass
(b) Kilogram-moles

19. State Avoqadro's hypothesis and write the relationship of equality between mass in kilograms, and moles.

20. State the symbol and value of the Universal gas constant.

21. Calculate the new pressure when a vessel of .2m^, already filled with nitrogen at 1.013 bar and 15°C has 0.2 kg more nitrogen added to it. Temperature is allowed to restore to 15°C.

22. Calculate the final temperature when 0.01 kg of a perfect gas at 0.003m3 and 7 bar and 131°C is allowed to expand to a pressure of 1 bar and a volume of 0.02 m^.

Specific Heats

23. Define the specific hear of a solid, a liquid, a gas.

24. State the two incremental equations for specific heats of gases.-

25. Explain why, when after integration of $dQ = c_v dT$, the constant of integration in $u = c_v T_t K$, the constant disappears.

26. State the meaning of the difference and the quotient of Cp and C_v.

27. Using the non flow energy equation, and substituting for the difference between internal energies, and work done at constant pressure, prove that R= cp - cv.

28. Determine the gas constant and the molecular weight of a gas knowing C_v=0.657 kJ/kgK and C_p=0.896 kJ/kgK.

TOPIC 2

Reversible and Irreversible Processes

71.e student will be able to:

1. List the pertinent formulae for the non flow, constant volume process, and the non flow constant pressure process.

2. Explain why it is that heat transferred in a constant pressure process is determined by the difference in enthalpies, while for the constant volume process, Q is determined by thedifference in internal energies.

3. Determine the heat supplied and the work done when 0.05 kg of a certain fluid is heated of constant pressure of 2 bar, until the volume is 0.0658 m^3 when:

   (a) the fluid is steam initially drysat.
   (b) the fluid is air initially at 130°C.

4. Explain why tables must be used when doing thermal calculations involving steam.

5. Calculate the work done per kg of steam when steam at 7 bar and dryness fraction 0.9 expands isothermally and reversibly behind a piston, to a pressure of 1.5 bar. Assume heat supplied is 400 kj/kg.

6. Prove by means of the non flow equation that for a perfect gas, heat transferred is equal to work done for an isothermal process.

7. Recall the definition of adialsatic.

8. Write the non-flow energy equation for the adeabatic case and indicate which terms are zero value.

9. Recall that for a reversible adiabatic process for a perfect gas.

10. Recall that for any polytropic reversible process for a perfect gas.

11. Calulate the workdone when 1 kg of steam at 100 bar and 375°C expands reversibly in a perfectly insulated cylinder behind a piston until the pressure is 38 bar and the steam is dry saturated. Show the process on a p-v diagram.

12. Calculate the final temperature, the final volume and the work done on the air in a cylinder initially at 1.02 bar, and 22°C, occupying a cylinder of volume $0.015m^3$, when it is compressed reversibly and adiabatically by a piston to 6.8 bar. Show the process on a p-v diagram.

13. Calculate the work done per kg of steam and the heat flow per kg of steamto or from the cylinder during the expansion stroke of a steam engine which starts at 7 bar and dryness fraction 0.95 along the law pv^-1 = c to a pressure of 0.34 bar. Show the process on a p-v diagram.

14. Recall the formulae for polytropic work done and polytropic heat transferred.

15. Calculate the heat flow to and from the cylinder walls when 1 kg of ethane (assume perfect gas) is compressed from 1.1 bar, 27°C according to $pv^{**3} = c$. The steam is initially drysat. Draw the appropriate p-v diagram.

16. Calculate the heat flow, and the work done per kg of steam, when steam in a cylinder expands from 5.5 bar to 0.75 bars according to the law pv=c. The steam is initially drysat. Draw the appropriate p-v diagram.

17. State the special considerations that have to be made to accountfor the fact that a steam vapour does not obey the perfect gas law. Draw the appropriate p-v diagram.

18. On p-v co-ordinates draw the process characteristic curves for processes with the characteristic n= 0, n= 1, n=   , and n=   and list at the side the various meanings for the different values on
M „_ It

n .

<u>Irreversible Processses</u>

20. Recall the criteria of reversibility.

21. List the significant features of an unresisted free expansion.

22. Calculate the final temperature when air at 20 bar inititally at a volume of lm^3 is allowed to freely expand to $2m^3$. The vessel is well lagged. Draw the process on a p-v diagram.

<u>Throttling</u>

23. Define throttling, and write the general energy equation for the condition of throttling.

24. Calculate the initial dryness fraction of the steam, when steam at 19 bar is throttled to 1 bar and 150°C. Draw the process on a p-v diagram.

Adiabatic Mixing

25. Write the equation showing the relationship between enthalpies for the mixing of two streams of fluids.

Reversible Flow Processess

26. Write the flow equation for a reversible flow process, and explain why the work done in a reversible flow process is not equal to the work done in a reversible adiabatic non flow process.

27. Calculate the work done per kg of gas, when a gas turbine receives gases from the combustion chamber at 7 bar and 650°C and a velocity of 9 m/s. The gases leave the turbine at 1 bar with a velocity at 45 m/s. Assume that the expansion is adiabatic and reversible in the ideal case.

TOPIC 3

The Second Law, and Entropy

The student will be able to:

1. State the general meaning of the Second law of themodynamics in terms of gross heat and net work done.

2. Write the equatfon for thermal efficiency of a heat engine. Show the quantities involved in a diagrammatic representation fo a heat engine.

3. Write the classic statement of the Second Law.

4. Draw diagrammatic representations of and open, and closed cycle gas turbine cycle.

5. Write Clausius' statement of the Second Law that relates to the heat pump or refrigeration cycle.

Entropy

6. Recall the list of properties of a thermodynamic system and add the name "entropy" to that list.

7. On p-v co-ordinates, draw the family of constant temperature lines.

8. On p-v co-ordinates, draw the family of constant entropy lines.

9. Develop the non flow energy equation for a reversible process, using substitutions for the terms of internal energy and work, and divide each term by T. Mote that

   $\frac{dQ}{T}$ is the differential change in entropy, ds, and $\frac{Q^\wedge}{T}$ is entropy.

10. State the meaning of S2 - $\ - $\frac{^\wedge Q}{T}$ for

    (a) A reversible adiabatic process
    (b) For any other reversible process.

11. Draw a diagram that shows Q = TdS

12. Draw a T-s diagram for vapours with 3 constant pressure times running from saturated liquid to superheated vapour. Sketch in 3 constant volume lines.

13. Label on the T-s diagram above, S_g, S_f, and S_{fg}.

14. Write the formula defining dryness fraction in terms of

(a) entropy
(b) enthalpy
(c) specific volume
(d) internal energy

Steam & Vapours

15. Draw the T-s diagram (done) for water-steam, and draw in a line representing constant pressure of 1 bar. Cross hatch in different colours or schemes, the the area representing

(a) h_f
(b) h_g
(c) h_{fg}
(d) the enthalpy of super-heated steam

16. Calculate the heat supplied, and show on a T-s diagram, the area which represents heat flow, for kg of steam at 7 bar and S = 6.5 kg/kgk which is heated reversibly at constant pressure until the temperature becomes 250°C.

17. Calculate the state of the steam after cooling and the amount of heat rejected, when steam at 80 bars and 350°C in a rigid cylinder is cooled to 50 bar. Sketch the process on a T-s diagram indicating the area which represents heat flow.

Perfect gases

18. Plot lines of constant pressure and constant volume on a T-s diagram for a perfect gas.

19. Calculate the net heat flow to or from the air and the net entropy change for air initially at 15°C and 1.05 bar and occupying 0.02 m and first heated at constant volume until the pressure is 4.2 bar and then is cooled at constant pressure back to the original pressure. Show the processes on a T-s diagram.

The Reversible process on a T-s diagram

20. On a T-s diagram for (a) steam and (b) perfect gas, draw the process line for a constant temperature (isothermal) process. Shade in the area representing heat added. Draw an isothermal process on a p-v diagram for (a) steam and (b) perfect gas, and shade in the areas for work done.

21. Calculate the heat added and the work done per kg of steam for steam initially at 100 bar and expanding isothermally and reversibly to a pressure of 10 bar. Draw the process on T-s and p-v diagrams.

22. List the formulae for change in entropy between points 1 and 2 for a perfect gas, expanding isothermally.

23. Calculate the change of entropy, the heat flow, and the work done when 0.03 m of nitrogen contained on a cylinder behind a piston, initially at 1.05 bar, and 15°C is compressed isothermally and reversibly until the pressure is 4.2 bar. Show the process on both a p-v and a T-s diagram.

<u>Reversible Adiabatic Processes</u>

24. Note that a "reversible adiabatic" process in which the entropy remains constant is called an "isentropic process".

25. Calculate the work done per kg of steam when initially at 100 bar and 375°C it expands isentropically in a cylinder behind a piston to a pressure of 10 bar. Show the process on a T-s and a p-v diagram.

26. Draw the process for a perfect gas expanding from p.v^ to P2V2 isentropically. State the formulae for work done and heat added.

<u>Polytropic Processes</u>

27. Recall that when process end points are fixed as they are by Pl^{v}l^{n} = P2 ^{v}2^{r}> then entropy values can be determined by reading them from tables.

28. Calculate the change in entropy per kg of steam when the steam in a cylinder, behind a piston at the beginning of the expansion process where pressure is 7 bar, with x = .95, and the law pv>*i = c is observed down to a pressure of 0.34 bar. Draw the process on both T-s and p-v diagrams.

29. List the formulae for change of entropy for a perfect gas between two points, when the points are on:

   (a) a constant pressure line
   (b) a constant volume line

30. Using an intermediate point "A" develop an equation for change in entropy which takes advantage of the relationship *$2* " ^{s}l = ^^{S}A - *$>i)* - {s^ - S2). List the equation developed under the title "Polytropic change in entropy".

31. Calculate the change of entropy when 1 kg of air expands according to pv = c in a cylinder behind a piston from 6.3 bar and 330°C to 1.05 bar. Show the process on both p-v and T-s diagram.

32. Calculate the change of entropy that occurs when 0.05 kg of carbon dioxide (cp = .88 kj/kgk) is compressed from 1 bar at 15°C to 8.3 bar and volume of 0.0Q4nr.

<u>Entropy and Irreversibility</u>

33. Note that since entropy is a property, then the change of entropy depends only upon the end states and not on the process joining them.

34. Calculate the change of entropy when 1 kg of steam at 7 bar and x = .96 is throttled down to 3.5 bars. Show the process on p-v and T-s diagrams.

35. Note that from the Second Law, entropy of a thermally isolated system, must either increase or at best remain the same, and the gain in entropy is a measure of the irreversibility of the process.

36. Show that the process is irreversible, and calculate the change of entropy per kg of air, when it expands from 6.8 bar and 430°C through an air turbine to 1.013 bar and 150°C.

TOPIC 4

The Heat Engine Cycles

The student will be able to:

The Carnot Cycle

1. Draw the cycles comprising the Carnot cycle, on a T-s diagram and identify each process.

2. Using sketches of pistons in cylinders and stating the conditions of expansion and compression - explain the Carnot cycle.

3. Develp the expression for Carnot efficiency using

   $Q = \quad Tds$ and $\quad = 1 - \frac{Q_2}{Q_1}$

4. Determine the highest theoretical efficiency of a heat engine operating between 2000°C and 10°C. Draw the cycle on T-s and p-v diagrams.

5. Write the definition for "work ratio".

6. Calculate the thermal efficiency and the work ratio of a Carnot cycle using air as the working fluid, if the maximum and minimum pressures of the cycle are 210 bar and 1 bar.

The Constant Pressure Cycle

7. Draw the constant pressure cycle on T-s and p-v co-ordinates and label each process. Draw a schematic of the closed cycle gas turbine for which the constant pressure cycle is the ideal.

8. List the formulae for thermal efficiency and work ratio for the constant pressure cycle.

9. Calculate the thermal efficiency and work ratio for the ideal constant pressure cycle, when the maximum cycle temperature is 800°C, and air is drawn in at 1,02 bar and 15°C and is compressed to 6.12 bar. Show the cycle on p-v and T-s diagrams.

10. State the meaning and significance of "air standard cycle".

The Otto Cycle

11. Draw the Otto cycle on both T-s and p-v diagrams and label each of the processes.

12. List the formulae for compression ratio and thermal efficiency utilizing compression ratio.

13. Calculate the ideal air standard thermal efficiency based on the Otto cycle for a gasoline engine having a cylinder bore of 50 mm and a stroke of 75 mm, and clearance volume 6f 21.3 cm.

The Diesel Cycle

14. Draw the diesel cycle on both T-s and p-v diagrams and label each of the processes.

15. Define the "cut off ratio" and list the formulae for thermal efficiency using the cut off ratio.

16. Calculate the air standard efficiency based on the diesel cycle for a diesel engine with inlet temperature and pressure of 15°C and 1 bar, compression ratio 12/1 and maximum cycle temperatures of 1100°C. Draw the cycle on both p-v and T-s diagrams.

The Dual Combustion Cycle

17. Draw the Dual Combustion on both T-s and p-v diagrams and label each of the processes.

18. List the compression ratio, ratio of pressures, and ratio of volumes and the thermal efficiency.

19. Calculate the air standard thermal efficiency based on the dual combusion cycle, for an oil engine taking in air at 1.01 bar, 20°C, and maximum cycle pressure of 69 bar. The compression ratio is 18/1, and heat added at constant volume equals heat added at constant pressure. Draw the p-v and T-s diagrams for the cycle.

20. Define "mean effective pressure" and illustrate on a p-v diagram.

Gas Turbines

21. Make a schematic diagram of an open cycle gas turbine and draw the T-s diagram showing the ideal and practical cycle. Label each process.

22. Define compressor and turbine iseutropic efficiencies in terms of temperatures.

23. Calculate the power output from a gas turbine unit with a pressure ratio of 6/1 and a maximum cycle temperature of 600°C. The iseutropic efficiencies of the compressor and the turbine are 0.82 and 0.85 respectively and air enters at 15°C and 15 kg/s.

C_p = 1.005 KJ/KgK and = 1. for compression
C_D = 1.11 KJ/KgK and = 1.333 for compression

Show on a T-s diagram.

24. Calculate the thermal efficiency and the work ratio of the plant in 23, above.

25. Draw the schematic of a compressor-turbine combination showing two separate turbines, one which drives the compressor and one which provides output power. Draw a T-s diagram of the cycle. Identify H. P. and L.P turbines.

26. Calculate the pressure and temperature of the gases entering the power turbine, the net power developed, the work ratio and thermal efficiency for a gas turbine unit taking in air at 17^{D}C and 1.01 bar and having a pressure ratio of 8/1. The compressor is driven by the H.P. turbine, and the L.P. turbine drives a separate power shaft. The isentropic efficiencies of the compressor, the H.P. and L.P. turbines are 0.8, 0.85 and 0.83 respectively. Maximum cycle temperature is 650°C. For compression cp - 1.005 kJ/kgK and = 1.4. For the combustion and expansion processes use cp = 1.15 kJ/kgK and = 1.333.

Modifications to the Basic Cycle

27. List the factors that have an effect on gas turbine efficiency.

28. Draw a schematic showing an intercooler in proper position, and sketch the cycle for an intercooler gas turbine cycle on a T-s diagram.

29. Prove by determining work input for two cases with intercoolng and without intercooling that intercooling improves work ratio.

30. Draw a schematic showing a reheater between the L.P. and H.P. turbines, and sketch the cycle for a gas turbine with reheat.

31. List the advantage and disadvantage of reheating.

32. Draw a schematic showing a heat exchanger placed in a simple gas turbine arrangement. Draw the cycle that results from heat exchanging.

33. Define heat exchanger effectiveness.

34. Calculate the thermal efficiency, the work ratio of the plant and the mass flow in kg/s. Draw the schematic showing turbines, compressors, intercoders, heat exchanger and reheat and the T-s diagram for the following plant:

A 5000 K W gas turbine generator operates with two compressor stages with intercooling between stages; the overall pressure ratio is 9/1. A high-pressure trubine is used to drive the compressors, and a low-pressure turbine drives the generator. The temperature of the gases at entry to the high-prrssure turbine is 650°C and the gases are reheated to 650°C after expansion in the first turbine- The exhaust gases leaving the low-pressure turbine are passed through a heat exchanger to heat the air leaving the high-pressure stage compressor- The compressors have equal pressure ratios and intercooling is complete between stages. The air inlet temperature to the unit is 15°C. The iseutropic efficiency of each compressor stage is 0.8 and the iseutropic efficiency of each turbine stage is 0.85; the heat exchanger thermal ratio is 0.75. A mechanical efficiency of 98% can be assumed for both the power shaft and the compressor turbine shaft.

For air, cp = 1.055 kJ/kgK and = 1.4, and for gases in the combustion chamber and in turbines and heat exchanger, use cp = 1,15 kJ/kgK and 1.333. Neglect fuel mass.