A Laboratory Manual for

Engineering Thermodynamics (BE03000201)

B.E. Semester 3
(Mechanical and allied branches)

Directorate of Technical Education
Gandhinagar, Gujarat

Government Engineering College, Bhuj

Certificate

This is to certify that Mr./Ms. ____ Enrollment No. _________________ of B.E. Semester **III** Mechanical Engineering of this Institute (GTU Code: **019**) has satisfactorily completed the Practical / Tutorial work for the subject **Engineering Thermodynamics (BE03000201)** for the academic year 2025-26.

Place: ___________

Date: ___________

Name and Sign of Faculty member

Head of the Department

Practical – Course Outcome matrix

Course Outcomes (COs):

CO1: To identify the unique vocabulary associated with thermodynamics and explains the basic concepts of thermodynamics.

CO2: To apply first law of thermodynamics for closed and open systems undergoing different thermodynamic processes and evaluate the feasibility of thermodynamic cycles and processes using second law of thermodynamics.

CO:3 To apply the concept of entropy and exergy to different thermodynamic processes and cycles.

CO:4 To make use of different gas and vapor power cycles.

Sr. No.	Objective(s) of Experiment	CO1	CO2	CO3	CO4
1.	To understand applications of SFEE.		√		
2.	To verify First and Second Law with Mechanical Heat Pump		√		
3.	To verify First and Second Law with I.C. Engine		√		
4.	To determine heat loss from pipe-in-pipe heat exchanger using SFEE and to verify entropy principle for the heat exchanger.		√	√	
5.	To understand applications of entropy principle.			√	
6.	To understand applications of Gouy-Stodola theorem.			√	
7.	To compare Otto, Diesel and Dual cycles				√
8.	To study variables affecting the performance of Rankine cycle				√
9.	To study variables affecting the performance of Brayton cycle.				√
10.	To study Brayton cycle with reheat, regeneration and intercooling.				√

Industry Relevant Skills

The following industry relevant competency is expected to be developed in the student by undertaking the practical work of this laboratory.

1. Basic understanding and working knowledge of the components such as heat pump, refrigerator, condenser, evaporator, I.C. engine.
2. Fundamentals knowledge as well as applications knowledge about thermodynamics law will be developed.

Guidelines for Faculty members

1. Teacher should provide the guideline with demonstration of practical to the students with all features.
2. Teacher shall explain basic concepts/theory related to the experiment to the students before starting of each practical
3. Involve all the students in performance of each experiment.
4. Teacher is expected to share the skills and competencies to be developed in the students and ensure that the respective skills and competencies are developed in the students after the completion of the experimentation.
5. Teachers should give opportunity to students for hands-on experience after the demonstration.
6. Teacher may provide additional knowledge and skills to the students even though not covered in the manual but are expected from the students by concerned industry.
7. Give practical assignment and assess the performance of students based on task assigned to check whether it is as per the instructions or not.
8. Teacher is expected to refer complete curriculum of the course and follow the guidelines for implementation.

Instructions for Students

1. Students are expected to carefully listen to all the theory classes delivered by the faculty members and understand the COs, content of the course, teaching and examination scheme, skill set to be developed etc.
2. Students shall organize the work in the group and make record of all observations.
3. Students shall develop maintenance skill as expected by industries.
4. Student shall attempt to develop related hand-on skills and build confidence.
5. Student shall develop the habits of evolving more ideas, innovations, skills etc. apart from those included in scope of manual.
6. Student shall refer technical magazines and data books.
7. Student should develop a habit of submitting the experimentation work as per the schedule and s/he should be well prepared for the same.

Common Safety Instructions

1. Students are expected to carefully handle the various equipment and instruments during experimentation.

Index
(Progressive Assessment Sheet)

Sr. No.	Title of Experiment	Page No.	Date of performance	Date of submission	Assessment Marks	Sign. of Teacher with date	Remarks
1	To understand applications of SFEE.						
2	To verify First and Second Law with Mechanical Heat Pump						
3	To verify First and Second Law with I.C. Engine						
4	To determine heat loss from pipe-in-pipe heat exchanger using SFEE and to verify entropy principle for the heat exchanger.						
5	To understand applications of entropy principle.						
6	To understand applications of Gouy-Stodola theorem.						
7	To compare Otto, Diesel and Dual cycles						
8	To study variables affecting the performance of Rankine cycle						
9	To study variables affecting the performance of Brayton cycle.						
10	To study Brayton cycle with reheat, regeneration and intercooling.						
Total							

Experiment No: 1

To Understand the Applications of SFEE

Date:

Competency and Practical Skills: The student will able to understand of the first law of thermodynamics, SFEE and its application to various thermodynamics system.

Relevant CO: To state and apply first law of thermodynamics for closed and open systems undergoing different thermodynamic processes and evaluate the feasibility of thermodynamic cycles and processes using second law of thermodynamics. (CO2)

Objectives: (a) To understand general equation of steady flow.
(b) To carry out SFEE analysis for a various system.

Theory:
The principles of conservation of mass and the conservation of energy apply to open systems or control volume systems having mass crossing the system boundary or control surface. The mass and energy content of the open system may change when mass enters or leaves the control volume. Thermodynamic processes involving control volumes can be considered in two groups: steady-flow processes and unsteady-flow processes. During a steady-flow process, the fluid flows through the control volume steadily, experiencing no change with time at a fixed position.

General Control Volume and Conservation of Energy
We can write the conservation of energy principle for the control volume or open system same as the first law for the closed system. Expressing the energy transfers on a rate basis, the control volume first law is

$$\begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{into control volume}\end{bmatrix} - \begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{from control volume}\end{bmatrix} = \begin{bmatrix}\text{Time rate change}\\ \text{of energy inside}\\ \text{control volume}\end{bmatrix}$$

or

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}}_{\substack{\text{Rate change in internal, kinetic,}\\ \text{potential, etc., energies}}} \qquad (kW)$$

During the steady-state the energy of the control volume is constant with time, steady-flow process, the conservation of energy principle becomes

$$\begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{into control volume}\end{bmatrix} = \begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{from control volume}\end{bmatrix}$$

Considering that energy flows into and from the control volume with the mass, energy cross the boundary and heat is transferred to the control volume, and energy leaves because the control volume does work on its surroundings, the steady-state, steady-flow first law becomes

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \underbrace{\dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + gz_i \right)}_{\text{for each inlet}} = \dot{Q}_{out} + \dot{W}_{out} + \sum \underbrace{\dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + gz_e \right)}_{\text{for each exit}}$$

Often this result is written as

$$\dot{Q}_{net} - \dot{W}_{net} = \underbrace{\sum \dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + gz_e \right)}_{\text{for each exit}} - \underbrace{\sum \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + gz_i \right)}_{\text{for each inlet}}$$

Where,

$$\dot{Q}_{net} = \sum \dot{Q}_{in} - \sum \dot{Q}_{out}$$

$$\dot{W}_{net} = \sum \dot{W}_{out} - \sum \dot{W}_{in}$$

The concept of SFEE applies to various flow processes of the engineering applications, like flows through nozzles and diffusers, throttle devices, turbines and compressors, heat exchangers and pumps. In many cases the value of some of the energy is small and negligible for certain flow processes, hence those are eliminated.

Turbine

Expansion of fluid takes place in turbine from high pressure to low pressure and as a result mechanical energy is developed.

When applying Steady Flow Energy Equation to turbine, Fig. 4.1

- No change in Potential Energy
- No change in Kinetic Energy
- As turbine is insulated heat transfer is very small hence it is negligible.
- Work done (W) by the turbine, so its value is positive.

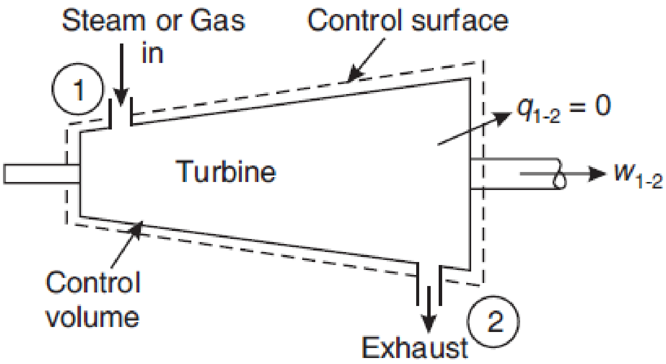

Fig. 1 Flow through a Turbine

SFEE is reduced to

$m_s h_1 = m_s h_2 + W$

$W = m_s (h_1 - h_2)$

m_s = mass flow of steam, kg/s

h_1 = enthalpy of steam entering turbine, kJ/kg

h_2 = enthalpy of steam leaving the turbine, kJ/kg

W =work developed by the turbine, kW

Compressor and Pump

Compressor and pump use mechanical energy and convert into pressure energy. Here, work is done on the system. Applying Steady Flow Energy Equation to compressor and pump, Fig. 4.2.

No change in Potential Energy and in Kinetic Energy

- H
  ere, heat transfer is zero
- W
  ork done (W) on the system, so its value is negative.

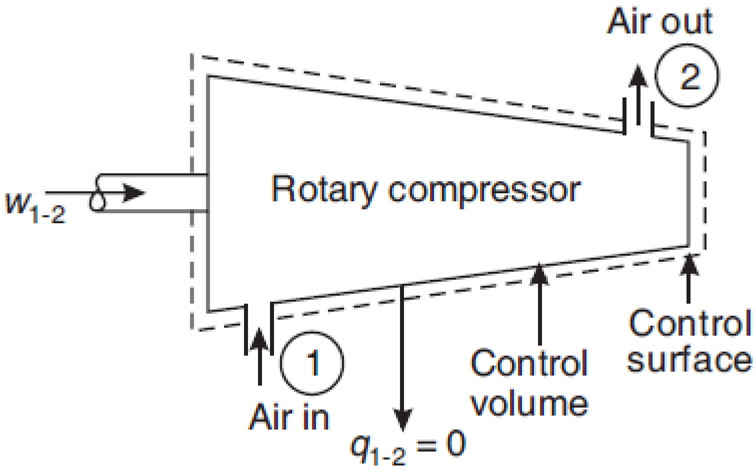

Fig. 2 Flow through compressor

W = m (h_1 - h_2)
Here W is negative.

Nozzles and Diffusers

Nozzle converts pressure energy of the fluid into velocity. Nozzles and diffusers perform opposite task. In diffuser velocity converts into pressure energy. So in nozzle kinetic energy increases at the exit, where as in diffuser pressure energy increases at the exit. Generally they are used in jet engines, spacecraft and rockets.

Fig. 4.3 shows a convergent-divergent nozzle which is commonly in practice, is insulated. While applying SFEE to nozzle and diffuser the heat transfer and work is zero, and nozzles have one entrance and one exit.

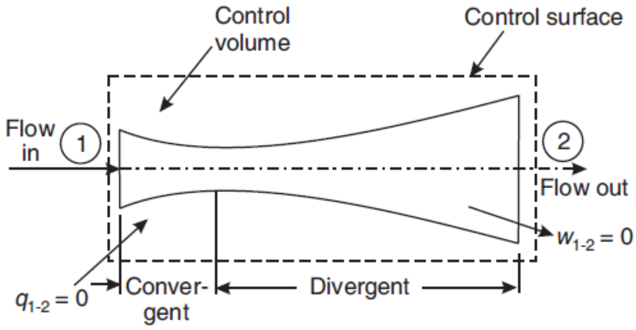

Fig. 3 Flow through Nozzle

The conservation of energy becomes,

$h_1 + V_1^2/2 = h_2 + V_2^2/2$

Velocity at inlet is very small as compared to the velocity at exit, so we neglect it. Hence,

$h_1 = h_2 + V_2^2/2$

$\therefore V_2 = \sqrt{2(h_1 - h_2)}$ m/s

Heat Exchangers

In heat exchanger, transfer of heat takes place between hot and cold medium either directly mixing or through surface. Generally heat transfer takes place between hot and cold fluids without mixing the fluids in majority applications. Condensers and Evaporators are the main types of heat exchangers. Condenser is used in thermal power plant to condense the steam. An **evaporator** is a heat exchanger which is used in refrigeration system to extract heat from the places where we want to maintain the low temperature. Fig. 4.4 & 4.5 shows the various systems.

Heat exchangers are insulated in general and there is no external heat transfer. While applying Steady Flow Energy Equation to condenser and evaporator, no work done, value of potential energy and kinetic energy are very small so we do not consider.

Using SFEE

For condenser,

Heat lost by the steam = Heat gained by the water

$h_1 - h_2 = m_w \times c_p \times (t_{w\ in} - t_{w\ out})$

h_1 = enthalpy of steam entering into the condenser

h_2 = enthalpy of condensate leaving the condenser

m_w = mass of water

c_p = Specific heat of water

$t_{w\ in}$ = temperature of water entering the condenser

$t_{w\ out}$ = temperature of water leaving the condenser

For Evaporator,

$Q = m_{ref} \times (h_1 - h_2)$

h_1 = enthalpy of refrigerant entering the evaporator, kJ/kg

h_2 = enthalpy of refrigerant leaving the evaporator, kJ/kg

m_{ref} = mass of refrigerant, kg

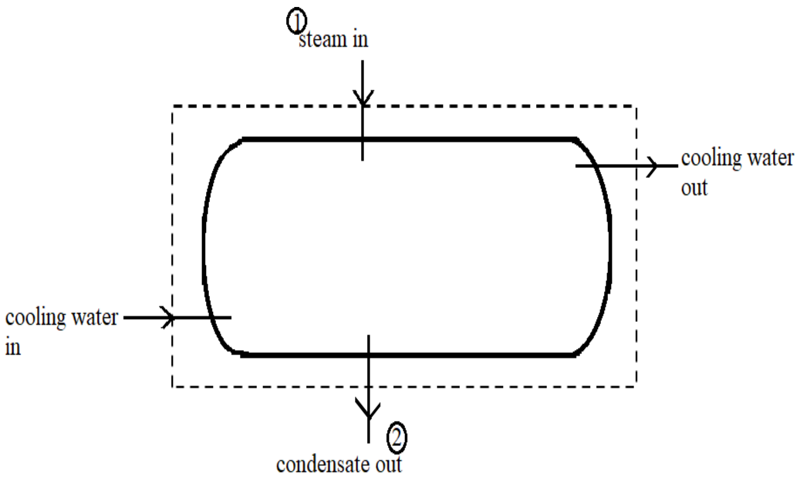

Fig. 4 Steam Condenser

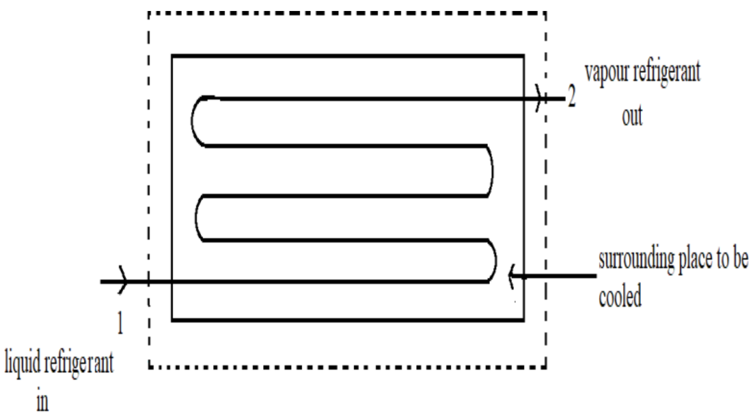

Fig 5 Evaporator of Refrigeration System

Boiler is used for the generation of steam. Heat energy is released as combustion of fuel and heat is transferred to water which vaporizes and gets converted into steam at the desired pressure and temperature. While applying Steady Flow Energy Equation to boiler, work done is zero, value of potential energy and kinetic energy are very small so we do not consider.

Energy balance $m_w \times h_1 + Q = m_s \times h_2$
Heat transfer, $Q = m_s \times (h_2 - h_1)$
Where, h_1 = enthalpy of water
h_2 = enthalpy of steam
m_s = mass of steam generated
m_w = mass of water

Conclusion:

Quiz:

1. Differentiate Flow process and non-flow process.
2. What are the requirements of steady flow process?
3. Derive the general energy equation for steady flow system.
4. Steam enters a nozzle at a pressure of 7 bar and 200°C and leaves at a pressure of 2 bar. The initial velocity of steam at the entrance is 50 m/s and exit velocity from nozzle is 750 m/s. The mass rate through the nozzle is 1500 kg/h. The heat loss from nozzle is 12000 kJ/h. Determine the final enthalpy of the steam and nozzle area if the specific volume is 1.25 m^3/kg. Take initial enthalpy 2850 kJ/kg.
5. A turbine operating under steady flow conditions, receives steam at 4500kg/hour. Steam enters at the velocity of 2800 m/min, an elevation of 5.5 m and a specific enthalpy of 2800 kJ/kg. It leaves the turbine at a velocity of 5600 m/min, an elevation of 1.5 m and specific enthalpy of 2300 kJ/kg. Heat losses from the turbine to the surroundings amount to 16000 kJ/hr. Determines the power output of the turbine.
6. A ir at a temperature of 15°C passes through a heat exchanger at a velocity of 30 m/s where it is heated to 800°C. It then enters a turbine with the same velocity of 30 m/s and expands until the temperature falls to 650°C. On leaving the turbine air is taken at velocity 60 m/s to nozzle where it expands until the temperature has fallen to 500°C. If the air flow rate is 2 kg/s. Calculate (1) Rate of heat transfer to the air in the heat exchanger (2) Power output from the turbine (3) The velocity of air at the exit of nozzle.

Suggested Reference:

1. Engineering Thermodynamics by P.K. Nag, McGraw-Hill Education
2. Fundamentals of Thermodynamics by Borgnakke & Sonntag, 7th Ed. Wiley India (P) Ltd.
3. Thermodynamics – An Engineering Approach by Yunus Cengel & Boles, McGraw-Hill Education
4. Engineering Thermodynamics by Gordon Rogers and Yon Mayhew, Pearson Education Ltd.

5. Engineering Thermodynamics by Krieth, CRC Press

References used by the students:

Rubric-wise marks obtained:

Rubrics	**1**	**2**	**3**	**4**	**Total**
Marks					

Signature of the faculty member

Experiment No: 2

Verification of First and Second Law with Heat Pump

Date:

Competency and Practical Skills: Student will be able to understand the first and second law of thermodynamics with reference to heat pump and its utility.

Relevant CO:

- To state and apply first law of thermodynamics for closed and open systems undergoing different thermodynamic processes and evaluate the feasibility of thermodynamic cycles and processes using second law of thermodynamics. (CO-2)

Objectives: (a) To show that Heat pump is a closed system.
(b) To carry out first law analysis of a Heat pump.
(c) To show that it also satisfies Clausius statement of second law of thermodynamics.

Equipment/Instruments: Mechanical heat pump, stop watch

Theory:

Calculations required verifying first and second law of thermodynamics with Mechanical Heat pump are: (1) Heat rejected in condenser (2) Heat absorbed in evaporator (3) Power supplied to compressor.

(1) Heat rejected in condenser: Water cooled condenser is used in Mechanical Heat pump. Working fluid rejects heat to the cooling medium (water) so temperature of cooling medium increases. If m_1 is the mass flow rate of water and T_1 and T_2 be the inlet and outlet temperature of water in the condenser respectively, amount of heat rejected to water can be found out using the equation

$$Q_c = m_1 \times c_{pw} \times (T_2 - T_1)$$

(2) Heat absorbed in evaporator: Water is circulated around the evaporator coil and working fluid absorbs heat from water so temperature of water falls. If m_2 is the mass flow rate of water in evaporator and T_3 and T_4 be the inlet and outlet temperature of water, amount of heat absorbed by water is given by

$$Q_c = m_2 \times c_{pw} \times (T_3 - T_4)$$

(3) Power supplied to the compressor: With help of energy meter one can measure the power supplied to compressor W_c.

$$W_c = \frac{Initialreading - Finalreading}{t}$$

Set up diagram:

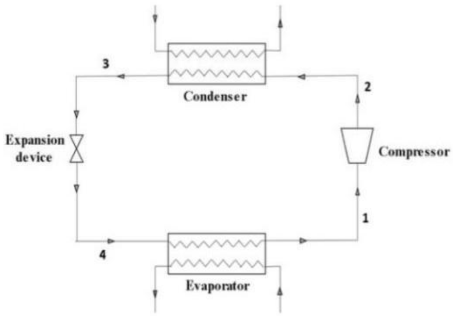

Fig. 1 Basic Experimental Diagram for Heat Pump

Safety and necessary Precautions:

1. Do not start the compressor before starting the water flow through the condenser and evaporator

Procedure:

1. Start water flow through condenser and evaporator and then the start the compressor.
2. At steady state conditions take following observation.

Observations:

(1) Mass flow rate of water in condenser m_1= __________ kg/sec
(2) Inlet temperature of water in condenser T_1 = _________K
(3) Outlet temperature of water in condenser T_2= __________ K
(4) Mass flow rate of water in evaporator m_2 = __________ kg/sec
(5) Inlet temperature of water in evaporator T_3 = __________ K
(6) Outlet temperature of water in evaporator T_4 = ___________ K
(7) Energy meter reading
  (i) Initial = ___________ kWh
  (ii) Final = ____________ kWh
(8) Time duration between two readings t = __________ sec

Calculation:

Result:

Conclusion:

Quiz:

1. What is heat pump?
2. Differentiate between heat pump and refrigerator.
3. What is the relation between COP of Carnot heat pump and COP of Carnot refrigerator?
4. Differentiate between Carnot heat pump and actual heat pump.
5. Heat pump has thermodynamic advantage over electric heater: Justify

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1. Engineering Thermodynamics by P.K. Nag, McGraw-Hill Education
2. Fundamentals of Thermodynamics by Borgnakke & Sonntag, 7th Ed. Wiley India (P) Ltd.
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References used by the students:

Rubric wise marks obtained:

Rubrics	**1**	**2**	**3**	**4**	**Total**
Marks					

Signature of the faculty member

Experiment No: 3

To verify First and Second Law with I.C. Engine

Date:

Competency and Practical Skills: The students will be able to understand the first and second law of thermodynamics. The students will also be able to understand the heat balance sheet of IC engine and determine thermal efficiency of the engine.

Relevant CO:

- To state and apply first law of thermodynamics for closed and open systems undergoing different thermodynamic processes and evaluate the feasibility of thermodynamic cycles and processes using second law of thermodynamics. (CO-2)

Objectives:

a) To understand first and second law of thermodynamics
b) To verify First Law with I.C. Engine
c) To verify Second Law with I.C. Engine

Equipment/Instruments: I.C. Engine, Air box, fuel supply tank, dynamometer, coolant supply system, thermometer

Theory:

First law of thermodynamics: "Energy can neither be created nor be destroyed, but it changes its form one form to another form." The first law is based on energy conservation principle which provides energy balance. But it doesn't provide the direction of process.

Second law of thermodynamics: The second law provide the direction in which a process can be occurred. There are two statements of second law of thermodynamics.

Kelvin -Plank statement: "It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work." In other words, no heat engine can have a thermal efficiency of 100%.

Clausius statement: "It is impossible to construct a device which operates in a cycle and produces no effect other than the transfer of heat from a cooler body to a hotter body."

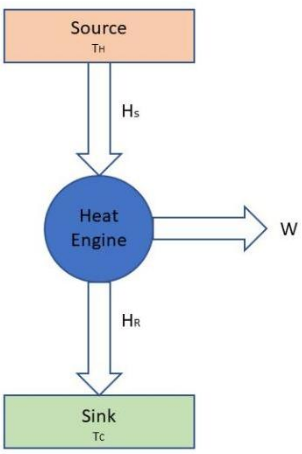

Fig. 1 Heat engine

By applying first law of thermodynamics on heat engine,

$$H_S = W + H_R$$
$$W = H_S - H_R$$

The above equation gives heat balance of heat engine which justify the first law of thermodynamics. Where the heat rejected by the heat engine is some of heat of exhaust gas, heat carried out by coolant and some unaccountable losses that we cannot measure experimentally at our laboratory.

$$H_R = Q_{coolant} + Q_{exh}$$

The value of H_R is always greater than zero due to heat loss at higher temperature than surrounding temperature and heat loss in cooling. That justify the second law of thermodynamics, that the heat must be rejected by heat engine to develop the work i.e. without the heat reaction to surrounding the heat engine can't be possible.

The efficiency of the heat engine can be calculated by, $\eta = \dfrac{H_S - H_R}{H_S}$

The efficiency equation determines the value of efficiency which is less than 100%. Which represents that, the 100% conversion of heat to work is not possible according to the second law of thermodynamics.

The Carnot efficiency of the heat engine is given by, $\eta_{Carnot} = \dfrac{T_H - T_C}{T_H}$

Experimental set up:

Engine	Any single/four cylinder, 4-S petrol/diesel engine, water cooled **Engine Description** **Maximum Torque** **Fuel Type**
Dynamometer	
Air box	
Speed indicator	
Temperature sensor	
Water meter	
Number of cylinders	
Orifice dia. of Air measurement	
Outer dia. of drum	
Air density	

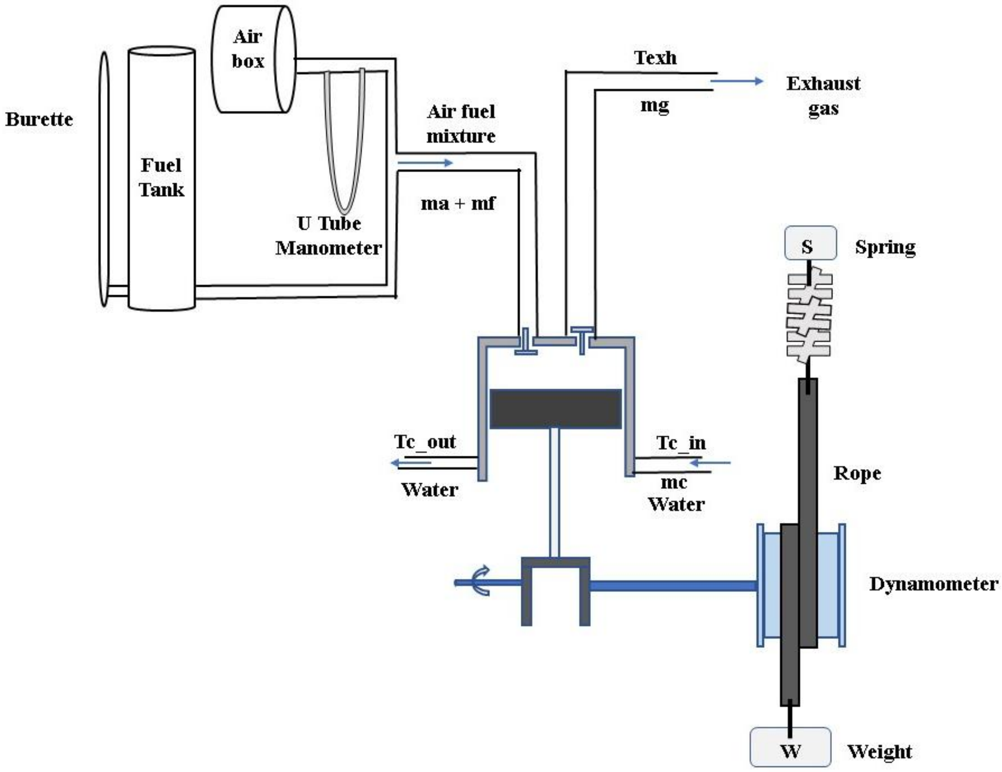

Fig. 2 Experiment set up out line

Procedure:

1. Fill oil in sump of the engine. It must fall between the oil dipstick's given markings. Open the cover of the given valve at the top of the engine to add clean oil (SAE-40) to the crankcase if the oil level is low.
2. Fill fuel in tank the fuel supply tank of the engine
3. Fill the measuring fluid in manometer i.e., water, up to the height half of the manometer.
4. Fill the burette with fuel and supply the fuel to the engine by opening the valve provided at the left side of burette.
5. Turn on the panel's mains power supply.
6. Turn on the cold-water supply to the exhaust calorimeter and engine jacket.
7. Insert the ignition key and turn it clockwise to the position labelled "ignition on" by an indicator lamp. To start the engine, turn the ignition switch key one more turn anticlockwise. Keep the ignition key in the ignition once the engine has started and let it run for two minutes with no load.
8. Use an electrical dynamometer to load the engine once it has started to run smoothly.
9. To stabilize the engine, run it for two minutes.
10. Take note of the weight reading on the dynamometer's output shaft and the RPM with the aid of the tachometer.
11. In order to measure fuel usage, close the fuel supply valve located on the left side of the burette. Record the amount of time needed to consume 10 or 20 ml of petrol.
12. Next, open the fuel supply valve to continue getting petrol into the burette.
13. Record the manometer reading in order to determine the engine's air consumption.
14. Using a thermocouple, record the temperatures at the water's entrance and output as it circulates through the engine jacket.
15. Use a stopwatch to measure the water flow rate from the water meter.
16. Note down air box meter manometer reading.
17. Record the temperature of the water and exhaust gas streams entering and leaving the calorimeter. Use a measuring cylinder and stopwatch to determine the water flow rate.

18. Rerun the test with a different load.
19. Note down all necessary observations and calculate required parameters.
20. After the experiment is complete, the load is reduced and, then gradually dropping the throttle while removing the dynamometer's weights.
21. Detach the ignition key from the switch by turning it off.
22. Next, turn off the engine's fuel and water-cooling systems.

Precaution to be taken for the test:

- Never put your hands near hot pipes.
- Wear the appropriate clothing and safety footwear.
- Maintain proper distance from the rotating components of the set up.
- Use equipment and tools properly.
- Be Conscious of Your Environment.
- Handle the burette carefully during the experiment.

Data table:

Sr. no.	System Constant	Value
1.	Orifice diameter (m)	
2.	Drum radius (m)	
3.	Dead weight W(kg)	
4.	Spring load S(kg)	
5.	Coefficient of discharge for orifice, Cd	
6.	Manometer reading h_m (mm)	
7.	Rope diameter r_d (m)	
8.	Ambient temperature (°C)	
9.	Fuel density(kg/m^3)	
10.	Fuel calorific value (kJ/kg)	
11.	No of cylinders	
12.	No. of rev./cycle	
13.	Specific heat of exhaust (kJ/kg K)	

Observation table:

Drum Speed RPM	Dead weight (kg) (Rope Brake)	Load of Electrical dynamo meter (kg)	Manometer deflection (mm)	Fuel flow Rate		Water flow rate in engine water jacket (LPM)	Temperatures			
				Vol.	Time		T_{c_in}	T_{c_out}	T_{exh}	T_{atm}

The heat supplied is balanced by the sum of heat of exhaust gas, heat carried out by coolant, friction losses

$$Hs = m_f * C.V.$$

$$Hs = B.P. + F.P + Q_{coolant} + Q_{exh}$$

$$B.P. = \frac{2 * N * \prod * T}{60}$$

$$T = (W - S) * r_d$$

$$m_{air} = C_d * \rho_{air} * A_{orific} * \sqrt{(2gh)}$$

$$Q_{coolant} = m_c * C_{p-c} * (T_{c\_out} - T_{c\_in})$$

$$Q_{exh} = m_g * C_{Pg} * (T_{exh} - T_{atm})$$

Where,
Hs = heat supplied
H_R = heat rejected
W= Work output
N= RPM
T= Torque measured by electronic dynamometer or rope break dynamometer
C_{p-c} = Specific heat of coolant
T_{c_in} = Coolant temperature inlet=T_3
T_{c_out} = Coolant temperature out=T_4
T_{exh} = Exhaust gas temperature =T_5
T_{atm} = Atmospheric temperature =T_6
m_{air} = mass of air
ρ_{air} = density of air
C_d = coefficient of discharge of orifice of air box meter
h = manometer reading of air box meter

Result Table:

BP kW	**BSFC kg/kWh**	**Break Thermal eff. (%)**	**Air flow kg/h**	**A/F Ratio**	**Heat Equi. of work (%)**	**Heat by jacket water (%)**	**Heat by exhaust (%)**	**Unaccounted (%)**

Calculation:

Result:

Conclusion:

Quiz:

1. State the first law of thermodynamics.
2. State the two statements of second laws of thermodynamics.
3. List the measuring instruments and devices used for the experiment performance.
4. Describe the process for creating the heat balance sheet for an IC engine.
5. Mention the different losses during performance test of internal combustion engine.

Suggested Reference:

1. Engineering Thermodynamics by P.K. Nag, McGraw-Hill Education
2. Fundamentals of Thermodynamics by Borgnakke & Sonntag, 7th Ed. Wiley India (P) Ltd.
3. Thermodynamics – An Engineering Approach by Yunus Cengel & Boles, McGraw-Hill Education
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5. Engineering Thermodynamics by Krieth, CRC Press

References used by the students:

Rubric-wise marks obtained:

Rubrics	1	2	3	4	Total
Marks					

Signature of faculty member

Experiment No: 4

To determine heat loss from pipe-in-pipe heat exchanger using SFEE and to verify entropy principle for the heat exchanger.

Date:

Competency and Practical Skills: The students will able to understand the principle of heat transfer through heat exchanger. And the students will also understand the concept of entropy and determine the entropy change of the heat exchanger.

Relevant CO:

- To state and apply first law of thermodynamics for closed and open systems undergoing different thermodynamic processes and evaluate the feasibility of thermodynamic cycles and processes using second law of thermodynamics. (CO-2)
- To apply the concept of entropy and exergy to different thermodynamic processes and cycles. (CO-3)

Objectives:

a) To determine heat loss from pipe-in-pipe heat exchanger using SFEE
b) To verify entropy principle for the heat exchanger.

Equipment/Instruments:

1. Pipe in pipe heat exchanger
2. Thermometer
3. Flow meter

Theory:

The heat exchanger is a device which transfers heat from one working substance to another working substance. In pipe-in-pipe heat exchanger, the fluid flowing through a pipe is surrounded by fluid in peripheral pipe as shown in Fig. 3.1. The examples of heat exchangers are condenser, evaporator, boiler, shell and tube heat exchanger. These devices are applicable in chemical industries, air conditioning, refrigeration and different process industrial application.

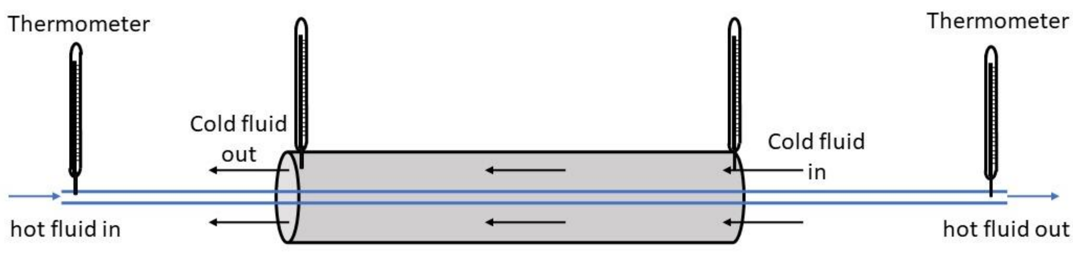


Fig. 1 pipe in pipe heat exchanger

Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1+\frac{c_1^2}{2}+gz_1\right)+Q=m\left(h_2+\frac{c_2^2}{2}+gz_2\right)+W_s$$

In case of the flow through a heat exchanger:

- No shaft work; $W_s = 0$
- Kinetic energy is equal on both ends. As the mass conservation law applied to constant area flow. $C_1=C_2$
- As $z_1=z_2$, for same elevation, Potential energy as equal at both end

Hence SFEE

$$m(h_1)+Q=m(h_2)$$

$$Q=m(h_2-h_1)$$

Applying the SFEE equation to the hot fluid. The heat transfer by hot fluid given by below equation,

$$Q_h = m_h(h_{hi}-h_{ho})$$

$$Q_h = m_h * Cp * (T_{hi}-T_{ho})$$

Applying the SFEE equation to the cold fluid. For heat transfer by cold fluid given by below equation,

$$Q_c = m_c(h_{co}-h_{ci})$$

$$Q_c = m_c * Cp * (T_{co}-T_{ci})$$

Heat loss by pipe in pipe heat exchanger

$$Q_{loss} = Q_h - Q_c$$

Change in entropy of hot fluid

$$\Delta S_h = m_h c_{ph} \ln \frac{T_{ho}}{T_{hi}}$$

Change in entropy of cold fluid

$$\Delta S_c = m_c c_{pc} \ln \frac{T_{co}}{T_{ci}}$$

Entropy change of the ambient/surroundings

$$\Delta S_{sur} = \frac{Q_{loss}}{T_{amb}}$$

Entropy change of the universe = Entropy change of the system + Entropy change of the surroundings

Entropy change of the system = Entropy change of hot fluid + Entropy change of cold fluid

$$\Delta S_{uni} = \Delta S_h + \Delta S_c + \Delta S_{sur}$$

As per entropy principle $\Delta S_{uni} \geq 0$

Procedure:

1. Start the cold fluid supply through pipe.
2. Start the heater and achieve certain predefined temperature of hot fluid in supply tank.
3. Start the hot fluid supply through pipe.
4. Maintain the steady flow through the hot and cold flow pipe through valve and flow meter.
5. Measure the flow rate of cold and hot fluid.
6. Measure the temperature hot and cold fluid at hot and cold ends.

Precaution to be taken for the test:

- When not in use, turn off heat sources.
- Never put your hands near hot pipes.
- Wear the appropriate clothing and safety footwear.
- Use equipment and instruments properly.

Observation table:

Sr no	Cold fluid inlet temperature (°C) **T_{ci}**	Cold fluid outlet temperature (°C) **T_{co}**	Hot fluid inlet temperature (°C) **T_{hi}**	Hot fluid outlet temperature (°C) **T_{ho}**	Flow rate of the hot fluid (LPM) **m_h**	Flow rate of the cold fluid (LPM) **m_c**
1						

Calculation:

Conclusion:

Quiz:
1. Define heat exchanger.
2. List the equipment which works on principal of heat exchange and also list the application of heat exchangers.
3. List the consideration for application of Steady flow energy equation on heat exchanger.
4. Classify type of heat exchange can be possible with heat exchanger in thermodynamic processes.
5. Justify the entropy principle for change of entropy for heat exchanger, surrounding and total entropy change.

Suggested Reference:

1. Engineering Thermodynamics by P.K. Nag, McGraw-Hill Education
2. Fundamentals of Thermodynamics by Borgnakke & Sonntag, 7th Ed. Wiley India (P) Ltd.
3. Thermodynamics – An Engineering Approach by Yunus Cengel & Boles, McGraw-Hill Education
4. Engineering Thermodynamics by Gordon Rogers and Yon Mayhew, Pearson Education Ltd.
5. Engineering Thermodynamics by Krieth, CRC Press

References used by the students:

Rubric-wise marks obtained:

Rubrics	**1**	**2**	**3**	**4**	**Total**
Marks					

Signature of the faculty member

Experiment No: 5

To understand applications of entropy principle

Date:

Competency and Practical Skills:
The students should able to understand the concept of entropy and its applications to thermodynamic process.

Relevant CO:
- To apply the concept of entropy and exergy to different thermodynamic processes and cycles. (CO3)

Objectives: To understand applications of entropy principle.

Theory:
Entropy is an important property of a working substance, which increases with heat addition and decreases with rejection. It is complicate to understand the term Entropy. However, the definition of a change in entropy of working substances is very straightforward.

- Entropy is a key concept in the study of heat engines and contributes to significant findings that would require much more work to get using other techniques.
- Not all heat can be used to create work equally. A substance's ability to convert heat into work is stronger when it receives heat at a high temperature than when it receives heat at a lower temperature.
- Entropy is a function of heat amount that depicts the potential for converting that heat into work. Entropy increases more when heat is added at a lower temperature than it does when heat is added at a higher temperature.
- As a result, the availability for conversion into work is minimum for maximum entropy and maximal for minimum entropy.

For a temperature range the heat absorbed or rejected by the working substance is calculated by multiplying the increase or reduction in entropy by the absolute temperature. Mathematically, heat supplied and rejected by the substance, which leads to the Clausius inequality states.

For reversible cycle, $\left(\frac{\delta Q}{T}\right)_{rev} = 0$

The cyclic integral of $\left(\frac{\delta Q}{T}\right)_{rev}$ is zero. Therefore, $\left(\frac{\delta Q}{T}\right)_{rev}$ is a property, this thermodynamic property was as entropy by Clausius. So, it can be defined as

$$\oint \left(\frac{\delta Q}{T}\right)_{rev} = ds$$

The change in entropy (ΔS) for process1-2 can be determine by

$$\Delta s = \oint \left(\frac{\delta Q}{T}\right)_{rev} = s_2 - s_1$$

In general net change in entropy during a thermodynamic process is defined as

$$\oint ds = \oint \left(\frac{\delta Q}{T}\right) = 0 \quad \text{; for cycle is reversible}$$

$$\oint \left(\frac{\delta Q}{T}\right) < 0 \quad \text{; for cycle is irreversible and possible}$$

$$\oint\left(\frac{\delta Q}{T}\right)>0 \qquad \text{; for cycle is impossible}$$

For a reversible process, the change in entropy of the system is equal in magnitude but opposite in sign to the change in entropy for the surroundings. So, the net or total change in entropy, is summation of entropy change of system and surrounding, and is equal to zero.

$$\Delta S_{system}+\Delta S_{surrounding}=0 \qquad \text{; for reversible process}$$

$$\Delta S_{system}+\Delta S_{surrounding}>0 \qquad \text{; for irreversible process}$$

The change of entropy between two states is the identical whether the process is reversible or irreversible. Entropy can be considered as a measure of molecular disorder of the system. For pure substance at absolute zero temperature entropy is zero. This statement represents the third law of thermodynamics. The entropy of a pure crystallite substance at absolute zero temperature is zero. If the molecular disorder is generated during the process, the ability of doing work is degraded.

Entropy Principle:

"Entropy of the isolated system such as universe always increases and in limiting case remains constant."

$$ds_{isolated}\geq 0$$

For a reversible process, the change in entropy of the system is equal in magnitude but opposite in sign to the change in entropy for the surroundings. So, the net or total change in entropy, is summation of entropy change of system and surrounding, and is equal to zero.

$$ds_{universe}=ds_{system}+ds_{surrounding}$$

$$ds_{universe}\geq 0$$

$$ds_{system}+ds_{surrounding}\geq 0$$

$$ds_h+ds_c+ds_{surrounding}\geq 0$$

$$\frac{Q_h}{T_h}+\frac{Q_c}{T_c}+ds_{surrounding}\geq 0$$

Application of entropy principle:

(a) Determining change of entropy for mixing of two fluids: Suppose mixture of two streams at mass (m), specific heat (c) and temperature (t) represented by subscript 1 and 2 respectively mixes then and the final temperature is T_f, then

$$\Delta S_{univ}=m_1c_1\frac{T_f}{T_1}+m_2c_2\frac{T_f}{T_2}$$

(b) Determining entropy change during heat transfer through a finite temperature difference: The change of entropy for the heat transfer (Q) between two thermal reservoirs at finite temperature T_1 and T_2 connected by a rod is given by

$$\Delta S_{univ}=-\frac{Q}{T_1}+\frac{Q}{T_2}$$

(c) It helps to evaluate maximum work obtained from two finite bodies at different temperature: It two bodies at finite different temperature T_1 as hot and T_2 as cold junction and T_f is average temperature,

$$\Delta S_1=c_p\ln\frac{T_f}{T_1} \qquad \Delta S_2=c_p\ln\frac{T_f}{T_2}$$

The maximum work that can be obtained is given by, $W_{\max}=c_p(\sqrt{T_1}-\sqrt{T_2})^2$

(d) The maximum work obtained from TER and finite body: Consider a body at Temperature T and a thermal energy reservoir (TER) at temperature T_0($T > T_0$). The Q heat is consumed from the body which produce W work and remaining Q-W is rejected to the TER. The maximum work can be represented by

$$W_{\max} = c_p \left[(T - T_0) - T_0 \ln \frac{T}{T_0} \right]$$

(e) It helps to evaluate minimum work required for refrigeration and air conditioning system: Consider the refrigerator is to be maintained at temperature T_2 and the sink temperature is T_1. The minimum work supplied to the refrigerator is given by,

$$W_{\min} = mc_p \left[\frac{T_1^2}{T_2} + T_2 - 2T_1 \right]$$

(f) The concept of entropy can also be applied to the flow of electricity through a resistance: The flow of electric current I through resistance R and the surround absorb the heat at temperature T, generate entropy as follows,

$$\Delta S_{univ} = \frac{W}{T}$$

Third law of thermodynamics:

This is third law of thermodynamics which states that "The entropy of all perfect crystalline substance is zero at absolute zero temperature."

If a system is at equilibrium crystalline state, its atoms are placed in a manner such that it represents the maximum degree of order, and at absolute zero temperature, there must be a lowest disorder of thermal motion. So, it stands to reason that any system displaying its highest level of order and lowest level of thermal motion should be given a zero absolute entropy value. Entropy can be calculated using the third rule of thermodynamics as an unchanging benchmark. Absolute entropy refers to the entropy that has been calculated in relation to this reference point.

Application of Third law of thermodynamics

- Provides an absolute reference for the determination of entropy
- Represents the behavior of substance at very low temperature.
- Measurement of chemical reaction force substances.
- Analysing the phase and chemical equilibrium.

Quiz:

1. Define entropy.
2. Justify, entropy is the property of the system.
3. State the principal of increase of entropy.
4. 3 kg of water at 55 °C is mixed with 4 kg of water at 100 °C in a steady flow process. Determine the temperature of mixture, state whether the process is isentropic?
5. Mention the sign convection for entropy change of the system?

Suggested Reference:

1. Engineering Thermodynamics by P.K. Nag, McGraw-Hill Education
2. Fundamentals of Thermodynamics by Borgnakke & Sonntag, 7th Ed. Wiley India (P) Ltd.
3. Thermodynamics – An Engineering Approach by Yunus Cengel & Boles, McGraw-Hill Education
4. Engineering Thermodynamics by Gordon Rogers and Yon Mayhew, Pearson Education Ltd.
5. Engineering Thermodynamics by Krieth, CRC Press

References used by the students:

Rubric-wise marks obtained:

Rubrics	1	2	3	4	Total
Marks					

Signature of faculty member

Experiment No: 6

To understand applications of Gouy-Stodola theorem

Date:

Competency and Practical Skills:
The students should able to understand the applications of Gouy-Stodola theorem.

Relevant CO:

- To apply the concept of entropy and exergy to different thermodynamic processes and cycles. (CO3)

Objectives: To study the applications of Gouy-Stodola theorem.

Theory:
Gouy-Stodola theorem:
The difference between reversible work (W_{rev}) and actual work done (W) by a system is called irreversibility (I). It is also called degradation or dissipation. For closed as well as open systems, it can be shown that irreversibility (I) is given by

$$I = T_0 \Delta S_{uni} = T_0 \Delta S_{gen}$$

The above relation is called the Gouy-Stodola theorem which states that the rate of exergy loss is proportional to entropy generation. The Gouy-Stodola theorem offers the theoretical foundation for assigning irreversibility and figuring out the highest efficiency achievable for every type of energy conversion system. The loss of work during a thermodynamic process, or the rate at which exergy is degrades, is directly proportional to the rate entropy generation, and the proportionality coefficient is the ambient temperature which act as ambient thermal reservoir.

Irreversibility (I) indicates wasted amount of work potential or lost opportunity to do work.
If

$I = 0$: Reversible process ($S_{gen} = 0$)

$I > 0$: Irreversible (actual) process (S_{gen} is always positive)

$I < 0$: Impossible as S_{gen} can never be negative.

A process that is thermodynamically efficient would have a low rate of entropy production and a low rate of exergy loss.

Application of Gouy-Stodola theorem:

(a) Heat transfer through a finite temperature difference: If heat (Q) is transferred from a reservoir T_1 to ambient at T_0, entropy generation is given by

$$S_{gen} = \frac{Q}{T_0} - \frac{Q}{T_1}$$

Therefore, lost work or irreversibility can be written as

$$I = W_{lost} = T_0 S_{gen} = Q\,\frac{T_1 - T_0}{T_1}$$

(b) Mixing of two fluids: Let two streams at mass (m), specific heat (c) and temperature (t) represented by subscript 1 and 2 respectively mixes and the final temperature is T_f, then

$$S_{gen} = m_1 c_1 \ln\frac{T_f}{T_1} + m_2 c_2 \ln\frac{T_f}{T_2}$$

and from Gouy-Stodola theorem, irreversibility is given by

$I = T_0 S_{gen}$

Quiz:

1. What is the significance of Gouy – Stodola theorem.
2. An air compressor receives air at 1 bar and 27 °C. It compresses the air to a pressure of 10 bar, while its temperature reaches 270 °C. The compressor releases 55 kJ/kg of heat from its body during the process. Determine reversible and actual work done by the compressor and irreversibility in the process.
3. State the applications of Gouy-Stodola theorem.
4. Is fluid flow due to friction a reversible process? If yes, why?
5. What do you mean by dead state?
6. Who propounded the concept of availability?

Suggested Reference:

1. Engineering Thermodynamics by P.K. Nag, McGraw-Hill Education
2. Fundamentals of Thermodynamics by Borgnakke & Sonntag, 7th Ed. Wiley India (P) Ltd.
3. Thermodynamics – An Engineering Approach by Yunus Cengel & Boles, McGraw-Hill Education
4. Engineering Thermodynamics by Gordon Rogers and Yon Mayhew, Pearson Education Ltd.
5. Engineering Thermodynamics by Krieth, CRC Press

References used by the students:

Rubric-wise marks obtained:

Rubrics	**1**	**2**	**3**	**4**	**Total**
Marks					

Signature of faculty member

Experiment No: 7

To compare Otto, Diesel and Dual cycles

Date:

Competency and Practical Skills: To understand the working of heat engine based on different gas cycles and can know on which cycle is better under which conditions.

Relevant CO: To make use of different gas and vapor power cycles. (CO4)

Objectives: (a) To know the different gas cycles on which heat engine works.
(b) To understand the working of the cycles and to identify which one is better under different conditions.

Theory:
Air is the working fluid in the most of gas power cycle. Generally, gas-based power plants operate on these cycles, wherein mixture of air and fuel burnt and heat energy released. The working fluid of these cycles has properties similar to the air; hence gas power cycle can be analyzed as standard cycle which is known as Air-Standard cycle, in which we assume that air behaves as an ideal gas. By adopting this concept, we may estimate the performance of actual engine and may study number of variables which affect the performance of power plants/heat engines.
Following Air Standard cycles we study at this point.
(1) Otto Cycle (2) Diesel Cycle (3) Dual Cycle.

Otto Cycle
Fig. 1 shows the p-V and T-s diagrams of Otto cycle. The cycle consists of two adiabatic reversible and two constant volume processes which are as under:
Process 1-2 – Adiabatic compression process
Process 2-3 – Addition of heat at constant volume
Process 3-4 – Adiabatic expansion process
Process 4-1 – Rejection of heat at constant volume
Efficiency of the cycle can be given by $\eta_{otto} = 1 - (T_4 - T_1) / (T_3 - T_2)$

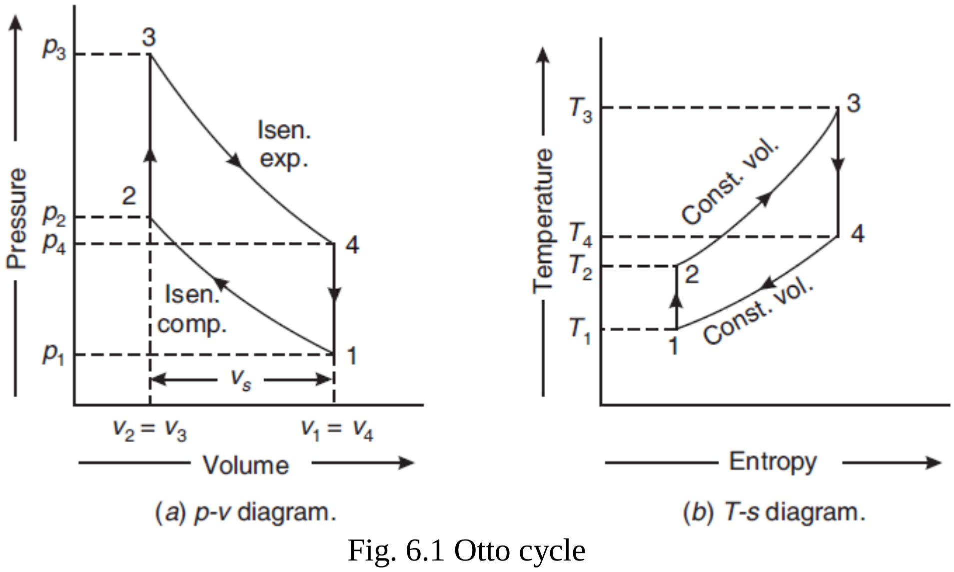


Fig. 6.1 Otto cycle

$\eta_{otto} = 1 - [1 / (r)^{\gamma - 1}]$
Where r is compression ratio, $r = V_1 / V_2$ and γ is specific heat ratio.

Diesel Cycle

In this cycle heat addition takes place at constant pressure instead of constant volume. Fig. 6.2 shows the p-V and T-s diagrams of Diesel cycle. The cycle consists of two adiabatic reversible and one constant pressure and one constant volume processes which are as under:

Process 1-2 – Adiabatic compression process

Process 2-3 – Addition of heat at constant pressure

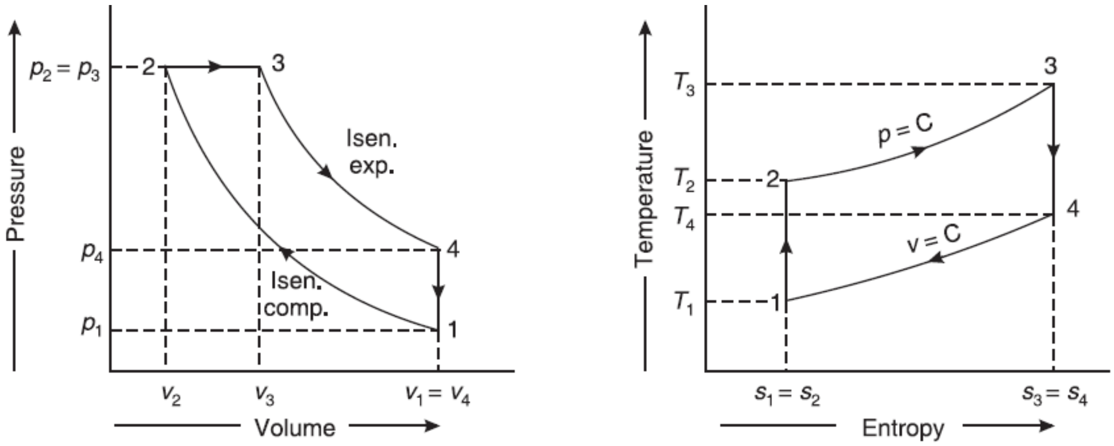
Process 3-4 – Adiabatic expansion process

Process 4-1 – Rejection of heat at constant volume

Efficiency of the cycle can be given by $\eta_{diesel} = 1- (T_4 – T_1) / r\,(T_3 – T_2)$

$$\eta_{diesel} = 1- [1 / (r)^{\gamma -1}]\,[\,(\rho^{r} – 1) / (\rho – 1)\,]$$

where ρ is the cut off ratio, $\rho = V_3 / V_2$



(*a*) *p-v* diagram. (*b*) *T-s* diagram.

Fig. 2 Diesel cycle

Dual cycle

This cycle is the combination of Otto and Diesel cycle. So, heat is added partially at constant volume and partially at constant pressure as shown in Fig. 6.3.

Process 1-2 – Adiabatic compression process

Process 2-3 – Addition of heat at constant volume

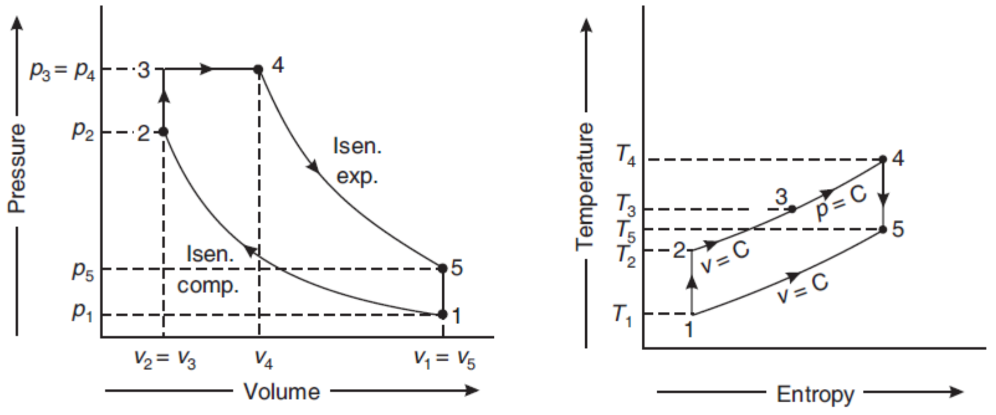
Process 3-4 – Addition of heat at constant pressure

Process 4-5 – Adiabatic expansion process

Process 5-1 - Rejection of heat at constant volume

Efficiency of the cycle can be given by $\eta_{dual} = 1- [1 / (r)^{\gamma -1}]\,[\,(\beta \rho^{\gamma} – 1) / (\beta – 1) + \beta \gamma\,(\rho – 1)\,]$

β = pressure ratio, p_3/p_2.

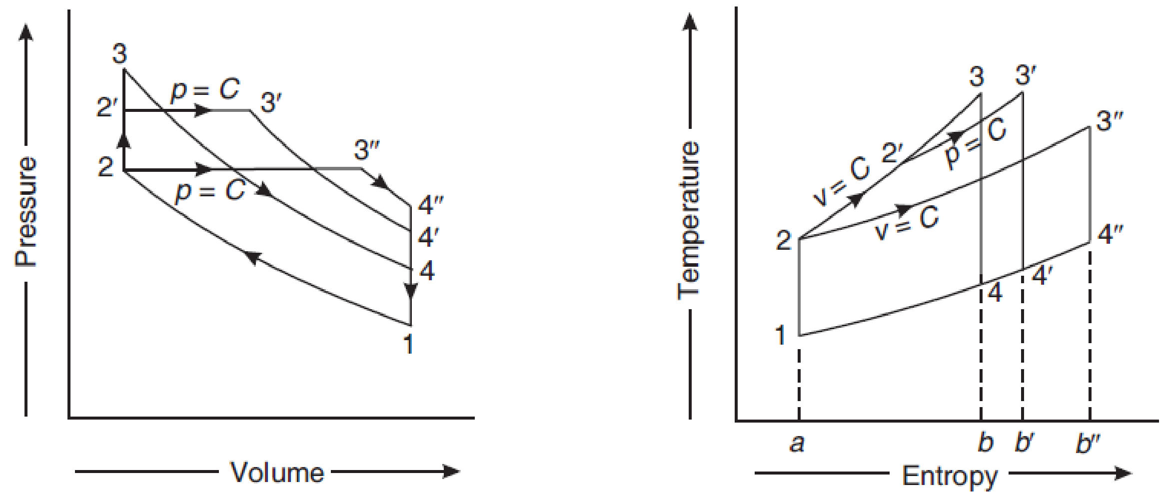


(*a*) *p-v* diagram. (*b*) *T-s* diagram.

Fig. 3 Dual cycle

Comparison of Otto, Diesel and Dual cycles
To know the relative performance of Otto, Diesel and Dual cycle, we compare them on the basis of various factors which affect the cycle efficiency.

(1) Equal Compression Ratio and Same Heat Input
Fig. 6.4 shows the comparison among Otto, Diesel and Dual cycle on P-V and T-s diagram.
Otto Cycle = 1-2-3-4
Diesel cycle = 1-2-3'-4'
Dual cycle = 1-2-2'-3"-4"



(a) p-v diagram. (b) T-s diagram.

Fig. 4 Otto, Diesel and dual cycles for equal compression ratio and heat input

We know that cycle efficiency η = 1 – (Heat rejected / Heat Supplied). We are supplying equal amount of heat to all the cycle, so the cycle which rejects the least amount of heat will be more efficient. From fig. 6.4, T-s diagram for all the cycles, we can say that Otto cycle has least amount of heat rejection, so it has highest efficiency.

$$\eta_{otto} > \eta_{dual} > \eta_{diesel}$$

(2) Same Heat Input and Maximum Pressure
Otto Cycle = 1-2'-3'-4'
Diesel cycle = 1-2-3-4
Dual cycle = 1-2'-2-3"-4"

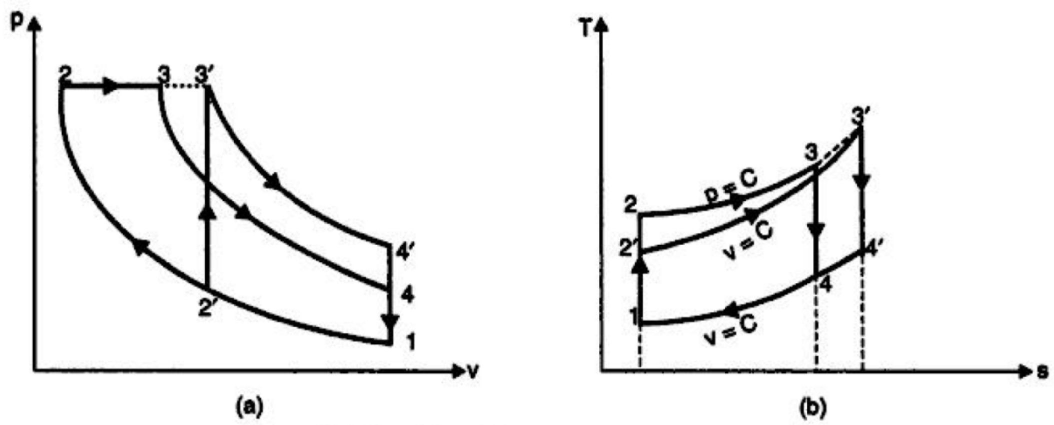


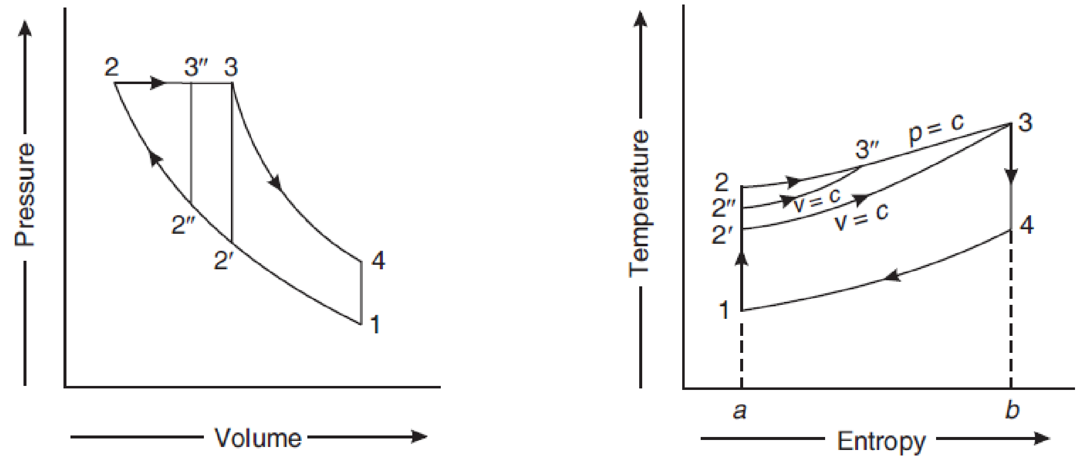
Fig. 5 Otto, Diesel and dual cycles for same heat input and maximum pressure

We know that cycle efficiency η = 1 – (Heat rejected / Heat Supplied). Comparing the cycle on constant maximum pressure with same heat input, we can see that point 3 and 3' are on the same constant pressure line. Referring T-s diagram we can conclude that the area under line 4’-1 which represent the heat rejected during the cycle and has minimum area and it is also less than the Otto cycle. Hence Diesel cycle has maximum efficiency than two other cycles.

$$\eta_{diesel} > \eta_{dual} > \eta_{otto}$$

(3) Maximum pressure and temperature

Otto cycle = 1-2-3-4
Diesel cycle = 1-2’-3-4
Dual Cycle =1-2”-3”-3-4



(*a*) *p-v* diagram. (*b*) *T-s* diagram.

Fig. 6 Otto, Diesel and dual cycles for same maximum pressure and temperature

We know that cycle efficiency η = 1 – (Heat rejected / Heat Supplied). Comparing the cycle on constant maximum pressure and temperature, referring Fig. 6.6 T-s diagram we can conclude that the area under line 4-1 which represent the heat rejected during the cycle and it same for all. So amount of heat supplied during the cycle detect the efficiency of the cycle. Higher the amount of heat supplied higher the efficiency. We can see that heat supplied is higher in case of Diesel cycle as compare to other two cycles. Hence Diesel cycle has maximum efficiency than two other cycles.

$$\eta_{diesel} > \eta_{dual} > \eta_{otto}$$

Conclusion:

Quiz:

(1) For the same compression ratio and heat rejection, which cycle is more efficient: Otto, Diesel and Dual?
(2) For the same compression ratio and heat supplied, which cycle is more efficient: Otto, Diesel and Dual?
(3) With the help of p-v and T-s diagrams, show that for the same maximum pressure and

temperature of the cycle and the same heat rejection, $\eta_{diesel} > \eta_{dual} > \eta_{otto}$

(4) Derive the mean effective pressure for Otto cycle.

(5) An I.C. engine is working on the Otto cycle, having cylinder diameter is 250 mm and a stroke is 375 mm. If the clearance volume is 0.00263 m^3, and the initial pressure and temperature are 1 bar and 50^{o}C, calculate the air standard efficiency and mean effective pressure of the cycle. The maximum cycle pressure is limited to 25 bar.

Suggested Reference:

1. Engineering Thermodynamics by P.K. Nag, McGraw-Hill Education
2. Fundamentals of Thermodynamics by Borgnakke & Sonntag, 7th Ed. Wiley India (P) Ltd.
3. Thermodynamics – An Engineering Approach by Yunus Cengel & Boles, McGraw-Hill Education
4. Engineering Thermodynamics by Gordon Rogers and Yon Mayhew, Pearson Education Ltd.
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References used by the students:

Rubric wise marks obtained:

Rubrics	**1**	**2**	**3**	**4**	**Total**
Marks					

Signature of faculty member

Experiment No: 8

To study variables affecting the performance of Rankine cycle

Date:

Competency and Practical Skills: Students will be able to understand about steam and its properties. Student will also able to understand the different components of vapor power system.

Relevant CO: To make use of different gas and vapor power cycles. (CO4)

Objectives: (a) To understand and analyse Rankine vapor power cycles.
(b) To understand the variables which affect the performance of Rankine cycle.

Theory:
Majority thermal power plants in the world are working on Rankine cycle. In majority plants fossil fuel is used and we all know that these resources are finite in quantity on the earth. They are depleting and darer by every day. Conservation of these resources are vital for the growth and development of the world. A small increase in the cycle efficiency can save the large amount of fuels. So that are efforts are made to improve the efficiency of the Rankine cycle. For this, to understand the effects of different variables on cycle is paramount important.

Rankine Cycle
Theoretically the Carnot cycle is the most efficient cycle between the fixed temperatures limits of T_1 and T_2, but impracticalities associated with it makes the Carnot cycle unviable and uneconomical for thermal power plant. Rankine cycle is the improvement over the Carnot cycle. In this cycle complete condensation is carried out in condenser and then water is fed back to boiler. Schematic of simple steam power plant is shown in Fig. 7.1 and the ideal Rankine cycle on T-s diagram is shown in Fig. 7.2.

It consists of four processes as under:
1-2: Isentropic expansion in turbine
2-3: Heat rejection in condenser at constant pressure
3-4: Isentropic compression in pump
4-1: Heat addition in boiler at constant pressure

Following assumptions are made in Rankine cycle.
1) Assume 1 kg of steam steady flow in the cycle.
2) Changes in kinetic energy and potential energy are negligible.
3) Condition of the working fluid at the exit of condenser is saturated liquid.

Applying SFEE to all the four components of the cycle.
For process:
1-2 in turbine, heat transfer is zero, so turbine work, $W_T = h_1 - h_2$
2-3 in Condenser, work transfer is zero, heat transfer $Q_2 = h_2 - h_3$
3-4 in pump, heat transfer is zero, so pump work, $W_p = h_4 - h_3$
4-1 in Boiler, work transfer is zero, heat transfer $Q_1 = h_1 - h_4$

$$\eta_{cycle} = W_{net} / Q_1$$
$$= W_T - W_p / Q_1$$
$$= (h_1 - h_2) – (h_4 - h_3) / (h_1 - h_4)$$

Pump work is small as compare to turbine work so we neglect it.

$$\eta_{cycle} = (h_1 - h_2) / (h_1 - h_4)$$

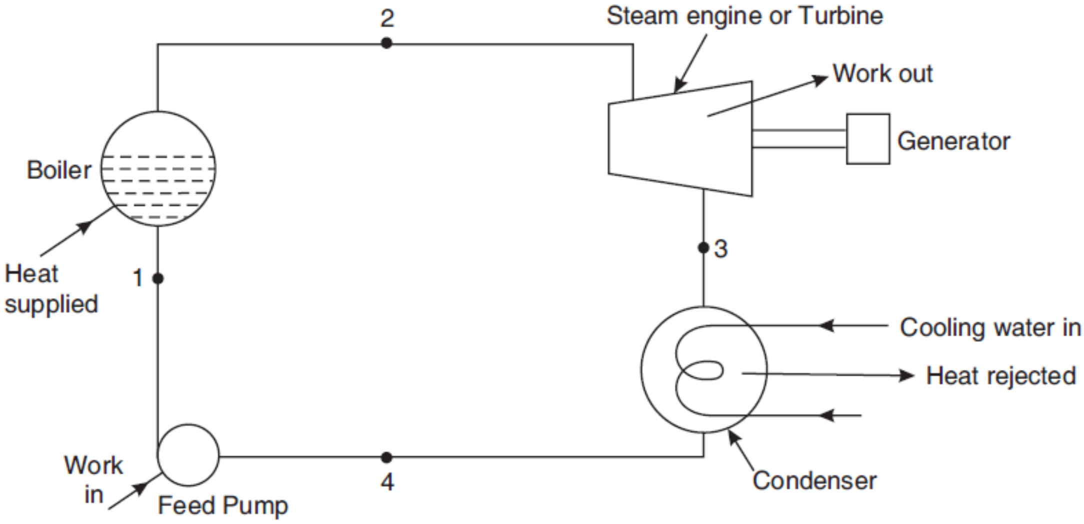

Fig. 1 Simple steam power plant

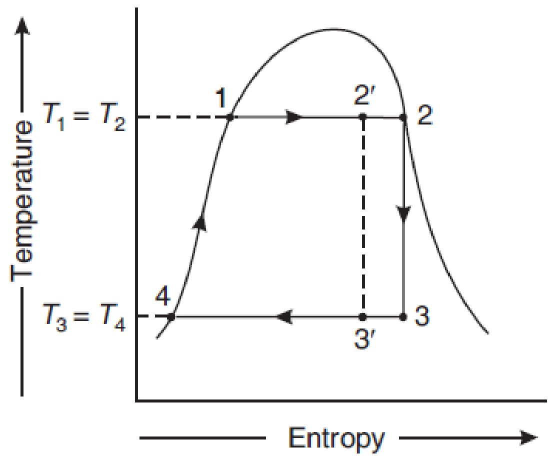

Fig. 2 Rankine cycle on T-s diagram

Effect of Variables on The Performance of Rankine Cycle

Effect of Inlet Superheat

As shown in Fig. 7.3 cycle 1-2’-3’-4-1 represents Rankine cycle using dry and saturated steam, whereas cycle 1-2-3-4-1 represents using superheated steam. When steam at entry point of the turbine is changed from 2’ to 2 due to superheated steam mean temperature increases, results into higher work deliver. This higher work is represented by area 2’-2-3-3’. We can say that as the superheat increases the cycle efficiency increases as compared to dry and saturated steam.

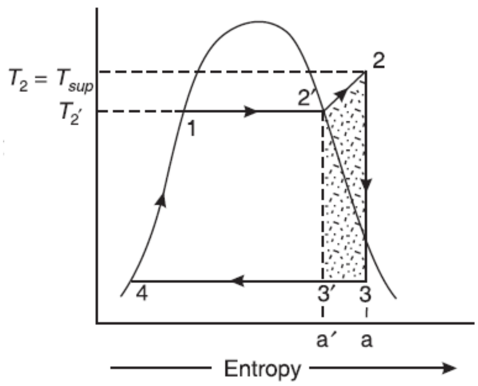

Fig. 3 Effect of inlet superheat

Effect of increase in the boiler pressure

Refer Fig. 7.4, cycle 1-2s-3-4s-1 represents when the working pressure is p_1 and cycle 5-6s-3-7s-5 represents when the working pressure is p_2, where $p_2 > p_1$. But temperature of steam T_{max} at entry point of turbine is same for both the cycle. It is clear from the T-s diagram that for a fixed temperature of steam T_{max} at entry point of turbine, diagram for a cycle which is working at higher pressure i.e. p_2 shifts towards left side. As a result, there is not much effect efficiency because net-work available remains unchanged; however, heat rejection is reduced for the cycle which is working at higher pressure p_2. As the heat rejection reduces the cycle efficiency increases. When heat addition takes place at higher pressure, the average temperature of heat addition also increases and we can achieve higher efficiency, but at the same time steam which is coming out from the turbine is having more moisture. This higher moisture condition is not desirable, because it erodes the blade surfaces as a result the blade life reduces.

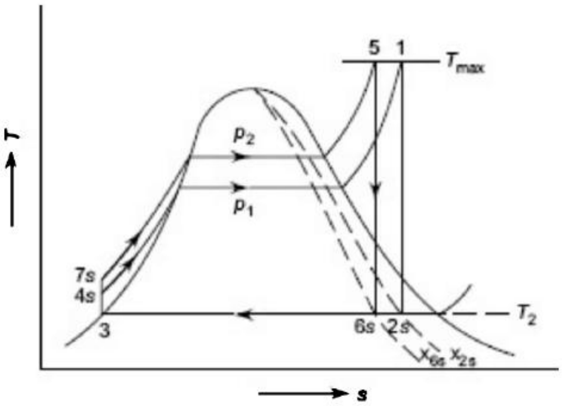

Fig. 4 Effect of boiler pressure

Effect of decrease in the condenser pressure

Two Rankine cycles 1 – 2 – 3 – 4 at condenser pressure, p_4 and the cycle 1'– 2' – 3 – 4'– 1' with decreased condenser pressure from p_4 to $p_{4'}$ are shown on T-s diagram in Fig.7.5. The condition of the steam at the turbine inlet is same. It can be seen that net-work output increases as a result of decrease in the condenser pressure from p_4 to $p_{4'}$. However, heat supplied also increases, but increase in heat requirement is very small as compared to increase in net work output. So, the resultant effect is in increase in the cycle efficiency.

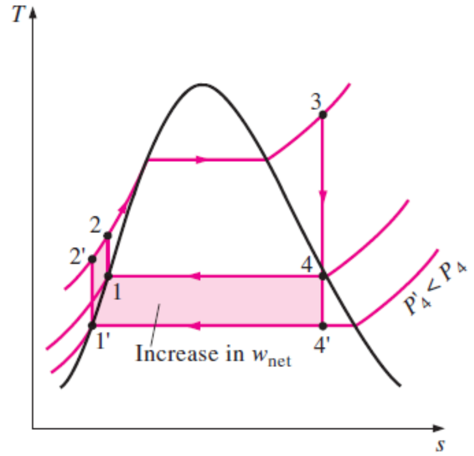

Fig. 5 Effect of condenser pressure

The condenser of power plant generally operates well below the atmospheric pressure, so we can achieve higher efficiency at low pressure. However, the pressure in condenser cannot go below the saturation pressure corresponding to the temperature of the cooling medium. Enough care should be taken to prevent the air leakage into condenser while lowering the condenser pressure.

Conclusion:

Quiz:

1. Explain the Rankine cycle for a steam power plant with p-V and T-s diagram.
2. what do you understand by the mean temperature and heat addition?
3. For a given temperature T_2, show how the Rankine cycle efficiency depends on the mean temperature of heat addition.
4. What is metallurgical limit?
5. A steam turbine power plant operating on ideal Rankine cycle, receives steam at 30 bar, 350° C at the rate of 2kg/s and it exhausts at 0.09 bar. Calculate the following: (1) Net power output (2) steam rate (3) heat rejection in condenser in kW (4) Rankine cycle efficiency (5) Actual thermal efficiency of the plant if the boiler efficiency is 85%.

Suggested Reference:

1. Engineering Thermodynamics by P.K. Nag, McGraw-Hill Education
2. Fundamentals of Thermodynamics by Borgnakke & Sonntag, 7th Ed. Wiley India (P) Ltd.
3. Thermodynamics – An Engineering Approach by Yunus Cengel & Boles, McGraw-Hill Education
4. Engineering Thermodynamics by Gordon Rogers and Yon Mayhew, Pearson Education Ltd.
5. Engineering Thermodynamics by Krieth, CRC Press

References used by the students:

Rubric wise marks obtained:

Rubrics	1	2	3	4	Total
Marks					

Signature of faculty member

Experiment No: 9

To Study Variables Affecting the Performance of Brayton Cycle

Date:

Competency and Practical Skills: Student will be able apprise variables affecting performance of Brayton cycle.

Relevant CO: To make use of different gas and vapor power cycles. (CO4)

Objective: To study variables affecting the performance of Brayton cycle.

Theory:

The thermal efficiency of actual open cycle depends on the following thermodynamic variables:

(a) Pressure ratio
(b) Turbine inlet temperature (T_3)
(c) Compressor inlet temperature (T_1)
(d) Efficiency of the turbine (η_t)
(e) Efficiency of the compressor (η_c)

Effect of Turbine Inlet Temperature and Pressure Ratio:

If the permissible turbine inlet temperature of an open cycle gas turbine power plant is increased keeping the other variables being constant, its thermal efficiency increases significantly. A practical limitation to increasing the turbine inlet temperature, however, is the ability of the material available for the turbine blading to withstand the high thermal stresses.

For a given turbine inlet temperature, as the pressure ratio increases, the heat supplied as well as the heat rejected are reduced (Fig.1). But the ratio of change of heat supplied is not the same as the ratio of change heat rejected. Consequently, there exists an optimum pressure ratio producing maximum thermal efficiency for a given turbine inlet temperature.

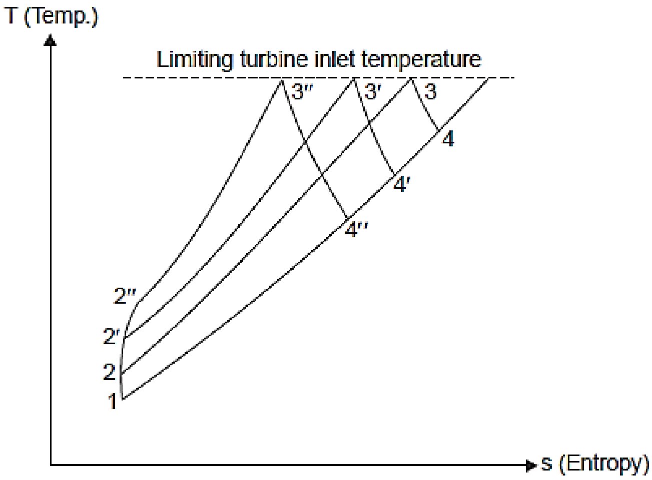

Fig.1 Effect of pressure ratio with fixed turbine inlet temperature

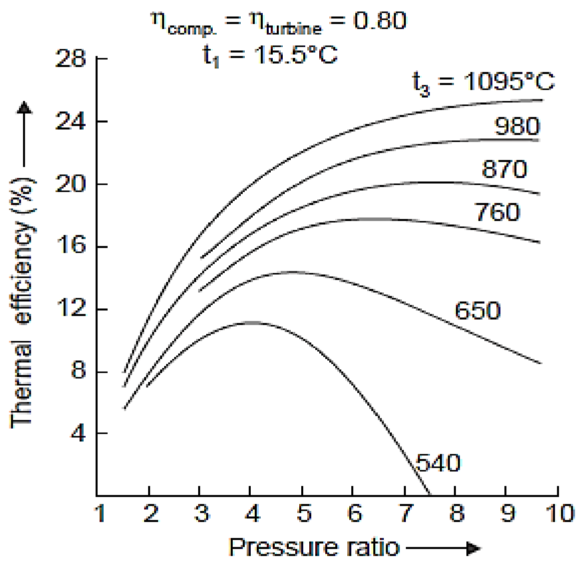

Fig. 2 Effect of pressure ratio and turbine inlet temperature on thermal efficiency

As the pressure ratio increases, the thermal efficiency also increases until it becomes maximum and then it drops off with a further increase in pressure ratio (Fig.2). Also, as the turbine inlet temperature increases, the peaks of the curves flatten out giving a greater range of pressure ratios for optimum efficiency.
Following particulars are worth noting:
Gas temperatures: Cycle efficiency
550 to 600°C: 20 to 22%
900 to 1000°C: 32 to 35%
Above 1300°C: more than 50%

Effect of Turbine and Compressor Efficiencies:
The thermal efficiency of the actual gas turbine cycle is very sensitive to variations in the efficiencies of the compressor and turbine. There is a particular pressure ratio at which maximum efficiencies occur. For lower efficiencies, the peak of the thermal efficiency occurs at lower pressure ratios and vice versa.

Effect of Compressor Inlet Temperature:
Fig. 4 shows the effect of compressor inlet temperature on the thermal efficiency of Brayton cycle. As shown, with the decrease in the compressor inlet temperature there is increase in thermal efficiency of the cycle. Also, the peaks of thermal efficiency occur at high pressure ratio and the curves become flatter giving thermal efficiency over a wider pressure ratio range.

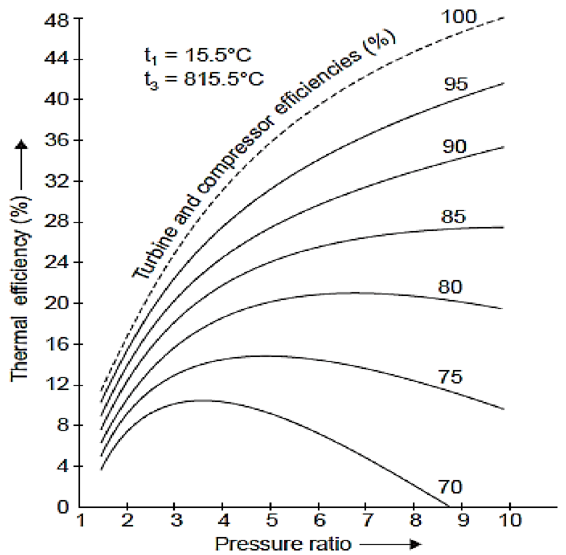

Fig. 3 Effect of turbine and compressor efficiencies on thermal efficiency

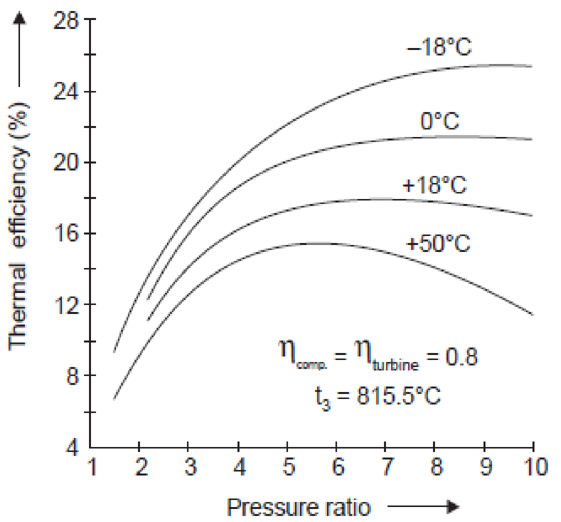

Fig.4 Effect of compressor inlet temperature

Effect of Working Fluid:
The working fluid plays a crucial role in the performance of the Brayton cycle, especially in closed Brayton cycles which are used in nuclear reactors, space power systems, supercritical CO_2 turbines, etc. In open cycles (like jet engines), the working fluid is air or combustion gases, and its properties are relatively fixed. However, in closed systems, the choice of working fluid directly influences thermal efficiency, specific work output, component size, and material compatibility.

Key Thermodynamic Properties Affected by Working Fluid:

Property	Influence on Brayton Cycle Performance
Specific Heat Ratio ($\gamma = c_p/c_v$)	Higher γ increases efficiency
Molecular Weight	Affects density and therefore component size
Specific Heat (c)	Influences energy exchange; higher c → more work per kg
Thermal Conductivity	Affects heat exchanger design (in closed cycles)
Viscosity	Impacts pressure drops and pumping work
Critical Temperature & Pressure	Important for supercritical cycle operation
Chemical Stability	Important at high TIT (e.g., > 1200 K)
Toxicity / Reactivity	Crucial for safety in enclosed environments (e.g., spacecraft)

Comparison of Common Working Fluids:

Fluid	γ	Density (kg/m³)	Temp Limit (K)	Remarks
Air	1.4	~1.2 (at STP)	~1600	Standard in Open Cycles
Helium	1.66	~0.18	>2000	High η, Low Density
sCO_2	1.3–1.5	~100 – 800 (supercritical)	~850 – 900	High Density, Compact Design
Nitrogen	1.4	~1.25	~2000	Inert, Used in Nuclear
Refrigerants (e.g., R134a)	~1.1–1.3	~4 – 7	Low (<400 K)	For Low-Temp Brayton Applications

Applications Based on Working Fluids:

Application	Typical Working Fluid
Aircraft Jet Engines	Air (open cycle)
Closed-loop nuclear Brayton cycles	Helium, Nitrogen
Spacecraft power systems	Helium, sCO_2
sCO_2 power plants	Supercritical CO_2
Portable refrigeration Brayton cycle	R134a, R1234yf (Closed Loop)

The performance of the Brayton cycle is highly sensitive to its operating parameters. Increasing turbine inlet temperature and optimizing pressure ratio significantly enhance efficiency. Real-world constraints such as component inefficiencies and working fluid properties must be considered in design. Improvements in material science, cooling technologies, and working fluid selection continue to drive advancements in Brayton cycle efficiency across aerospace, power generation, and space propulsion systems.

Conclusion:

Quiz:

1. What are the constraints to achieve higher turbine inlet temperature?
2. Define isentropic efficiency of turbine and compressor.
3. Which is minimum compressor inlet temperature in case of open cycle Brayton cycle?
4. Why does the thermal efficiency of Brayton cycle decrease with decrease in isentropic efficiencies of turbine and compressor?

Suggested Reference:

1. Engineering Thermodynamics by P.K. Nag, McGraw-Hill Education
2. Fundamentals of Thermodynamics by Borgnakke & Sonntag, 7th Ed. Wiley India (P) Ltd.
3. Thermodynamics – An Engineering Approach by Yunus Cengel & Boles, McGraw-Hill Education
4. Engineering Thermodynamics by Gordon Rogers and Yon Mayhew, Pearson Education Ltd.
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References used by the students:

Rubric wise marks obtained:

Rubrics	**1**	**2**	**3**	**4**	**Total**
Marks					

Signature of faculty member

Experiment No: 10

To study Brayton cycle with reheat, regeneration and intercooling

Date:

Competency and Practical Skills: Student will be able to make calculation for Brayton cycle with reheat, regeneration and intercooling.

Relevant CO: To make use of different gas and vapor power cycles. (CO4)

Objective: To analyze Brayton cycle with reheat, regeneration and intercooling.

Theory:
Gas turbine plant is based either on a constant pressure heat addition cycle (Brayton cycle) or a constant volume heat addition cycle (Atkinson cycle). In a gas cycle plant air or gases are used as a working fluid.

As shown in Fig. 1, in an ideal constant pressure heat addition cycle, air from atmosphere is compressed in a compressor, driven by the turbine, to a pressure of about 4 to 10 bar or more at constant entropy. The compressed air is then used in a combustion chamber for the combustion of fuel at constant pressure. The hot gases generated are then expanded through a turbine at constant entropy to atmospheric pressure. A part of the turbine output is utilized to compress air in the compressor and the net work output is the difference of turbine gross output and compressor input. The gases from the turbine are then exhausted to the atmosphere. Such a cycle is known as an open cycle.

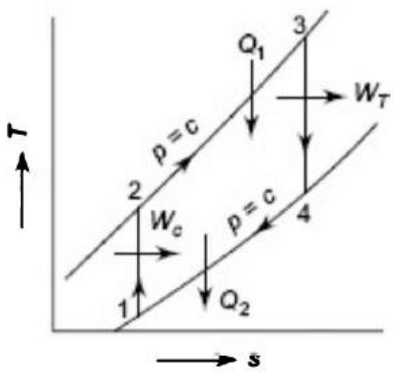


Fig. 1 Brayton cycle on T-s diagram

In a closed cycle the processes are the same as for an open cycle but the working fluid, gases, is confined to the cycle only at high pressure. Product of combustion transfers heat to the working fluid in a heat exchanger at constant pressure. The gases coming out of turbine are cooled in a heat exchanger to the initial state point at constant pressure. Efficiency of such a simple cycle is very less which can be improved by the means discussed below.

Means of Improving the Efficiency and the Specific Output of Simple Cycle:
The improvement of the simple cycle plant may be done by the following methods.

(1) Regeneration: This is done by preheating the air with the turbine exhaust, thus saving the fuel consumption.
(2) Improving turbine output. This may be done by
    (a) Reheating: The whole expansion in the turbine is achieved in two or more stages and reheating is done after each stage.

(b) Increasing the value of maximum cycle temperature i.e. turbine inlet temperature. This requires better quality of fuel, new materials which can withstand high temperatures and/or blade cooling methods

(c) Improved turbine efficiency. It depends on design improvements.

(3) Reducing compressor input. This may be done by

(a) Intercooling: Compressor work is reduced by intercooling the air between compressor stages.

(b) By lowering inlet temperature to compressor. Practical lowest inlet temperature is ambient temperature.

(c) By increasing the compressor efficiency. This depends upon the design improvement.

(d) Water injection. By injecting water at the inlet to compressor, the work output and efficiency is increased due to the extra mass of water injected and cooling of air.

Open Cycle Gas Turbine with Regeneration:

In this method, the air delivered by the compressor passes through a heat exchanger (regenerator) utilizing the gases exhausted from the turbine, the heated air then passes into the combustion chamber and it is employed to burn the fuel. Since some heat is added to the air in the heat exchanger itself, so the same turbine gas inlet temperature is attained as that when no heat exchanger is employed, with a lower fuel consumption. Hence the thermal efficiency will accordingly be higher. The compressor, turbine and net work are not affected by the addition of the regenerator to the cycle. Only the heat required to be supplied in the combustion chamber is decreased which gives the gain in thermal efficiency.

Ideal cycle: Fig. 2 shows the ideal Brayton cycle with regeneration. As shown in the figure high pressure air at state 2 is passed through a regenerator (or heat exchanger) where it is heated at constant pressure from T_2 to T_3 due to which the exhaust gas from the turbine at state 5 is cooled from T_5 to T_6. With perfect heat exchange in the heat exchanger, in the ideal cases, temperature of air leaving the heat exchanger will be equal to temperature of exhaust gas entering the heat exchanger and the temperature exhaust gas leaving heat exchanger will be equal to the temperature of air entering the heat exchanger. Thus, $T_3 = T_5$ and $T_6 = T_2$ i.e. $h_3 = h_5$ and $h_6 = h_2$.

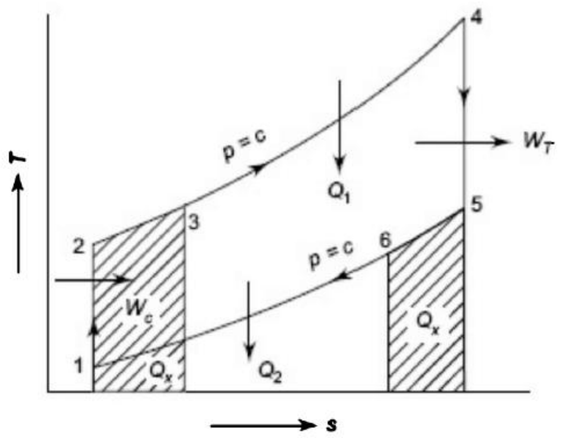


Fig. 2 Brayton cycle with regeneration

The air from the heat exchanger at temperature T_3 passes through the combustion chamber where it is heated from temperature T_3 to T_4 (i.e. from h_3 to h_4). The advantage of regenerator is that the amount of heat supplied in the combustion chamber is reduced form $(h_4 – h_2)$ to $(h_4 – h_3)$. Thus, the thermal efficiency is increased because the heat supplied is reduced.

Assuming 1 kg of air flowing through the compressor,

Turbine work: $W_t = h_4 – h_5 = c_p (T_4 – T_5)$ kJ/kg

Compressor work: $W_c = h_2 – h_1 = c_p (T_2 – T_1)$ kJ/kg

Net work done = $W_{net} = c_p (T_4 - T_5) - c_p (T_2 - T_1)$
Heat supplied = $Q_s = h_4 - h_3 = c_p (T_4 - T_3)$
Heat rejected = $Q_R = h_6 - h_1 = c_p (T_6 - T_1)$
So, the thermal efficiency is

$$\eta_{th} = \frac{W_{net}}{Q_s} = \frac{c_p[(T_4 - T_5)] - (T_2 - T_1)]}{c_p(T_4 - T_3)}$$

Which can also be written as

$$\eta_{th} = 1 - \frac{Q_R}{Q_s} = 1 - \frac{T_6 - T_1}{T_4 - T_3}$$

For ideal regenerative cycle, the same can be derived as

$$\eta_{th} = 1 - \frac{T_1}{T_4}(r_p)^{(\gamma-1)/\gamma}$$

In real case the temperature at 3 is less than that at 5. The ratio of actual temperature rise of air to the maximum possible rise is called effectiveness of regenerator (ε).
For the present case,

$$\varepsilon = \frac{T_3 - T_2}{T_5 - T_2}$$

A drawback of a regenerator is the low overall heat transfer coefficient when both the heating and heated fluids are gases. Maximum effectiveness is about 75 per cent. This in turn requires a large heat exchange area. Another drawback is the resistance to flow of the gases, which causes a pressure drop in the compressed air and increases the back pressure on the turbine. However, by careful design these losses can be kept low.

Open Gas Turbine Cycle with Reheat:
A further increase in work-done can be obtained by reheating or adding heat to the gases between two or more stages. In reheating, the gas temperature, which has dropped due to expansion is brought back to approximately the initial temperature for the expansion in the next stage. Since the working fluid contains about 5 per cent air, additional fuel can be burnt by injecting it into the gases without any additional air supply.

Ideal cycle: 1-2-3-4-5-6-1 is the ideal cycle gas turbine with reheat as shown in Fig. 3. The combustion gases at temperature T_3 are partially expanded in the high-pressure turbine from pressure p_2 to intermediate pressure p_x. The combustion gases are then passed through second combustion chamber where it is reheated at constant pressure p_x so that the temperature of the gas is raised from T_4 to $T_5 = T_3$. The gases are then expanded in the second stage turbine from pressure p_x to p_1

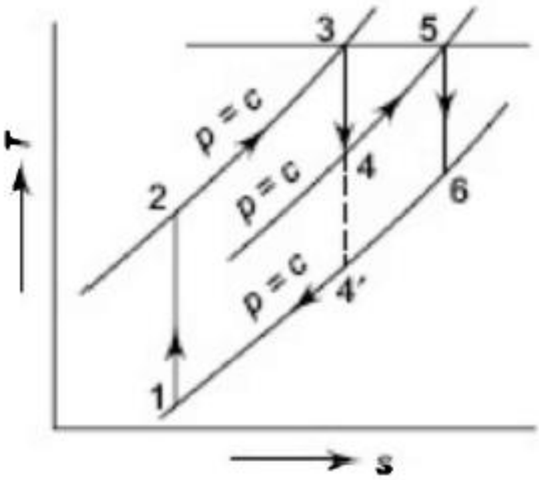


Fig. 3 Brayton cycle with reheating

Net work done is more with reheat compared to the ideal cycle without reheat. The efficiency with which the heat is added to the gases in the second combustion chamber at intermediate pressure p_x is lower than the efficiency when this heat is added to the gases in the first combustion chamber at higher pressure p_2. So, efficiency decreases because of reheating, and only net work done is higher.

Net work done = $W_{net} = c_p [(T_3 - T_4) + (T_5 - T_6) - (T_2 - T_1)]$ kJ/kg
Heat supplied $Q_s = c_p [(T_3 - T_2) + (T_5 - T_4)]$ kJ/kg

So, the thermal efficiency is given by

$$\eta_{th} = \frac{(T_3 - T_4) + (T_5 - T_6) - (T_2 - T_1)}{(T_3 - T_2) + (T_5 - T_4)}$$

For maximum output there must be an optimum pressure at which reheating should be done and it is given by

$$p_x = \sqrt{(p_1 p_2)} \quad \text{or} \quad r_{p_1} = r_{p_2} = \sqrt{(r_p)}$$

To find out the thermal efficiency for maximum output in this cycle, this value of intermediate pressure should be used.

Open Gas Turbine Cycle with Intercooling:
The net work done of the gas turbine cycle may be increased by saving some compression work. This is done by using several stages of compression with intercooling of air between stages. The air from the first stage compressor is cooled in an intercooler approximately to initial temperature before entering to the second stage compressor. The effect of intercooling is to increase the work and decrease the efficiency as compared to the simple ideal cycle without intercooling.

Ideal cycle: 1-2-3-4-5-6-1 is the ideal cycle gas turbine with intercooling as shown in Fig. 3. In first stage compressor, atmospheric air is compressed from p_1 to p_2, it is then cooled from temperature T_2 to $T_3 = T_1$ in the intercooler at constant intermediate pressure p_x and finally compressed from p_x to p_2 in the second stage of compressor. At constant pressure p_2 heat is added in the combustion chamber up to T_5 and then it is expanded in the turbine from pressure p_2 and temperature T_5 to pressure p_1.

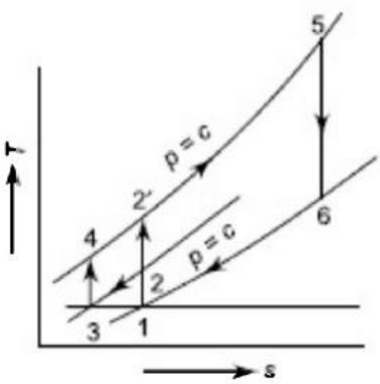


Fig. 4 Brayton cycle with intercooling

It is evident from the figure that the turbine work is the same as for the simple cycle but the work supplied to the compressor is reduced because the constant pressure lines converge towards the left. The work supplied to compressor is saved due to intercooling. But the heat supplied is increased by amount $(h_{2'} - h_4)$ because the compressed air delivered by second stage compressor is at lower temperature T_4 than in the simple cycle. So, the effect of the intercooling is to decrease the thermal efficiency of the cycle. This result is to be expected because the heat rejected in the intercooler is a complete loss, no part of it is converted into useful work.

For minimum compression work in the compressor or maximum work output in this cycle, the intermediate pressure of compression is given by

$$p_x = \sqrt{(p_1 . p_2)}$$

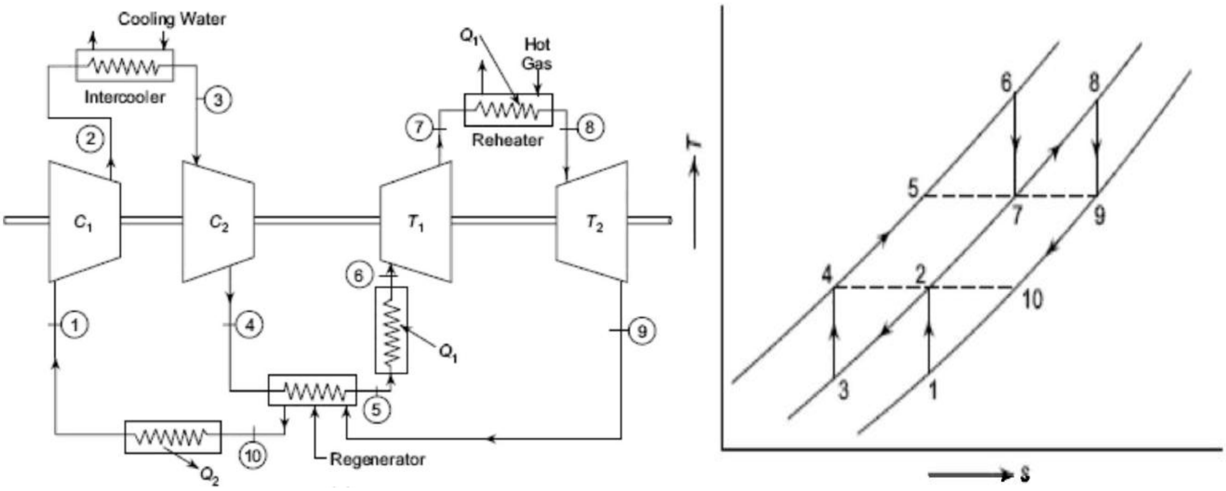
Net work done = $W_{net} = c_p [(T_5 - T_6) - (T_4 - T_3) - (T_2 - T_1)]$ kJ/kg
Heat supplied $Q_s = c_p (T_5 - T_4)$ kJ/kg

So, the thermal efficiency is given by

$$\eta_{th} = \frac{(T_5 - T_6) - (T_4 - T_3) - (T_2 - T_1)}{(T_5 - T_4)}$$

Open Gas Turbine Cycle with Intercooling, Reheating and Regeneration:
The power output as well as the thermal efficiency of this cycle is considerably greater than that of the simple cycle. It is to be noted that the power output is increased due to reheat and intercooling, and thermal efficiency rise is due to regeneration.

Schematic diagram and corresponding T-s diagram of an ideal regenerative gas turbine cycle with two stage compression and a single reheat is shown in Fig. 5.



Turbine work: $W_t = c_p [(T_6 - T_7) + (T_8 - T_9)]$
Compressor work: $W_c = c_p [(T_2 - T_1) + (T_4 - T_3)]$
Heat supplied: $Q_s = c_p [(T_6 - T_5) + (T_8 - T_7)]$
Thermal efficiency

$$\eta_{th} = \frac{(T_6 - T_7) + (T_8 - T_9) - (T_2 - T_1) - (T_4 - T_3)}{(T_6 - T_5) + (T_8 - T_7)}$$

In the present ideal case, regenerator effectiveness is 1, however in case of actual cycle, T_5 will be lower than T_9 and regenerative effectiveness is given by

$$\epsilon_r = \frac{T_5 - T_4}{T_9 - T_4}$$

Exercise: (attach separate sheet for solution)
The following data refer to an ideal gas turbine cycle.
Pressure ratio = 4, Compressor inlet temperature = 26°C, Turbine inlet temperature = 600°C
Regenerative effectiveness = 0.8, Inlet pressure to compressor = 1 bar

Determine (a) cycle thermal efficiency (b) specific output for the following cases.

1. Simple cycle
2. Regeneration
3. Reheat
4. Intercooling
5. Reheat, Intercooling plus Regeneration

Conclusion:

Quiz:

1. What are the methods to improve the thermal efficiency of simple gas turbine cycle?
2. What is the effect of regeneration on Brayton cycle efficiency?
3. Define the effectiveness of regenerator.
4. What is the effect of reheating on Brayton cycle efficiency?
5. What is the effect of intercooling on Brayton cycle efficiency?

Suggested Reference:

1. Engineering Thermodynamics by P.K. Nag, McGraw-Hill Education
2. Fundamentals of Thermodynamics by Borgnakke & Sonntag, 7th Ed. Wiley India (P) Ltd.
3. Thermodynamics – An Engineering Approach by Yunus Cengel & Boles, McGraw-Hill Education
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References used by the students:

Rubric wise marks obtained:

Rubrics	1	2	3	4	Total
Marks					

Signature of faculty member