THERMODYNAMICS & FLUIDS

(Thermodynamics level 1\Thermo & Fluids Module -Thermo Book 2-Contents-December 07.doc)

UFMEQU-20-1

THERMODYNAMICS NOTES - BOOK 2 OF 2

Students must read through these notes and work through the various exercises in their own time in parallel with the course of lectures.

Thermodynamics is the study of the relationships that exist between the properties of a gas or a vapour and the transfer of heat and work energy to or from that gas or vapour.

Contents

FORMULAE & DATA

GENERAL

Density ρ = mass / volume = m/V   Specific volume v = V/m $\rho = 1 / v$

$\rho = 1000 kg/m^3$ for water $\rho = 13600 kg/m^3$ for mercury $1 m^3 = 1000$ litres

$KE = ½mC^2$ $PE = mgZ$ $g = 9.81 m/s^2$ $1 bar = 10^5 N/m^2$

PRESSURE:

Pressure p = force / area = F / A   Absolute pressure $p = p_{gauge} + p_{atmos}$

Note that h_p is sometimes represented by 'z'

Atmospheric pressure $p_{atmos} = \rho g h_b$ where h_b is the barometric head

Standard atmospheric pressure $p_{atmos} = 1.01325 bar$ $1 bar = 10^5 N/m^2$

FOR GASES

$T^oK = T^oC + 273$ R = gas constant

$pV = mRT$ $v = V/m = RT/p$ $V = mv$ $\rho = m/V = p/RT$

For any process, change in internal energy: $(U_2 - U_1) = mc_v(T_2 - T_1)$

For any process, change in internal energy per kg: $(u_2 - u_1) = c_v(T_2 - T_1)$ $U = mu$

For any process, change in enthalpy: $(H_2 - H_1) = mc_p(T_2 - T_1)$

For any process, change in enthalpy per kg: $(h_2 - h_1) = c_p(T_2 - T_1)$ $H = mh$

Gas constant: $R = c_p - c_v$ $\gamma = c_p / c_v$

For any process: $p_1V_1/T_1 = p_2V_2/T_2$;

For a polytropic process:

$p_1V_1^n = p_2V_2^n$ and $p_1V_1/T_1 = p_2V_2/T_2$ and $T_2/T_1 = (p_2/p_1)^{(n-1)/n} = (V_1/V_2)^{(n-1)}$

For an adiabatic process (Q = 0):

$p_1V_1^\gamma = p_2V_2^\gamma$ and $p_1V_1/T_1 = p_2V_2/T_2$ and $T_2/T_1 = (p_2/p_1)^{(\gamma-1)/\gamma} = (V_1/V_2)^{(\gamma-1)}$

For constant volume heating: $Q = mc_v(T_2 - T_1)$ (i.e. $Q = U_2 - U_1$)

For constant pressure heating: $Q = mc_p(T_2 - T_1)$ (i.e. $Q = H_2 - H_1$)

FOR WET STEAM

$u = xu_g + (1\text{-}x)u_f$

$h = xh_g + (1\text{-}x)h_f$ or $h = h_f + xh_{fg}$

$v = xv_g + (1\text{-}x)v_f$ or $v = xv_g$ approximately

NON-FLOW THERMODYNAMIC PROCESSES FOR GASES & VAPOURS

NFEE: Heat in – Work out = change in Internal Energy

NFEE: $Q - W = (U_2 - U_1)$

NFEE per kg of fluid: $q – w = (u_2 - u_1)$

$U = mu$

$Q = 0$ for adiabatic processes

$W = 0$ when V = constant

$W = p(V_2 - V_1)$ when p = constant

$W = p_1V_1\ln(V_2/V_1)$ when pV = constant

$W = (p_1V_1 - p_2V_2)/(n-1)$ when pV^n = constant (Polytropic process)

$W = (p_1V_1 - p_2V_2)/(\gamma-1)$ when pV^γ = constant (GAS undergoing an adiabatic process)

STEADY FLOW THERMODYNAMIC PROCESSES FOR GASES & VAPOURS

SFEE:

Heat in – Work out = change in potential energy + change in kinetic energy + change in enthalpy

SFEE: $Q - W = mg(Z_2 - Z_1) + \frac{1}{2}m(C_2^2 - C_1^2) + (H_2 - H_1)$

SFEE for 1kg of fluid: $q - w = g(Z_2 - Z_1) + \frac{1}{2}(C_2^2 - C_1^2) + (h_2 - h_1)$

$H = mh$

$Q = 0$ for adiabatic processes

Mass flow rate $\dot{m} = A_1C_1/v_1 = A_2C_2/v_2$ or $\dot{m} = \rho_1A_1C_1 = \rho_2A_2C_2$

Power = $w\dot{m}$

NON-FLOW PROCESSES – GASES

(Thermodynamics\ level 1\ non-flow gas.doc)

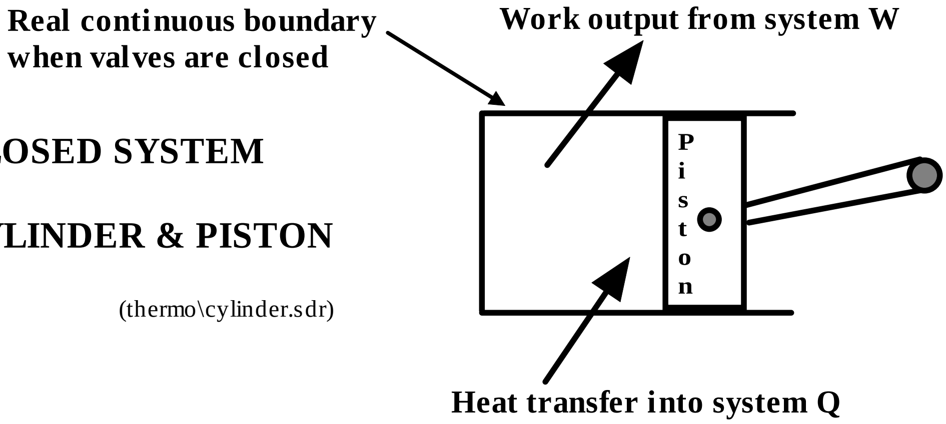
CLOSED SYSTEMS

Non-flow processes take place in closed systems

CLOSED SYSTEM

CYLINDER & PISTON

(thermo\cylinder.sdr)



THE GAS LAWS

The gas laws given below apply to **any process where the working fluid is a gas**.

$PV/T = mR = \text{Constant}$	**$pv/T = R$** for 1 kg	**$R = c_p - c_v$**	**$p_1V_1/T_1 = p_2V_2/T_2$**
$U_2 - U_1 = mc_v(T_2 - T_1)$	**$u_2 - u_1 = c_v(T_2 - T_1)$**	**$H_2 - H_1 = mc_p(T_2 - T_1)$**	**$h_2 - h_1 = c_p(T_2 - T_1)$**

THE NON-FLOW ENERGY EQUATION

The NFEE shown below applies to all non-flow processes.

$Q - W = (U_2 - U_1)$ or **$q - w = (u_2 - u_1)$** per kg

Q is the heat transfer **into** the system W is the work transfer **out of** the system

$(U_2 - U_1)$ is the change in internal energy of the system

$U_2 - U_1 = mc_v(T_2 - T_1)$ or **$u_2 - u_1 = c_v(T_2 - T_1)$** / kg **for all gas processes**

WORK DONE W

All the work done expressions for non-flow processes involve the product **(pV)** in some form. Thus for gases, **(pV)** can be replaced by **(mRT)** from the equation of state, **$pV = mRT$**

CONSTANT VOLUME PROCESS FOR A GAS

ISOMETRIC PROCESS

Process law:	**p/T = constant**	from	**pV/T = constant**	with	**V = constant**
Or	**$p_1/T_1 = p_2/T_2$**	from	**$p_1V_1/T_1 = p_2V_2/T_2$**	as	**$V_1 = V_2$**
	$Q = mc_v(T_2 – T_1)$	by definition of c_v.			
	$W = 0$				
	$U_2 – U_1 = mc_v(T_2 – T_1)$				

CONSTANT PRESSURE PROCESS FOR A GAS

ISOBARIC PROCESS

Process law:	**V/T = constant**	from	**pV/T = constant**	with	**p = constant**
Or	**$V_1/T_1 = V_2/T_2$**	from	**$p_1V_1/T_1 = p_2V_2/T_2$**	as	**$p_1 = p_2$**
	$Q = mc_p(T_2 - T_1)$	by definition of c_p			
	$W = p(V_2 - V_1)$	or	**$W = mR(T_2 - T_1)$**		
	$U_2 - U_1 = mc_v(T_2 - T_1)$				

CONSTANT TEMPERATURE PROCESS FOR A GAS

ISOTHERMAL PROCESS

A **constant temperature process** is known as an **isothermal process**.

Process law:	**pV = constant**	from	**$pV = mRT$**	with	**T = constant**
Or	**$p_1V_1 = p_2V_2$**	from	**$p_1V_1/T_1 = p_2V_2/T_2$**	as	**$T_1 = T_2$**
Also	**$(V_2/V_1) = (p_1/p_2)$**				
	$W = p_1V_1\ln(V_2/V_1)$ or **$W = p_1V_1\ln(p_1/p_2)$**			ln means "log to base e"	
Or	**$W = mRT\ln(V_2/V_1)$** or **$W = mRT\ln(p_1/p_2)$**			as	$pV = mRT$
	$U_2 - U_1 = mc_v(T_2 - T_1)$ = Zero			as	$T_1 = T_2$

POLYTROPIC PROCESS FOR A GAS

This is a general type of process.

Process law: $\mathbf{pV^n = constant}$ i.e. $\mathbf{p_1V_1^n = p_2V_2^n}$

"n" is known as the Polytropic index and has a value which is normally between 1 and 1.5.

Thus **two** equations apply to a **polytropic** process when the working fluid is a **gas**:

The **polytropic** law $\mathbf{p_1V_1^n = p_2V_2^n}$ which gives $\mathbf{p_2/p_1 = (V_1/V_2)^n}$ ----------------(1)

The **gas law** $\mathbf{p_1V_1/T_1 = p_2V_2/T_2}$ which gives $\mathbf{T_2/T_1 = (p_2/p_1)(V_2/V_1)}$ --------(2)

From (1) & (2) $\mathbf{T_2/T_1 = (V_1/V_2)^n(V_2/V_1) = (V_1/V_2)^n(V_1/V_2)^{-1} = (V_1/V_2)^{n-1}}$

i.e. $\mathbf{T_2/T_1 = (V_1/V_2)^{n-1}}$ ---(3)

From (1) $\mathbf{V_1/V_2 = (p_2/p_1)^{1/n}}$

Substitute in (3) $\mathbf{T_2/T_1 = [(p_2/p_1)^{1/n}]^{n-1}}$ or $\mathbf{T_2/T_1 = (p_2/p_1)^{(n-1)/n}}$ --------(4)

Combine (3) & (4)

$$\mathbf{T_2/T_1 = (p_2/p_1)^{(n-1)/n} = (V_1/V_2)^{n-1}}$$

Also $\mathbf{W = (p_1V_1 - p_2V_2)/(n-1)}$ or $\mathbf{W = mR(T_1 - T_2)/(n-1)}$

And $\mathbf{U_2 - U_1 = mc_v(T_2 - T_1)}$

ADIABATIC PROCESS FOR A GAS

An adiabatic process is a special type of polytropic process in which there is **zero heat transfer**, i.e. $\mathbf{Q = 0}$

A reversible adiabatic process is also known as an **isentropic process**, i.e. a process in which the property **entropy remains constant**.

Adiabatic conditions can be achieved if either:

(a) The temperature difference between the system and the surroundings is zero

(b) The system is perfectly insulated

Thus for a gas undergoing an adiabatic process

$\mathbf{Q = 0}$

$\mathbf{U_2 - U_1 = mc_v(T_2 - T_1)}$

$\mathbf{W = (p_1V_1 - p_2V_2)/(n-1) = mR(T_1 - T_2)/(n-1)}$

But $\mathbf{Q - W = U_2 - U_1}$ (NFEE)

$\therefore$ $\mathbf{0 - mR(T_1 - T_2)/(n-1) = mc_v(T_2 - T_1)}$

$\therefore$ $\mathbf{R(T_2 - T_1)/(n-1) = c_v(T_2 - T_1)}$ $\therefore \mathbf{R/(n-1) = c_v}$ $\therefore \mathbf{R/c_v = n-1}$

But $\mathbf{R = c_p - c_v}$ for a gas $\therefore \mathbf{(c_p - c_v)/c_v = n-1}$ $\therefore \mathbf{c_p/c_v - 1 = n-1}$

$\therefore$ $\mathbf{n = c_p/c_v}$

Thus an adiabatic process for a gas is a special case of a polytropic process in which the index of the process "n" is equal to the ratio of the specific heats of the gas.

The ratio of the specific heats of the gas is written as γ (gamma), ie. $\boldsymbol{\gamma = c_p/c_v}$

Hence the process law for a gas undergoing an **adiabatic process** is

$$pV^{\gamma} = \text{constant}$$

i.e. $\mathbf{p_1V_1^{\gamma} = p_2V_2^{\gamma}}$ where $\boldsymbol{\gamma = c_p/c_v}$

Also $\mathbf{W = (p_1V_1 - p_2V_2)/(\gamma - 1)}$ **or** $\mathbf{W = mR(T_1 - T_2)/(\gamma-1)}$

And $\mathbf{T_2/T_1 = (p_2/p_1)^{(\gamma-1)/\gamma} = (V1/V_2)^{(\gamma-1)}}$

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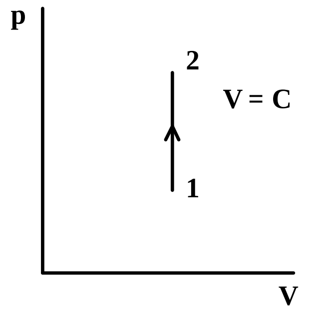
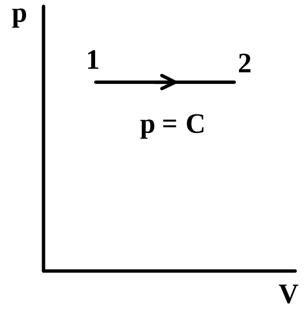
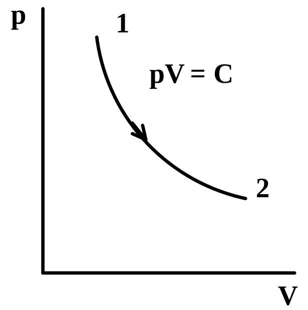
p – V DIAGRAMS FOR NON-FLOW PROCESSES



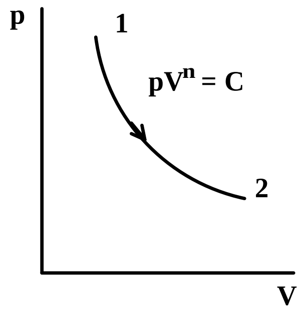
Constant volume heating process



Constant pressure expansion process



Constant temperature expansion process i.e. an isothermal expansion



Polytropic expansion process

(sdr-thermo\p-V diagrams)

AIR AS THE WORKING FLUID

Many thermodynamic systems use air as the working fluid. When this is the case, values of **R, the specific heats, etc**. may be obtained from page 26 of the tables of **Thermodynamic and Transport Properties of Fluids** by **Rogers and Mayhew**, and these are given below:

R kJ/kgK	**c_p kJ/kgK**	**c_v kJ/kgK**
0.287	**1.005**	**0.718**

EXERCISE - REVERSIBLE NON-FLOW PROCESSES – GASES

(Thermodynamics\ Level 1\Non-flow Gas Exercise.doc)

1. A rigid container holds 1kg of air initially at 4.8bar and 150^{o}C. The air is heated until its temperature is 200^{o}C. Determine
   (a) the final air pressure
   (b) the work done
   (c) the change in internal energy
   (d) the heat supplied.
   For air, R = 0.287 kJ/kgK, c_v = 0.718 kJ/kgK
   [Ans. 5.37bar; 0; 35.9kJ; 35.9kJ]

2 A mass of gas is heated at a constant pressure of 1.5bar in a closed system from an initial volume of 0.25m^3 to a final volume of 0.75m^3. The initial temperature is 15^{o}C. Determine
   (a) the mass of air
   (b) the final temperature
   (c) the work done
   (d) the internal energy change
   (e) the heat transfer.
   Take R = 0.3kJ/kgK and c_v = 0.73kJ/kg.
   [Ans 0.435kg; 864K; 75kJ; 183kJ; 258kJ]

3 A quantity of gas is compressed isothermally from an initial pressure of 1bar and an initial volume of 1m^3 through a volume ratio of 8. Determine
   (a) the work done
   (b) the change in internal energy
   (c) the heat transfer.
   [Ans -208kJ, zero, -208kJ]

4 1m^3 of air at 10bar and 150^{o}C expands polytropically in a closed system to a final volume of 6m^3 according to the law $PV^{1.2} = C$. Determine
   (a) the mass of air
   (b) the final pressure
   (c) the final temperature
   (d) the work done
   (e) the internal energy change
   (f) the heat transfer.
   Take R = 0.287kJ/kgK and C_v = 0.718kJ/kg.
   [Ans 8.25 kg, 1.162 bar, 295 K, 1500 kJ, -758 kJ, 742 kJ]

5 1kg of gas expands adiabatically in a closed system from 227C and 7bar to a final pressure of 1.5bar. Determine

(a) the final temperature
(b) the initial volume
(c) the final volume
(d) the work done
(e) the heat transfer
(f) the change in internal energy.

Take C_p = 0.994kJ/kgK and C_v = 0.72kJ/kgK.
[Ans 327 K, 0.1956 m^3, 0.597 m^3, 124.8 kJ, zero, -124.8 kJ]

6 A quantity of air, initially occupying a volume of 0.04m^3 at a pressure of 15bar and a temperature of 500^{o}C, is contained in a closed cylinder fitted with a piston.
The air is allowed to expand polytropically, displacing the piston, until its final volume is 0.32m^3, the law of the expansion process being $pV^{1.25}$ = constant.
Assuming the process to be reversible and treating the air as a perfect gas, calculate for the air

(a) the mass;
(b) the final pressure;
(c) the final temperature;
(d) the change in internal energy;
(e) the work done;
(f) the heat transfer.

For air: R = 287J/kgK and c_v = 718J/kgK.
[Ans 0.2705 kg, 1.115 bar, 459.6^{o}K, -60.86 kJ, 97.28 kJ, 36.42 kJ]

7 A quantity of air is compressed polytropically in a closed piston-in-cylinder type reciprocating compressor, the law of the process being $pV^{1.3}$ = constant.
At the beginning of the process, the air has a volume of 0.02m^3, a pressure of 1.2 bar and a temperature of 10^{o}C. At the end of the process, the volume of air is 0.002m^3.
Assuming the process to be reversible, and treating the air as a perfect gas, calculate for the air in the cylinder:

(a) the mass
(b) the final temperature
(c) the final pressure
(d) the work done
(e) the change in internal energy
(f) the heat transfer

For air, R =287 J/kgK and c_v = 718 J/kgK
[Ans: 0.02955 kg, 564.7 K, 23.94 bar, -7964 J, 5977 J, -1987 J]

8 Two points were chosen on the compression curve of an indicator diagram taken from a reciprocating air compressor. At the first point it was found that the pressure was $110kN/m^2$ and the volume was $0.027m^3$, whilst at the second point the pressure was $350kN/m^2$ and the volume was $0.01m^3$. The mass of air under compression was 0.027kg. Given that the compression process was polytropic and followed the law PV^n = constant, determine for the process between the two chosen points

(a) the polytropic index n
(b) the initial and final temperatures
(c) the work done on the air.

Take R = 0.287kJ/kgK.

[Ans 1.165, 383.3K, 451.7K, -3.21kJ]

9 0.4kg of gas is compressed adiabatically in a closed system from 20C and 1bar to a final pressure of 6bar. Determine

(a) the ratio of the specific heats γ
(b) the gas constant R
(c) the final temperature
(d) the initial volume
(e) the final volume
(f) the work done
(g) the heat transfer
(h) the change in internal energy.

Take c_p = 1.008 kJ/kgK and c_v = 0.72 kJ/kgK.

[Ans 1.4, 0.288 kJ/kgK, 488.9 K, 0.3375 m^3, 0.09387 m^3, -56.42 kJ, zero, 56.42 kJ]

10 A quantity of gas expands isothermally from an initial pressure of 5 bar and an initial volume of $0.2m^3$ to a final volume of $0.9m^3$. Determine

(a) the final pressure
(b) the work done
(c) the change in internal energy
(d) the heat transfer.

[Ans 1.111 bar, 150.41 kJ, zero, -150.41 kJ]

11 The cylinder of a reciprocating compressor, initially of volume 0.1 m^3, contains 0.25 kg of nitrogen at a pressure of 2.5 bar.

The gas is subjected to a reversible **adiabatic** compression process to a final volume of 0.04 m^3.

Assuming the nitrogen to be a perfect gas, calculate:-

(a) Its initial temperature
(b) The ratio of its specific heats (γ)
(c) Its final pressure at the end of the compression stroke
(d) Its final temperature
(e) The work done in compressing the nitrogen
(f) The change in internal energy of the nitrogen

For nitrogen: R = 297 J/kgK and c_v = 745 J/kgK.

[Ans 336.7 K, 1.4, 9.02 bar, 485.8 K, -27.7 kJ, 27.7 kJ]

12 Two points were chosen on the expansion curve of an indicator diagram taken from a piston engine. At the first point it was found that the pressure was 24 bar and the volume was 0.002 m^3, whilst at the second point the pressure was 1.2 bar and the volume was 0.02 m^3. The mass of gas in the cylinder was 0.03 kg. Given that the expansion procerss was polytropic and followed the law PV^n = constant, determine for the process between the two chosen points

(a) the polytropic index n
(b) the initial and final temperatures
(c) the work done by the expanding gases.

Take R = 0.287kJ/kgK.

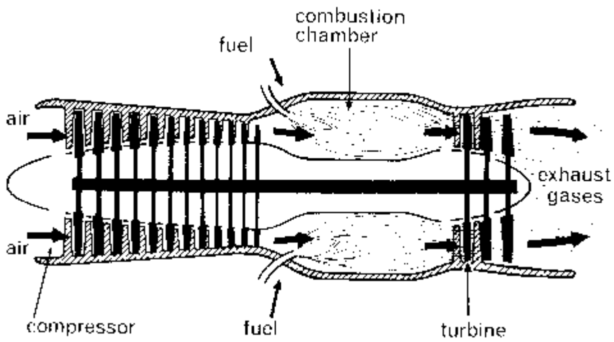
[Ans 1.301, 557.5K, 278.7K, 7975J]

STEADY-FLOW PROCESSES – GASES

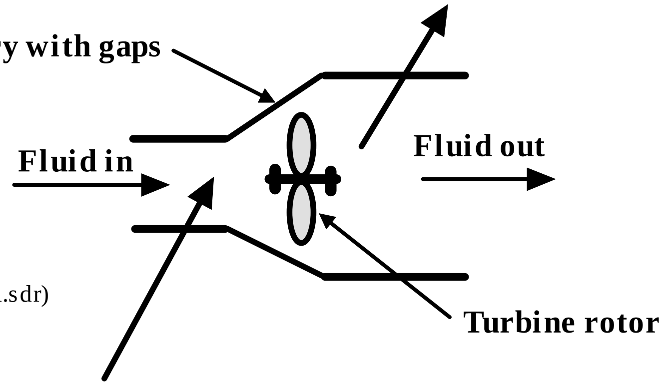
(Thermodynamics\ Level 1\ Steady-flow Gas.doc)

OPEN SYSTEMS

Flow processes take place in open systems. An example is a gas turbine engine



Alternatively, the compressor on its own, or the combustion chamber, or the turbine may be considered separately as open systems.



THE GAS LAWS

The gas laws given below apply to **any process where the working fluid is a gas**.

$PV/T = mR =$ Constant	**$pv/T = R$** for 1 kg	**$R = c_p - c_v$**	**$p_1V_1/T_1 = p_2V_2/T_2$**
$U_2 - U_1 = mc_v(T_2 - T_1)$	**$u_2 - u_1 = c_v(T_2 - T_1)$**	**$H_2 - H_1 = mc_p(T_2 - T_1)$**	**$h_2 - h_1 = c_p(T_2 - T_1)$**

THE STEADY FLOW ENERGY EQUATION

$$Q - W = mg(Z_2 - Z_1) + \tfrac{1}{2}m(C_2^2 - C_1^2) + (H_2 - H_1)$$

Or

$$q - w = g(Z_2 - Z_1) + \tfrac{1}{2}(C_2^2 - C_1^2) + (h_2 - h_1) \quad \textbf{for a mass of 1kg}$$

$$H_2 - H_1 = mc_p(T_2 - T_1) \quad \textbf{for all gas processes}$$

Or

$$h_2 - h_1 = c_p(T_2 - T_1) \quad \textbf{for a mass of 1kg}$$

UNITS

Always work in Joules throughout when using the SFEE, as the potential energy and kinetic energy terms will naturally come out in Joules when using kilograms, metres and seconds.

THE CONTINUITY EQUATION

$\rho_1 A_1 C_1 = \rho_2 A_2 C_2$ or $A_1 C_1 / v_1 = A_2 C_2 / v_2$	
$\dot{m} = \rho AC = AC/v$	$v = 1 / \rho$

Where **v = specific volume** and **ρ = density**

Units:	$\dot{m}$ = kg/s	ρ = kg/m^3	**v = m^3 / kg**	**A** = m^2	**C** = m/s

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SPECIFIC VOLUME OF A GAS v m^3/kg

Specific volume is the volume occupied by 1 kg of gas i.e. $\mathbf{v = V/m}$

$\mathbf{pV = mRT}$ for a gas, so $\mathbf{v = V / m = RT / p}$

$\mathbf{v = RT / p}$ **for a gas**

Note that specific volume v is the inverse of density ρ, i.e.

$\mathbf{v = 1 / \rho}$

POWER

Power = the rate of doing work = the work done per second

∴ Power = work done by each kg of gas x the number of kg of gas flowing per second

∴ Power = work done by each kg of gas x the mass flow rate of gas

∴ Power = work done per kg of gas x $\dot{m}$

∴ work done per kg of gas = power / $\dot{m}$

Units

Power	**Work done per kg of gas**	**Mass flow rate** $\dot{m}$
W or J/s	**J/kg**	**Kg/s**

EXERCISE - STEADY FLOW PROCESSES – GASES

(Thermodynamics\ Level 1\ Steady-flow Gas Exercise)

Note. Unless otherwise stated, always do the initial calculations taking the mass of gas as 1 kg. Then take the actual mass flow of gas into account at the end of the calculation.

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1 A steady flow of air enters a horizontal heater at 9^o C and leaves at 32^o C. The mass flow of air through the heater is 0.6 kg/s.
The air pressure at the exit from the heater is 1.2 bar
Ignoring any changes in kinetic energy, calculate
(a) The change in specific enthalpy of the air i.e. the enthalpy change per kg
(b) The heat transfer per kg of air
(c) The heater power i.e. the heat transfer per second
(d) The specific volume of the air as it leaves the heater
(e) The cross-sectional area of the heater exit duct if the exit velocity is 20m/s.
Take R = 287 J/kgK and c_p = 1005 J/kgK
[Ans. 23.115 kJ/kg, 23.115 kJ/kg, 13.869 kW, 0.7295 m^3/kg, 0.02188 m^2]

2 A steady flow of air enters a horizontal cooler at 95^o C and 120 m/s and it leaves at 20^o C and 10 m/s. The air pressure at the entry to the cooler is 2.5 bar. The mass flow of air through the cooler is 1.8 kg/s. Calculate
(a) The change in specific enthalpy of the air between entry and exit
(b) The change in kinetic energy per kg of air between entry and exit
(c) The heat transfer per kg of air
(d) The heat transfer rate i.e. the heat transfer per second
(e) The specific volume of the air at entry
(f) The cross-sectional area of the cooler entry duct.
Take R = 0.287 kJ/kgK and c_p = 1.005 kJ/kgK
[Ans. –75.375 kJ/kg, -7.15 kJ/kg, -82.525 kJ/kg, -148.545 kJ/s or kW, 0.4225 m^3/kg, 6337 mm^2]

3 Air enters a horizontal nozzle at a pressure of 2 bar, a temperature of 93^o C and a velocity of 50 m/s. The air expands adiabatically in the nozzle, leaving the nozzle with a temperature of 27^o C and a pressure of 1 bar. The air mass flow rate is 3.8 kg/s. Calculate
(a) The exit velocity
(b) The specific volume of the air at entry
(c) The cross-sectional area of the nozzle entry duct.
Take R = 0.287 kJ/kgK and c_p = 1.005 kJ/kgK
[Ans. 367.64 m/s, 0.52521 m^3/kg, 0.03992 m^2]

4 A steady flow of gas enters the horizontal turbine of a jet engine at 900^o C and 20 m/s, and leaves at 500^o C and 180 m/s. A heat loss of 10 kJ/kg of gas occurs during its passage through the turbine and the mass flow rate is 5 kg/s. The pressure of the gas at the turbine exit is 100 kN/m^2. Calculate

(a) The change in specific enthalpy of the gas between entry and exit
(b) The change in kinetic energy per kg of gas between entry and exit
(c) The work done per kg of gas
(d) The power output of the turbine
(e) The specific volume of the gas at the turbine exit
(f) The cross-sectional flow area of the turbine exhaust duct.

Take c_p = 1.080 kJ/kgK and R = 0.295 kJ/kgK

[Ans. –432 kJ/kg, 16 kJ/kg, 406 kJ/kg, 2.03 MW, 2.28035 m^3/kg, 0.06334 m^2]

5 A steady stream of air enters a horizontal compressor at the rate of 0.02 kg/s. The air temperature is 10^o C at entry and 300^o C at exit. The velocity of the air is 30 m/s at entry and 6 m/s at exit. During its passage through the compressor, the air experiences a heat loss of 105 kJ/kg of air. Calculate

(a) The change in kinetic energy per kg of air between entry and exit
(b) The change in specific enthalpy of the air between entry and exit
(c) The work done per kg of air
(d) The power required to drive the compressor
(e) The flow area of the entry pipe if the entry pressure is 1 bar

Take R = 0.287 kJ/kgK and c_p = 1.005 kJ/kgK for the air.

[Ans. –0.432 kJ/kg, 291.45 kJ/kg, -396.018 kJ/kg, 7.92036 kW, 541.47 mm^2]

6 A gas flows steadily into a horizontal cooler at 275^o C and 4.6 bar through a circular duct of 200 mm diameter. The gas leaves the cooler at 35^o C and 15 m/s. The mass flow rate of the gas through the cooler is 1.9 kg/s. Calculate

(a) The flow area of the entry duct and the specific volume of the gas at entry
(b) The entry velocity and the change in kinetic energy per kg of gas
(c) The change in specific enthalpy between entry and exit
(d) The heat transfer per kg of gas
(e) The heat transfer rate i.e. the heat transfer per second

Take R = 0.290 kJ/kgK and c_p = 1.010 kJ/kgK

[Ans. 0.0314159 m^2, 0.345478 m^3/kg, 20.894 m/s, -0.10578 kJ/kg, -242.4 kJ/kg, -242.50578 kJ/kg, -460.761 kJ/s or kW]

7 A horizontal axial compressor provides a steady flow of air. The air enters the compressor at a velocity of 5 m/s, a temperature of 15^o C and a pressure of 1 bar. The air leaves the compressor at a velocity of 85 m/s and a temperature of 115^o C. The outer surfaces of the compressor are exposed to the atmosphere and as a result, there is a heat loss of 6 kJ/kg of air as it passes through the compressor. The mass flow rate is 4 kg/s.
Calculate for the air flowing through the compressor:
(a) The change in enthalpy per kg of air
(b) The change in kinetic energy per kg of air
(c) The work done per kg of air
(d) The power required to drive the compressor
(e) The air density at entry
(f) The cross-sectional flow area of the entry pipe.

Take R = 0.287 kJ/kgK and c_p = 1.005 kJ/kgK

[Ans. 100.5 kJ/kg, 3.6 kJ/kg, -110.1 kJ/kg, 440.4 kW, 1.2098 kg/m^3, 0.6612 m^2]

8 Air flows steadily through a horizontal nozzle that is designed to produce a stream of high velocity air at its exit. The air enters the nozzle at a pressure of 3.2 bar, a temperature of 100^o C and with a velocity of 6m/s. The air expands adiabatically as it flows through the nozzle and leaves the nozzle with a pressure of 2 bar. The air mass flow rate is 0.8 kg/s. Calculate
(a) The temperature of the air as it leaves the nozzle
(b) The enthalpy change per kg of air
(c) The kinetic energy per kg of air at entry to the nozzle
(d) The kinetic energy per kg of air as it leaves the nozzle
(e) The velocity of the air as it leaves the nozzle
(f) The density of the air at the nozzle exit
(g) The required flow area at the nozzle exit

Take R = 287 J/kgK, c_p = 1005 J/kgK and $\gamma = 1.4$

Note that $\mathbf{T_2 / T_1 = (p_2 / p_1)^{(\gamma-1)/\gamma}}$ for a gas undergoing an adiabatic process

[Ans. 326.1^o K, -47.106 kJ/kg, 18 J/kg, 47.124 kJ/kg, 307 m/s, 2.137 kg/m^3 1220 mm^2]

9 A steady stream of air enters a horizontal compressor at 10^o C with a velocity of 50 m/s. The air leaves the compressor at 300^o C with a velocity of 10 m/s. During its passage through the compressor, the air experiences a heat loss of 20 kJ/kg of air. The air pressure at entry is 1 bar and the mass flow rate is 0.2 kg/s. Calculate:

(a) The change in kinetic energy per kg of air
(b) The change in enthalpy per kg of air
(c) The work done per kg of air
(d) The power required to drive the compressor
(e) The air density at entry
(f) The cross-sectional flow area of the entry pipe.

Take R = 287 J/kgK and c_p = 1000 J/kgK.

[Ans. –1.2 kJ/kg, 290 kJ/kg, -308.8 kJ/kg, 61.76 kW, 1.2312 kg/m^3, 3248 mm^2]

10 Air flows steadily through a horizontal heater. The air enters the heater at a temperature of 20^o C, and with negligible velocity. The air leaves the heater at a pressure of 1.4 bar, a temperature of 420^o C, and a velocity of 200 m/s. The air mass flow rate is 2.4 kg/s. Determine for the air

(a) The change in kinetic energy per kg
(b) The change in enthalpy per kg
(c) The heat transferred per kg
(d) The density of the air at exit
(e) The flow area of the exit pipe.

Take R = 287 J/kgK and c_p = 1005 J/kgK

[Ans. 20 kJ/kg, 402 kJ/kg, 422 kJ/kg, 0.7039 kg/m^3, 0.01705 m^2]

11 A steady flow of air enters a compressor with a velocity of 60 m/s, a temperature of 20^o C and a pressure of 1 bar, through a pipe that has a cross-sectional area of 0.5 m^2. The air leaves the compressor with a velocity of 70 m/s and a pressure of 2 bar through a pipe that has a cross-sectional area of 0.4 m^2. There is a heat loss of 1350 J per kg of air as it passes through the compressor. Calculate for the air flowing through the compressor:

(a) The volumetric flow rate at entry in m^3/s
(b) The mass flow rate in kg/s
(c) The volumetric flow rate at exit in m^3/s
(d) The air temperature at exit
(e) The change in enthalpy per kg of air
(f) The change in kinetic energy per kg of air
(g) The work done per kg of air
(h) The power required to drive the compressor.

Take R = 287 J/kgK and c_p = 1005 J/kgK

[Ans. 30 m^3/s, 35.68 kg/s, 28 m^3/s, 546.9^{o}K, 255.2 kJ/kg, 0.65 kJ/kg, -257.2 kJ/kg, 9.18MW]

12 A steady flow of gas enters the turbine of a jet engine at 900^o C and 20 m/s, and leaves at 500^o C and 180 m/s. A heat loss of 10 kJ/kg of gas occurs during its passage through the turbine and the mass flow rate is 5 kg/s.
Determine the power output of the turbine and also the exhaust duct flow area given that the exhaust pressure is 100 kN/m^2.

Take C_p = 1 kJ/kgK and R = 0.290 kJ/kgK.

[Ans. 1.87 MW; 0.0622 m^2]

13 Air enters a horizontal nozzle at a pressure of 1.6 bar, a temperature of 150^o C, and a velocity of 150 m/s. The air expands adiabatically and reversibly (i.e. without friction) in the nozzle, leaving the nozzle with an exit pressure of 1 bar. Calculate
(a) The air temperature at the nozzle exit
(b) The air velocity at the nozzle exit.

Take R = 287 J/kgK, c_p = 1005 J/kgK and $\gamma = 1.4$

Note that $\mathbf{T_2 / T_1 = (p_2 / p_1)^{(\gamma-1)/\gamma}}$ for a gas undergoing an adiabatic process

[Ans. 96.8^o C, 359.8 m/s]

14 A perfect gas flows steadily through a cooler. The entry temperature and velocity are 315^o C and 150 m/s respectively. The gas leaves the cooler through a duct of cross-sectional area 0.2 m^2 at a pressure of 250 kN/m^2 and at a temperature of 37^o C. The mass flow rate of the gas is 13.5 kg/s. Calculate the heat transfer rate.

Take R = 0.297 kJ/kgK and C_p = 1.035 kJ/kgK.

[Ans. -4.04 MJ/s or -4.04 MW]

15 A steady stream of air enters a compressor at the rate of 0.8kg/min. The air temperature is 15^oC at inlet and 30^oC at exit. The compressor is cooled by 4 kg/min of cooling water, the temperature rise of which is 20 degC. The velocity of the air is 20m/s at entry and 5m/s at exit. Determine the power required to drive the compressor, stating any assumptions made, and also the cross-sectional area of the entry pipe if the inlet pressure is 1bar.

Take the specific heat of water = 4.187 kJ/kgK
Take R = 0.287 kJ/kgK and c_p = 1.005 kJ/kgK for the air

[Ans. 5.79 kW, 0.00055 m^2]

16 A centrifugal compressor takes in 0.5 kg/s of air at 1.013 bar and 15^o C and compresses the air to a final pressure of 1.9 bar according to the law $pV^{1.6} = C$. Assuming that any heat losses through the casing and changes in potential energy and kinetic energy are all negligible, calculate

(a) The temperature of the air leaving the compressor *91.6 ^{o} C*

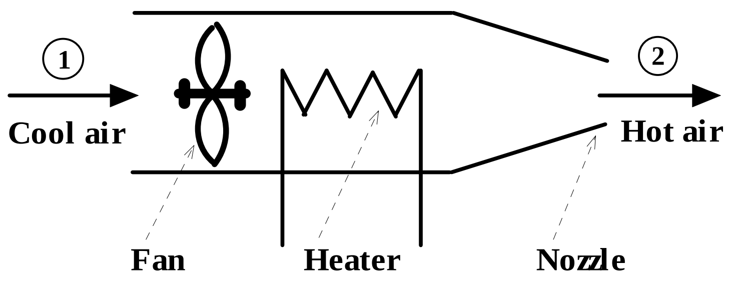
(b) The power required to drive the compressor *38.49 kW*

Take R = 0.287 kJ/kgK and c_p = 1.005 kJ/kgK

Note $\mathbf{T_2 / T_1 = (p_2 / p_1)^{(n-1)/n}}$ for a gas undergoing a process to the law $pV^n = C$

17 A horizontal "hot air blower" consists of a fan, an electrical heating element and a nozzle as shown.

(thermo\ blower.sdr)



The power input to the fan is 65J/s and the power input to the heating element is 1155J/s. During its passage through the blower, the air experiences a heat loss of 15J/s.

A steady flow of air enters the fan at a pressure of 1bar, a temperature of 24^oC, a velocity of 10m/s, and a volumetric flow rate of $0.02m^3$/second.

After passing over the heating element, the air leaves the nozzle at a pressure of 1.1bar and a temperature of 75^oC.

Treating the complete arrangement as a steady flow system, determine:

(a) The mass flow rate of air entering the fan in **kg per second** *0.02346kg/s*

(b) The change in enthalpy of the air occurring **per second** between entering the fan and leaving the nozzle *1202.4J/s*

(c) The kinetic energy of the air entering the fan **per second** *1.2J/s*

(d) The kinetic energy of the air leaving the nozzle **per second** *3.8J/s*

(e) The velocity of the air as it leaves the nozzle *18m/s*

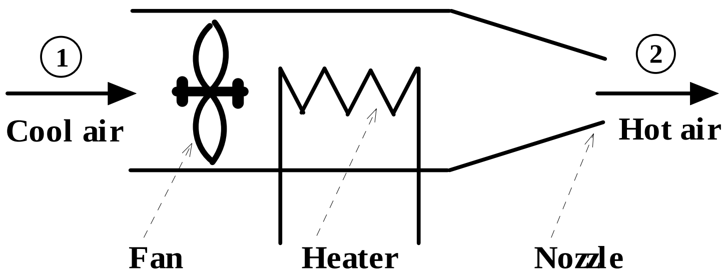
(f) The density of the air as it leaves the nozzle *$1.101kg/m^3$*

(g) The flow area at the nozzle exit. *$1184mm^2$*

For air, take R = 287 J/kg^oK and c_p = 1005 J/kg^oK

18 A horizontal "hot air blower" consists of a fan, an electrical heating element and a nozzle.

(thermo\ blower.sdr)



The power input to the fan is 50J/s and the power input to the heating element is 1.44kJ/s. The air enters the fan with negligible velocity at a pressure of 1 bar and a temperature of 20^o C, the volumetric flow rate being 0.5 m^3/min. After passing over the heating element, the air leaves the nozzle with a velocity of 25 m/s and a pressure of 1.1bar.

Treating the complete arrangement as a steady flow system and ignoring any heat loss from the system, determine:

(a) The mass flow rate of air entering the fan in **kg per second** *0.00991kg/s*
(b) The kinetic energy of the air leaving the nozzle **per second** *3.1J/s*
(c) The change in enthalpy of the air occurring **per second** between entering the fan and leaving the nozzle 1486.9*J/s*
(d) The temperature of the air as it leaves the nozzle. *169.3^o C*
(e) The density of the air as it leaves the nozzle 0.8666*kg/m^3*
(f) The flow area at the nozzle exit. $457.4 \times 10^{-6} m^2$

Take R = 0.287 kJ/kgK and c_p = 1.005 kJ/kgK

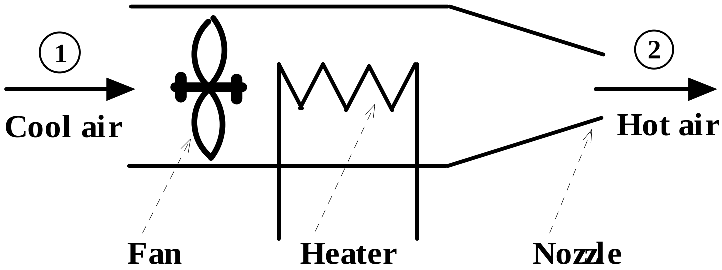
19 A steady stream of air enters a horizontal compressor at the rate of 0.02 kg/s. The air temperature is 10^o C at entry and 300^o C at exit. The velocity of the air is 30 m/s at entry and 6 m/s at exit. During its passage through the compressor, the air experiences a heat loss of 105 kJ/kg of air. Calculate:

(a) The change in kinetic energy per kg of air *–0.432 kJ/kg*
(b) The change in enthalpy per kg of air *291.45 kJ/kg*
(c) The work done per kg of air *-396 kJ/kg*
(d) The power required to drive the compressor *7.92 kW*
(e) The volume of air entering the compressor per second *0.01624 m^3/kg*
(f) The flow area of the entry pipe if the entry pressure is 1 bar *541.5 mm^2*

Take R = 0.287 kJ/kgK and c_p = 1.005 kJ/kgK

20 The diagram below shows a “hot air blower” consisting of a fan, an electrical heating element and a nozzle. The flow of air through the blower is horizontal

(thermo\ blower.sdr)



The power input to the fan is 80J/s and the power input to the heating element is 1500J/s. During its passage through the blower, the air experiences a heat loss of 10J/s. A steady flow of air enters the fan at a pressure of 1bar, a temperature of 20°C, a velocity of 9m/s, and a volumetric flow rate of 0.015m^3/second.After passing over the heating element, the air leaves the nozzle at a pressure of 1.2bar and a temperature of 107°C.

Treating the complete arrangement as a steady flow system, determine:

(a) The mass flow rate of air entering the fan in **kg per second** *0.01784kg/s*

(b) The change in enthalpy of the air occurring **per second** between entering the fan and leaving the nozzle *1559.7J/s*

(c) The kinetic energy of the air entering the fan **per second** *0.72J/s*

(d) The kinetic energy of the air leaving the nozzle **per second** *11.1J/s*

(e) The velocity of the air as it leaves the nozzle *35.23m/s*

(f) The density of the air as it leaves the nozzle *1.1kg/m^3*

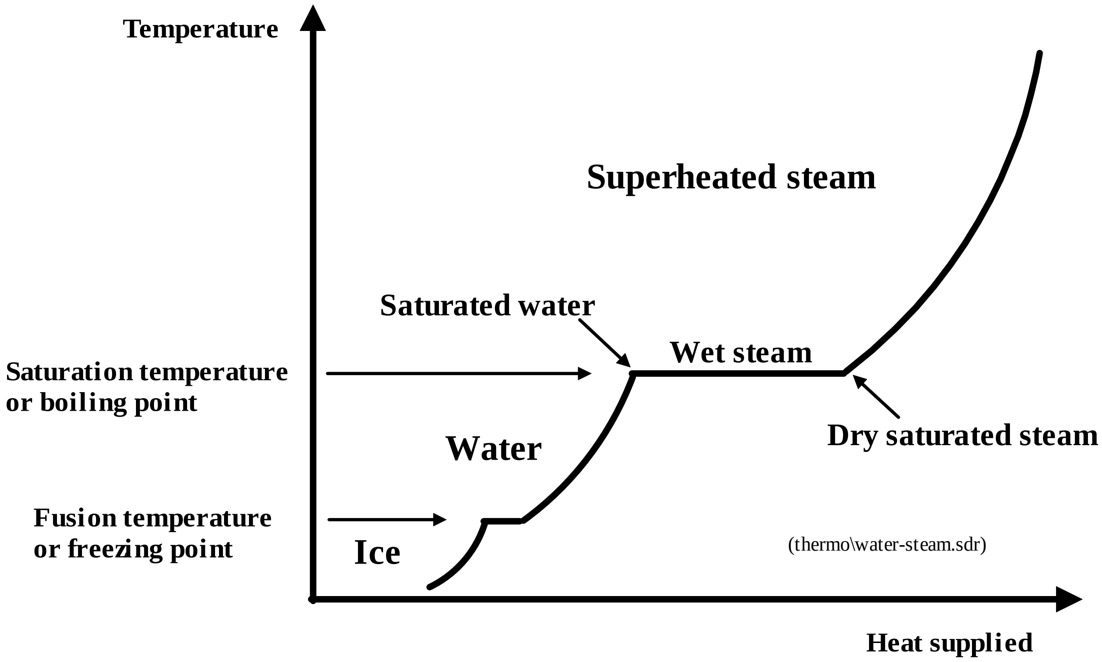
(g) The flow area at the nozzle exit. *460mm^2*

For air, take R = 287 J/kg°K and c_p = 1005 J/kg°K

STEAM TABLES

(Thermodynamics\ Level 1\ Steam-tables.doc)

CONSTANT PRESSURE HEATING OF WATER TO PRODUCE STEAM



- **Water changes into steam at the saturation temperature (boiling point)**
- **The saturation temperature increases with increasing pressure**
- **Water at its boiling or saturation temperature is known as saturated water**
- **The temperature remains constant while water is being changed into steam**
- **Steam at its saturation temperature is known as dry saturated steam**
- **When water is changing to steam, a water/steam mixture known as wet steam exists**
- **Steam above its saturation temperature is known as superheated steam**
- **Steam does not obey the Gas Laws**
- **Never use the Gas Laws for steam**
- **Always use Steam Tables for finding the properties of water and steam.**
- **The recommended tables are:**
- **Thermodynamic & Transport Properties of Fluids (SI units) by Rogers & Mayhew**

Thermodynamic & Transport Properties of Fluids (SI units)

by Rogers & Mayhew

These tables use the following notation and units:

Property	Symbol	Units
Pressure	**p**	**bar**
Temperature	**t**	**^oC**
Specific volume	**v**	**m^3/kg**
Specific internal energy	**u**	**kJ/kg**
Specific enthalpy	**h**	**kJ/kg**
Specific entropy	**s**	**kJ/kg ^oK**

SUBSCRIPTS USED IN THE TABLES

f refers to water at its boiling point or saturation temperature

g refers to dry steam that is still at the saturation temperature (dry saturated steam)

fg refers to the change from boiling water to dry saturated steam at constant pressure

s refers to the saturation temperature or pressure

PROPERTIES OF WATER BELOW ITS BOILING POINT

A liquid that is below its boiling point or saturation temperature is known as a **compressed liquid.**

Water is highly incompressible so its properties are little affected by changes in pressure.

For this reason the actual temperature of the water is taken as the boiling or saturation temperature and the actual pressure is ignored. So:

$\mathbf{v = v_f}$ (page 10)	$\mathbf{u = u_f}$ (pages 3 – 5)	$\mathbf{h = h_f}$ (pages 3 – 5)

Do not forget to insert two zeros after the decimal point in each case for v_f.

For example, at 25^o C, v_f = 0.0010030 m^3 / kg and not 0.10030 m^3 / kg

----

PROPERTIES OF WATER AT ITS BOILING POINT

This is water at its saturation temperature. It is known as "saturated water"

Subscript "**f** " applies. So:

$\mathbf{v = v_f}$ (page 10)	$\mathbf{u = u_f}$ (pages 3 to 5)	$\mathbf{h = h_f}$ (pages 3 to 5)

Do not forget to insert two zeros after the decimal point in each case for v_f.

For example, at 25^o C, v_f = 0.0010030 m^3 / kg and not 0.10030 m^3 / kg

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PROPERTIES OF DRY SATURATED STEAM

Dry saturated steam is steam that has no particles of water contained in it but that is still at the saturation temperature (boiling point) at which it was formed.

Subscript "**g**" applies. So:

$\mathbf{v = v_g}$ (pages 3 to 5)	$\mathbf{u = u_g}$ (pages 3 to 5)	$\mathbf{h = h_g}$ (pages 3 to 5)

PROPERTIES OF WET STEAM

Wet steam is a mixture of boiling (saturated) water and dry saturated steam that exists during the change of phase from boiling water to dry saturated steam.

The proportion of dry steam that is present in a wet steam mixture is known as the

Dryness fraction x

$$\therefore \textbf{Dryness fraction x} = \frac{\textbf{the mass of dry steam present in the wet steam mixture}}{\textbf{the total mass of the wet steam mixture}}$$

Thus in 1 kg of wet steam with dryness fraction **x**

Mass of dry steam present = x kg

Mass of water present = (1 – x) kg

Therefore

$v = xv_g + (1 - x)v_f$	$u = xu_g + (1 - x)u_f$	$h = xh_g + (1 - x)h_f$

Expanding the expression for h gives

$h = xh_g + h_f - xh_f$ or $h = h_f + x(h_g - h_f)$ or

$$\mathbf{h = h_f + xh_{fg}}$$

Values of u_f, h_f, u_g, h_g and h_{fg} are given on pages 3 – 5 of the tables.

Values of v_f are given on page 10 of the tables.

Do not forget to insert two zeros after the decimal point in each case for v_f.

For example, at 25^o C, $v_f = 0.0010030\ m^3 / kg$ and not $0.10030\ m^3 / kg$

APPROXIMATE EXPRESSION FOR SPECIFIC VOLUME OF WET STEAM

The volume of water present in wet steam is normally negligible compared with the volume of dry steam that is present. The volume of the water present may then be ignored and thus

The approximate specific volume of wet steam $v = xv_g$

PROPERTIES OF SUPERHEATED STEAM

This is steam that has been heated to temperatures in excess of the saturation temperature corresponding to the steam pressure.

v, u and h are given in the tables at various pressures and temperatures on pages 6 – 8.

To determine values of v, u and h at temperatures that are at different pressures and temperatures to those given in the tables, **linear interpolation** may be used.

STEAM TABLES - EXERCISE

Use steam tables to determine the specific enthalpy (h), the specific internal energy (u) and the specific volume (v) for the following cases.

Remember that the pressures in the tables are expressed in bars.

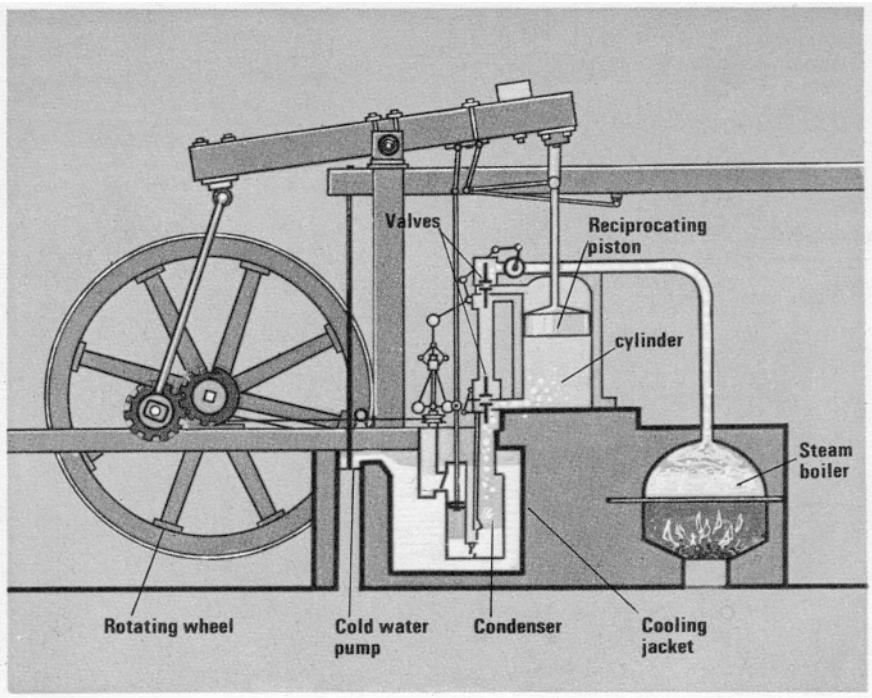
Note   100 kN/m^2 = 10^5 N/m^2 = 1 bar

Also   1 MN/m^2 = 10^6 N/m^2 = 10bar

		Answers in kJ / kg or m^3 / kg
1	Water at 88^o C and 1 bar	*[369, 369, 0.001034]*
2	Water at it saturation temperature at 2.7 bar	*[546, 546, 0.00107]*
3	Dry saturated steam at 5 bar	*[2749, 2562, 0.3748]*
4	Wet steam with dryness faction 0.9 at 10 bar	*[2576.5, 2401.8, 0.17507]*
5	Superheated steam at 6 bar and 250^o C	*[2958, 2722, 0.394]*
6	Superheated steam at 6 bar and 260^o C	*[2978.8, 2737.8, 0.4021]*
7	Water at normal atmospheric pressure and 80^o C	*[334.9, 334.9, 0.001029]*
8	Water at its saturation temperature at 200 kN/m^2	*[505, 505, 0.00106]*
9	Saturated steam at 400 kN/m^2	*[2739, 2554, 0.4623]*
10	Wet steam with dryness fraction 0.8 at 2 MN/m^2	*[2421, 2261.4, 0.07989]*
11	Steam at 1 MN/m^2 and 225^o C	*[2886.5, 2667, 0.21945]*
12	Water at 165^o C and 600 kN/m^2	*[697, 696, 0.001108]*
13	Boiling water at 2.6 MN/m^2	*[972, 969, 0.0012014]*
14	Saturated steam at 39 bar	*[2801.5, 2602, 0.051115]*
15	Wet steam with dryness fraction 0.92 at 16.5 bar	
	Use the approximate method to determine v	*[2640.18, 2457.86, 0.110584]*
16	Steam at 550 kN/m^2 and 320^o C	*[3104.9, 2834.3, 0.49598]*

NON-FLOW PROCESSES – STEAM

(Thermodynamics\ Level 1\ Non-flow steam.doc)



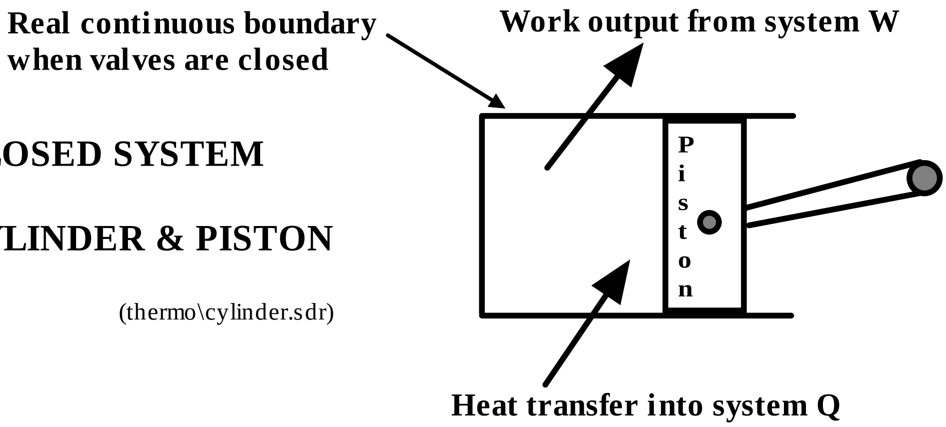
Simple Steam Engine

CLOSED SYSTEMS Non-flow processes take place in closed systems

CLOSED SYSTEM

CYLINDER & PISTON

(thermo\cylinder.sdr)



THE NON-FLOW ENERGY EQUATION – applies to **all** non-flow processes

$$Q - W = (U_2 - U_1) \quad \text{or} \quad q - w = (u_2 - u_1) \text{ per kg}$$

$(U_2 - U_1)$ is the change in internal energy of the system

STEAM TABLES

- **Steam does not obey the Gas Laws**
- **Do not use the Gas Laws for steam**
- **Always use Steam Tables for finding values of internal energy, specific volume, enthalpy, etc. for water and steam.**
- **The recommended tables are:**
- **Thermodynamic & Transport Properties of Fluids (SI units) by Rogers & Mayhew**

WORK DONE IN NON-FLOW PROCESSES W

Process	*Process law*	Work done W
Constant volume	$V_1 = V_2 =$ constant	**Zero**
Constant pressure	$p_1 = p_2 =$ constant	$p(V_2 - V_1)$
Hyperbolic	$p_1V_1 = p_2V_2 =$ constant	$p_1V_1\ln(V_2 / V_1)$
Polytropic	$p_1V_1^n = p_2V_2^n =$ constant	$(p_1V_1 - p_2V_2) / (n - 1)$

- **A hyperbolic process following the law *pV=constant* is NOT an isothermal process (constant temperature process) when the working fluid is steam, (although it is when the working fluid is a gas)**
- **When steam undergoes an adiabatic process (zero heat transfer, Q = 0), it does NOT follow the process law $pV^\gamma = constant$ (this only applies to gases undergoing an adiabatic process)**

EXERCISE – NON-FLOW PROCESSES - STEAM

1 Steam at a pressure of 9 bar and 0.9 dry occupies a volume of 0.42 m^3 in the cylinder of a steam engine. It is expanded according to the law $PV^{1.35} = C$ to a pressure of 3 bar. Determine:

(a) The mass of steam present
(b) The final volume
(c) The final dryness fraction
(d) The external work done
(e) The change in internal energy
(f) The heat transfer.
[Ans 2.17 kg, 0.948 m^3, 0.72, 267.7 kJ, -884.5 kJ, -616.8 kJ]

2 At a certain point during the expansion process in a steam engine cylinder, the steam pressure was 1.1 MN/m^2 and the dryness 0.85. At the end of the expansion process the pressure was 0.28 MN/m^2 and the dryness was 0.80. Assuming the expansion obeys the law $PV^n = C$, determine

(a) The value of the index n
(b) The work done per kg
(c) The internal energy change per kg
(d) The heat transfer per kg.
[Ans 1.1112, 191 kJ/kg, -172 kJ/kg, 19 kJ/kg]

3 The cylinder of a steam engine contains 0.2 kg of steam at 1.3 MN/m^2 and 0.9 dry. If the steam is expanded until the pressure falls to 0.6 MN/m^2, the law of expansion being PV = constant, determine

(a) The final dryness fraction
(b) The temperature at the end of the expansion
(c) The internal energy change
(d) The work done
(e) The heat transfer
[Ans 0.935, 158.8^{o}C, 6.38 Kj, 27.38 kJ, 33.76 kJ]

4 2m^3 of steam at 2 bar and 0.9 dry is compressed in a closed system according to the law PV^n = costant until the steam is at 10 bar and 200^{o}C. Determine

(a) The mass of steam present in the cylinder
(b) The value of the index n
(c) The work done
(d) The internal energy change
(e) The heat transfer.
[Ans 2.51 kg, 1.19, -616.9 kJ, 741.4 kJ, 124.5 kJ]

5 Steam, initially 0.85 dry at 500 kN/m^2 and occupying a volume of 0.5 m^3, expands in the cylinder of an engine according to the law PV = constant until the final pressure at the end of the expansion process is 100 kN/m^2. Determine

(a) The mass of steam
(b) The final volume
(c) The final dryness fraction
(d) The work done
(e) The change in internal energy
(f) The heat transfer
[Ans 1.569 kg, 2.5 m^3, 0.941, 402.4 kJ, 170.5 kJ, 572.9 kJ]

6 1 kg of steam 0.9 dry at 12 bar is expanded in a non-flow process until its final pressure is 1.2 bar according the law $PV^{1.15} = C$. Determine

(a) The final dryness fraction
(b) The work done
(c) The internal energy change
(d) The heat transfer
[Ans 0.762, 305.1 kJ, -390 kJ, -84.9 kJ]

7 A rigid vessel has a volume of $1m^3$ and contains steam at 2 MN/m^2 and 400^oC. The vessel is cooled until the steam is just dry saturated. Determine

(a) The mass of steam present
(b) The final pressure
(c) The heat transfer for the process
[Ans 6.618 kg, 13 bar, -2356 kJ]

8 1kg of wet steam having a dryness fraction of 0.8 and a pressure of 10bar expands in the closed cylinder of an engine, the relationship between the pressure and the volume during the process being given by the law pV = constant. At the end of the expansion process the steam pressure is 1bar and the steam is still wet. Determine for the steam:

(a) Its initial specific volume
(b) Its final specific volume
(c) Its final dryness fraction
(d) Its initial specific internal energy
(e) Its final specific internal energy
(f) The work done
(g) The heat transfer

Note. The approximate formula for the **specific volume of wet steam** may be used in your solution, i.e. $\mathbf{v = xv_g}$
[Ans 0.15552m^3/kg, 1.5552m^3/kg, 0.9181, 2219.6kJ/kg, 2334.9kJ/kg, 358.1kJ, 473.4kJ]

9 1kg of superheated steam, initially at a pressure of 10bar and a temperature of 200^{o}C, expands polytropically in the closed cylinder of an engine, the relationship between pressure and volume during the process being given by the law $pV^{1.2}$ = constant. At the end of the expansion process the steam pressure is 2bar and the steam is wet.
Determine for the steam:
(a) Its initial specific volume
(b) Its final specific volume
(c) Its final dryness fraction
(d) Its initial specific internal energy
(e) Its final specific internal energy
(f) The work done
(g) The heat transfer

Note. The approximate formula for the **specific volume of wet steam** may be used in your solution, i.e. $\mathbf{v = xv_g}$
[Ans 0.2061m^3/kg, 0.788m^3/kg, 0.89, 2623 kJ/kg, 2307 kJ/kg, 242.5 kJ, -73.5 kJ]

10 The cylinder of a steam engine contains 1kg of steam at an initial pressure of 15bar and a dryness fraction of 0.9. The steam then expands displacing the piston down the bore of the cylinder until the steam pressure has dropped to 3bar, the law of the expansion being pV = constant.
Determine for the steam:
(a) Its initial specific volume
(b) Its final specific volume
(c) Its final dryness fraction
(d) Its change in internal energy
(e) The work done
(f) The heat transfer

Note. The approximate formula for the **specific volume of wet steam** may be used in your solution, i.e. $\mathbf{v = xv_g}$
[Ans 0.11853m^3/kg, 0.59265m^3/kg, 0.9785, 81.56 kJ, 286.2 kJ, 367.7 kJ]

11 A rigid vessel has a volume of 1m^3 and contains superheated steam at 20bar and 400^{o}C. The vessel is then cooled with its volume remaining constant, until the steam pressure is 12bar, the steam being wet in its final condition. Determine:
(a) The initial specific volume of the steam
(b) The mass of steam present
(c) The dryness fraction of the steam after cooling
(d) The initial specific internal energy of the steam
(e) The final specific internal energy of the steam
(f) The actual quantity of heat transferred during the process

Note. The approximate formula for the **specific volume of wet steam** may be used in your solution, i.e. $\mathbf{v = xv_g}$
[Ans 0.1511m^3/kg, 6.618kg, 0.926, 2946 kJ/kg, 2455 kJ/kg, -3249 kJ]

12 1 kg of ammonia is cooled in a closed system under constant pressure conditions from 90^oC and 290.8 kN/m^2 until it is 0.9 dry. Using page 13 of the tables, determine

(a) The enthalpy change

(b) The heat transfer

(c) The final volume if the volume of liquid present is ignored

[Ans -362.1 Kj, -362.1 kJ, 0.37665 m^3]

13 A rigid vessel having a volume of 0.1 m^3 is filled with ammonia vapour and sealed. Its temperature is then lowered to -12^oC, and at this temperature the ammonia vapour has a dryness fraction of 0.52. The container is then allowed to warm up slowly until the ammonia vapour becomes just dry saturated. Using page 13 of the tables determine

(a) The temperature at which this occurs

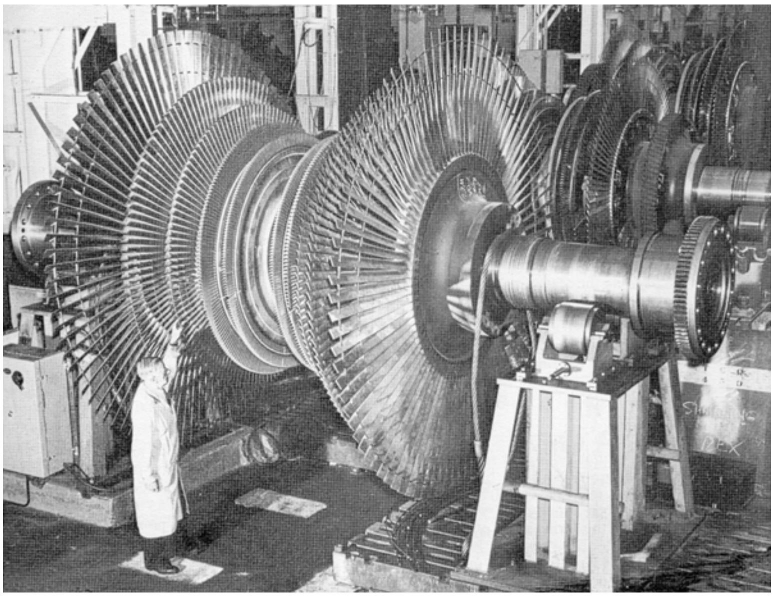
(b) The heat transfer that must have occurred during the warming process

Neglect the volume of liquid present in the container

[Ans 6^oC, 248 kJ]

STEADY FLOW PROCESSES – STEAM

(Thermodynamics\ Level 1\ Steady-flow Steam.doc)



Steam Turbine Rotor

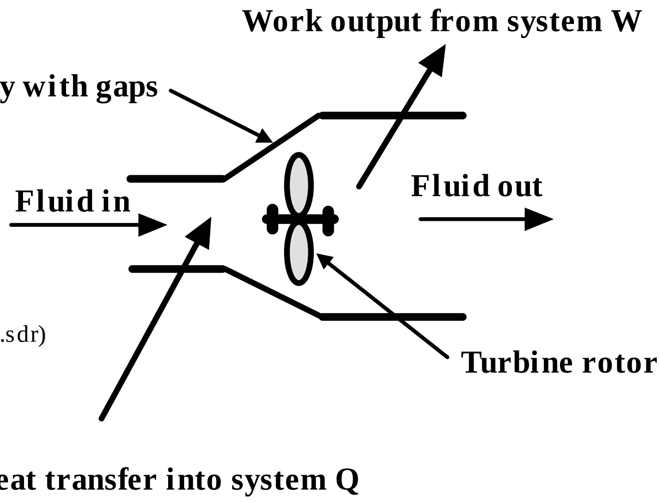
OPEN SYSTEMS

Flow processes take place in open systems. An example is a steam turbine

OPEN SYSTEM

TURBINE

(thermo\turbine1.sdr)



THE STEADY FLOW ENERGY EQUATION

$$\mathbf{Q - W = \Delta PE + \Delta KE + \Delta H}$$

Where **ΔPE = the change in potential energy = $mg(Z_2 - Z_1)$**

ΔKE = the change in kinetic energy = $\frac{1}{2}m(C_2^2 - C_1^2)$

ΔH = the change in enthalpy = $(H_2 - H_1)$

So

$$Q - W = mg(Z_2 - Z_1) + \tfrac{1}{2}m(C_2^2 - C_1^2) + (H_2 - H_1)$$

Or

$$q - w = g(Z_2 - Z_1) + \tfrac{1}{2}(C_2^2 - C_1^2) + (h_2 - h_1) \quad \text{for a mass of 1kg}$$

UNITS

Always work in Joules throughout when using the SFEE, as the potential energy and kinetic energy terms will naturally come out in Joules when using kilograms, metres and seconds.

THE CONTINUITY EQUATION

$\rho_1 A_1 C_1 = \rho_2 A_2 C_2$ **or** $A_1 C_1 / v_1 = A_2 C_2 / v_2$	
$\dot{m} = \rho AC = AC/v$	$v = 1/\rho$

Where **v = specific volume** and **ρ = density**

Units:	$\dot{m}$ **= kg/s**	**ρ = kg/m³**	**v = m³ / kg**	**A = m²**	**C = m/s**

DETERMINATION OF PROPERTIES (u, h and v etc)

For **steam**, (and other vapours such as ammonia etc) **TABLES** must be used to determine the values of specific enthalpy (h), specific volume (v) and any other property values that may be required.
The Gas Laws must **not** be used as these do not apply to steam.

EXERCISE - STEADY FLOW PROCESSES - STEAM

1 Superheated steam enters a horizontal turbine at a pressure of 20 bar, a temperature of 250^{o}C, and a velocity of 60 m/s. The steam leaves the turbine at a pressure of 0.3 bar, a dryness fraction of 0.95, and a velocity of 300 m/s.
A heat loss of 15 kJ/kg of steam occurs during its passage through the turbine.
Determine for the steam flowing through the turbine

(a) The change in kinetic energy **per kg** of steam
(b) The enthalpy **per kg** of steam at entry
(c) The enthalpy **per kg** of steam at exit
(d) The work done by **each kg** of steam
(e) The total power produced if the mass flow rate is 5kg/s
(f) The entry duct flow area if the mass flow rate is 5kg/s

[Ans 43.2kJ/kg, 2904kJ/kg, 2508.2kJ/kg, 337.6kJ/kg, 1.688MW, 9292mm^2]

2 Superheated steam enters a horizontal turbine at a pressure of 50bar, a temperature of 400^{o}C and with a velocity of 327m/s.
The steam exits the turbine at a pressure of 0.2bar, a dryness fraction of 0.9, and with a velocity of 150m/s.
A heat loss of 15kJ/kg of steam occurs during its passage through the turbine.
Determine for the steam flowing through the turbine:

(a) The change in kinetic energy **per kg of steam**
(b) The specific enthalpy at entry
(c) The specific enthalpy at exit
(d) The work done by **each kg of steam**, stating any assumptions made
(e) The total power produced if the mass flow rate is 400kg/s
(f) The cross sectional area of the entry duct if the mass flow rate is 400kg/s

[Ans –42.2kJ/kg, 3196kJ/kg, 2373kJ/kg, 850kJ/kg, 340MW, 0.0707m^2]

3 In a simple steam plant, a steady supply of saturated water (i.e. water at its saturation temperature) enters a boiler at a pressure of 10bar, and is converted into superheated steam at the same pressure.

The steam leaves the boiler at 10bar and 300^{o}C and enters a turbine at the same pressure and temperature. The steam flows steadily through the turbine without heat loss, and leaves the turbine as wet steam with a dryness fraction of 0.9 and a pressure of 1bar.

Changes in potential energy and kinetic energy throughout the system are negligible.

Determine

(a) the specific enthalpy of the water at entry to the boiler

(b) the specific enthalpy of the steam at the boiler exit

(c) the specific enthalpy of the steam at the turbine exit

(d) the heat transfer in the boiler per kg of steam

(e) the work output from the turbine per kg of steam

(f) the thermal efficiency of the combined boiler and turbine

(g) the required flow area at entry to the turbine if the steam velocity at that point is 80m/s when the mass flow rate is 1.5kg/s

[Ans 763kJ/kg, 3052kJ/kg, 2449.2kJ/kg, 2289kJ/kg, 602.8kJ/kg, 26.33%, 0.004838m^2]

4 A combined power and process plant is operating under steady flow conditions.

The working fluid enters the system as superheated steam at a pressure of 30 bar, a temperature of 400^{o}C and a velocity of 90 m/s.

The working fluid leaves the system as water having a specific enthalpy of 381kJ/kg and a velocity of 10m/s.

The exit point of the plant is 35m below the entry point.

A heat loss of 100kJ/kg of fluid occurs during its passage through the plant.

Determine for 1 kg of fluid flowing through the plant:

(a) The enthalpy at entry

(b) The change in kinetic energy

(c) The change in potential energy

(d) The work done by the fluid

(e) The power output from the plant if the actual mass flow rate is 1.4 kg/s

(f) The flow area of the entry pipe if the actual mass flow rate is 1.4 kg/s

[Ans 3231kJ/kg, -4kJ/kg, -0.343kJ/kg, 2754.3kJ/kg, 3.856MW, 1545mm^2]

5 A steam turbine is supplied with steam at 1MN/m^2 and 250^{o}C through a duct of area 0.1m^2, the mass flow rate being 5kg/s. The steam leaves the turbine at 50kN/m^2 and 100^{o}C, with a velocity of 130m/s. Heat losses amount to 10kJ/kg of steam.

Determine (a) entry velocity and (b) the power output of the turbine, neglecting any changes in potential energy.

[Ans 11.64m/s, 1.215MW]

6 The steam supply to an engine is at 7bar dry saturated, and the steam exhausts at 0.1bar with a dryness fraction of 0.85. The entry and exit velocities are 30m/s and 170m/s respectively, and a heat loss of 12kJ/kg of steam occurs during its passage through the engine. The steam mass flow rate is 2kg/s.

Determine (a) the power developed by the engine assuming that potential energy changes are negligible, and (b) the cross-sectional area of the exit pipe.

[Ans 1.032MW, 0.1466m^2]

7 Steam flows steadily at a rate of 2kg/s through a pipe of constant diameter. At entry to the pipe, the pressure is 1.6MN/m^2, the steam is dry saturated and has a velocity of 60m/s. At the pipe exit, the pressure is 1.5MN/m^2 and the steam is 0.98 dry.

Determine (a) the pipe diameter, (b) the velocity of the steam at exit, and (c) the heat loss rate from the pipe.

[Ans 72.4mm, 62.6m/s, 80kW]

8 Steam enters a combined power and process plant at a pressure of 30bar and a temperature of 400^{o}C with a velocity of 90m/s and leaves as liquid at 1bar and 90^{o}C with a velocity of 10m/s. The exit point is 35m below the entry point and the flow rate is 5040kg/hour. The heat loss rate from the plant is 140kW.

Determine for the plant (a) the power output (b) the exit pipe flow area.

[Ans 3.862MW, 145mm^2]

9 Steam enters a nozzle with negligible velocity at a pressure of 15bar and a dryness fraction of 0.95. At the nozzle exit the steam has a pressure of 10bar and a dryness fraction of 0.94.

Calculate the velocity of the steam at the exit from the nozzle, assuming that the flow through the nozzle is adiabatic.

[Ans 274m/s]

10 Steam enters a pipe at 7bar and 250^{o}C and flows steadily along the pipe at constant pressure. If heat is lost to the surroundings at a steady rate from the steam as it flows along the pipe, at what temperature will water droplets begin to form in the steam?

Calculate the heat lost per kg of steam flowing, up to the point where the water droplets first begin to form, stating any assumptions that you must make.

[Ans 165^{o}C, 191kJ/kg]
