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Basic Thermodynamics: Software Solutions – Part V

Dr. M. Thirumaleshwar

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Real and Ideal gases and Gas mixtures

Basic Thermodynamics: Software Solutions – Part V
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Contents


I WANT TO CHANGE DIRECTION,
AND THE WORLD.

9 Real and ideal gases and gas mixtures

Learning objectives:

1. ‘Ideal gas’, ‘Perfect gas’, ‘Semi-perfect gases’ and ‘Real gas’ are defined.
2. Various equations of state for Ideal as well as real gases are presented.
3. Next, ‘compressibility factor’ and ‘principle of corresponding states’ are discussed.
4. Topics of Internal energy, Enthalpy and Specific heats for Ideal gases are reviewed.
5. Next, properties of mixtures of ideal gases are dealt with.
6. Dalton’s Law, Gibbs-Dalton Law, Avogadro’s Law etc are stated. Procedures to calculate sp. heats, apparent Molecular weight, Gas constant, internal energy, enthalpy etc of a mixture of ideal gases is explained.
7. Above topics are illustrated by solving several problems.

9.1 Introduction:

In this chapter, we shall study the concept of ‘Ideal gas’, ‘Perfect gas’ and ‘Real gases’. We shall deal with property diagrams and various equations of state. We shall also explain about the principle of corresponding states and the generalized compressibility chart in connection with the real gases. Calculation of specific heats at constant volume and constant pressure for gases will be enumerated next.

9.2 Ideal, Perfect and Real Gases:

For an *Ideal gas*:

- Molecule is treated as a ‘point mass’
- It is assumed that gas molecules occupy negligible volume
- No molecular attraction
- Molecular collisions are elastic
- Follows the law: P.v = R.T, where P = pressure (Pa), v = sp. volume (m3/kg), T = temperature (K), and R = gas constant for that particular gas (J/kg.K)
- Specific heats are functions of temperature

For a *Perfect gas*:

- All the assumptions are the same, except that the specific heats are constants and do not vary with temperature

In reality, there is no ideal or perfect gas. H2, O2, N2, He etc behave nearly as perfect gases and are known as '*semi perfect gases*'.

For a *Realgas*:

- Molecular volumes and intermolecular attraction will be considered.
- Several equations of state have been proposed

9.3 Ideal Gas Laws and Property diagrams for an Ideal (or perfect) gas [1, 2]:

9.3.1 Boyle's Law:

It states: "Volume of a given mass of perfect gas varies inversely as the absolute pressure when the absolute pressure is constant". i.e.

$$P \cdot V = \text{const} \quad \text{for const. T..............(4.1)}$$

9.3.2 Charles' Law:

"If any gas is heated at constant pressure, its volume changes directly as its absolute temperature". i.e.

$$\frac{V}{T} = \text{const} \quad \text{when P is const.........(4.2a)}$$

$$\text{i.e.} \quad \frac{V1}{T1} = \frac{V2}{T2} \quad \text{.......(4.2b)}$$

9.3.3 P-V-T surface for Ideal gas:

Each point on the P-V-T surface represents an equilibrium point.

Note that P-V, P-T and T-V diagrams are the projections of this surface on the respective coordinates:

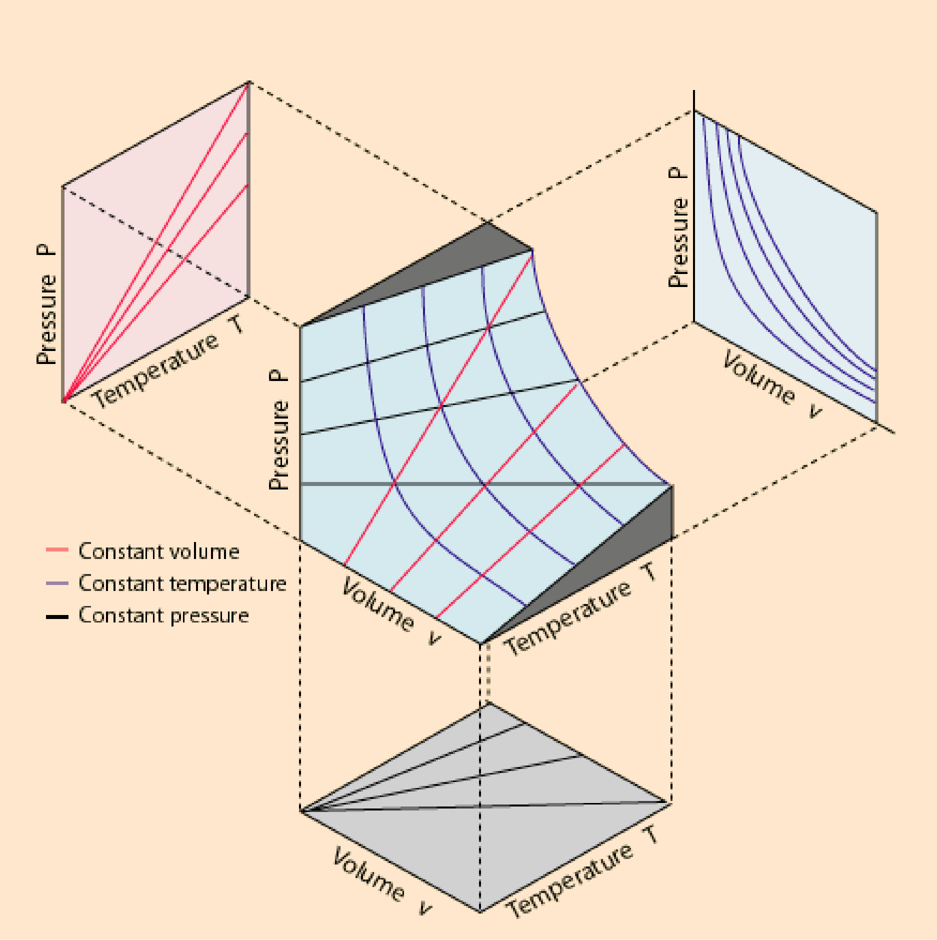


Fig. 9.1 P-V-T surface for an Ideal gas [13]

9.4 Ideal gas equation of state:

An equation of state gives a relation among the three measurable quantities P, V and T. Ideal gas equation of state is written in the following ways:

$P \cdot v = R \cdot T$ ......(4.3a)

$P \cdot V = m \cdot R \cdot T$ ....(4.3b)

$P = \rho \cdot R \cdot T$ ......(4.3c)

where:

P = pressure (kPa), V= volume (m3), m = mass (kg), v = specific volume (m3/kg),

T = absolute temperature (K), ρ = density (kg/m3),

R = particular gas constant (kJ/kg.K) = R_u/M, where

R_u = Universal gas constant = 8.314 (kg/kmol.K), M = Molar mass for the gas,

= 8.314 (kPa.m3/kmol.K)

= 0.08314 (bar.m3/kmol.K

= 1.986 (Btu/lbmol.R)

= 10.73 (psia.ft3/lbmol.R)

= 1545 ft.lbf/lbmol.R)

Other forms of Ideal gas equation are:

$P \cdot V = N \cdot R_u \cdot T$ .....(4.4a)

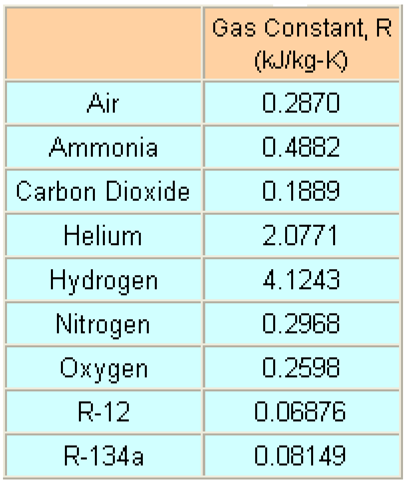
$P \cdot vbar = R_u \cdot T$ ....(4.4b)

where N = no. of moles, vbar = molar sp. volume

Note that:

$m = M \cdot N$ kg............(4.5)

Values of gas constant R for a few gases is given below:



	Gas Constant, R (kJ/kg-K)
Air	0.2870
Ammonia	0.4882
Carbon Dioxide	0.1889
Helium	2.0771
Hydrogen	4.1243
Nitrogen	0.2968
Oxygen	0.2598
R-12	0.06876
R-134a	0.08149

Table 9.1 Values of gas constant R for a few gases

9.5 Deviation from Ideal gas behavior – Compressibility factor:

While the Ideal gas equation is very simple to use, it must be noted that it is mostly applicable for gases at low densities, i.e. at low pressures and high temperatures. Gases deviate considerably from ideal gas behavior at regions near the critical point and saturation lines. This is shown below:

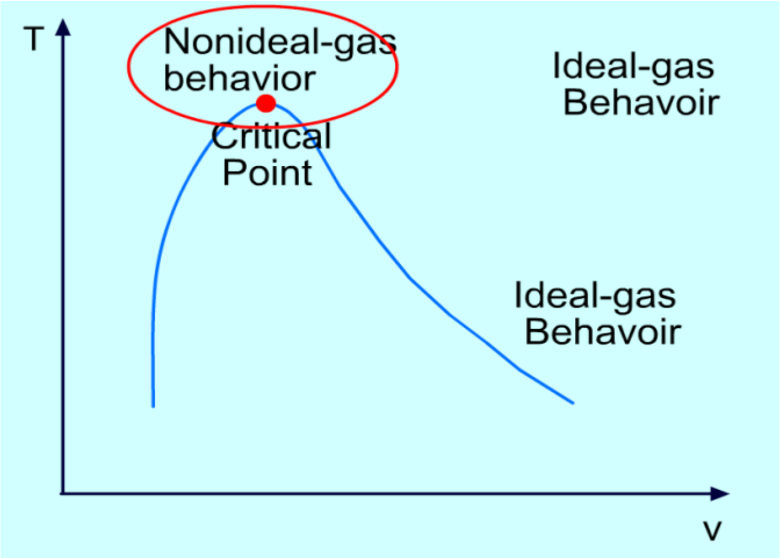


Fig. 9.2 Deviation from Ideal gas law [7]

Departure from Ideal gas behavior against pressure for some gases is illustrated below:

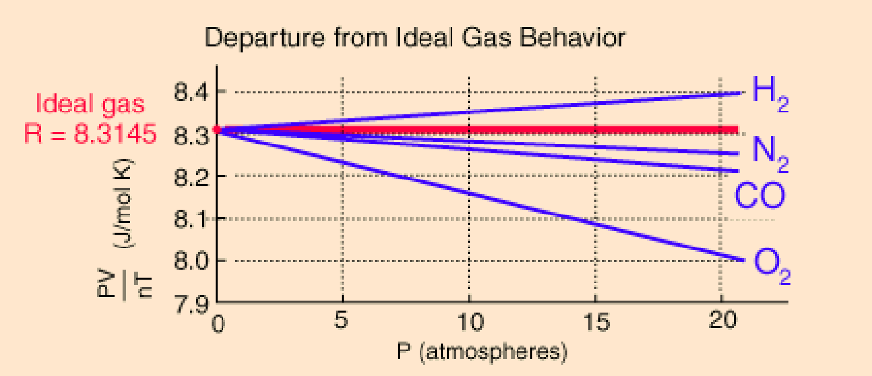


Fig. 9.3 Deviation from Ideal gas law for some gases [9]

For the specific case of Water/Steam, following graph illustrates the regions where Ideal gas law can be applied without much error. Note that around the critical point, the error is unacceptably high i.e. about 330%.

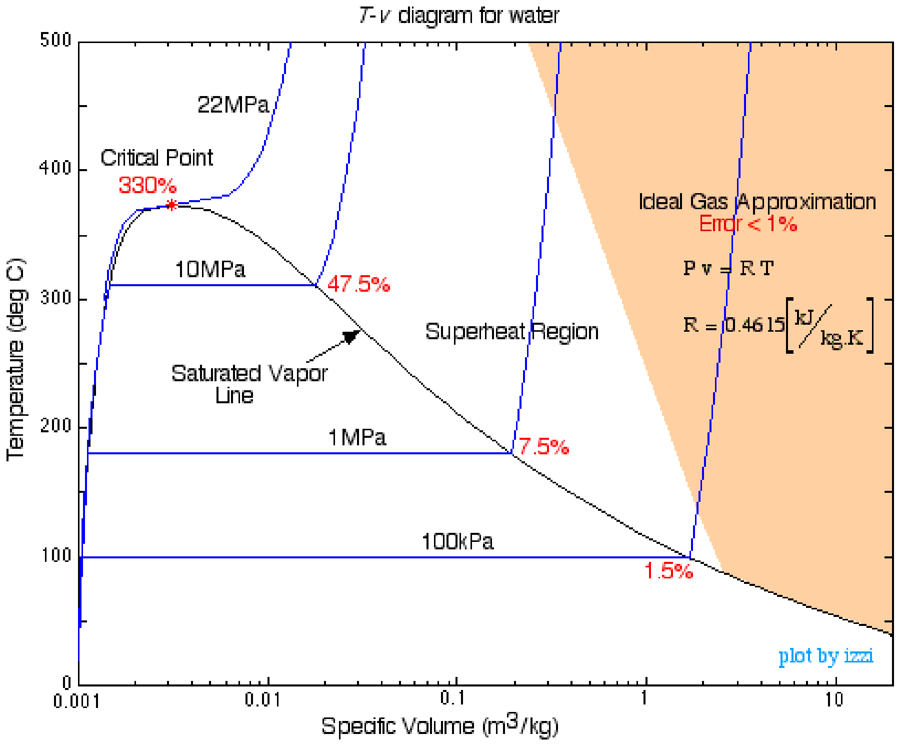


Fig. 9.4 Region where Ideal gas law is applicable for Water/Steam [8]

To account for the deviation from Ideal gas law, we introduce a correction factor, Z, called **'compressibility factor'**, as follows:

$$Z = \frac{P \cdot V}{R \cdot T} \quad ....(4.6)$$

or, $$P \cdot V = Z \cdot R \cdot T \quad .....(4.7)$$

Also, $$Z = \frac{v_{actual}}{v_{ideal}} \quad ....(4.8)$$

where $$v_{ideal} = \frac{R \cdot T}{P}$$

Note that Z = 1 for Ideal gas.

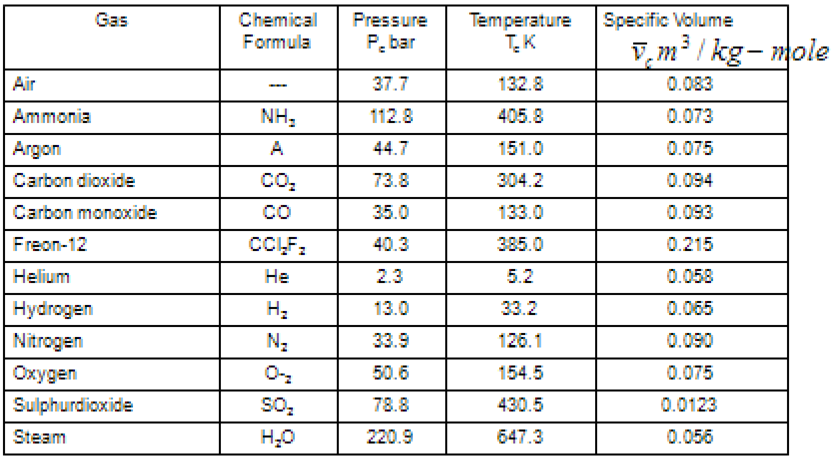
Different gases behave differently with variation of pressure and temperature, but their behavior is observed to be identical when the pressures and temperatures are 'normalized' with respect to the critical pressures and temperatures of respective gases. So, we define:

$$P_R = \frac{P}{P_{cr}} \quad .....(4.9a), \text{ and}$$

$$T_R = \frac{T}{T_{cr}} \quad .....(4.9b)$$

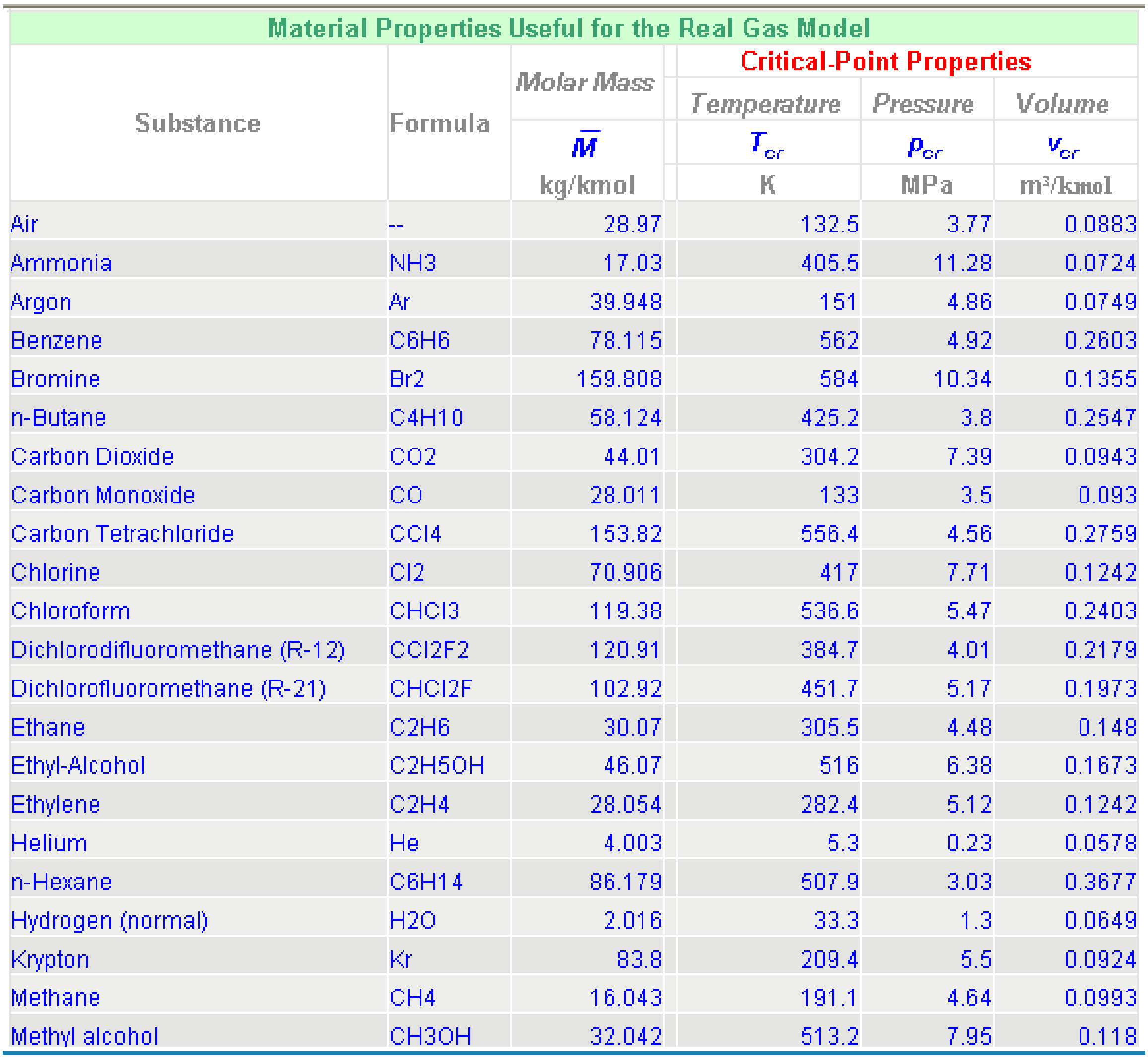
Where P_R is called 'Reduced pressure' and T_R is called 'Reduced temperature'.

Values of 'critical parameters' for a few substances are given below:



Gas	Chemical Formula	Pressure P_c bar	Temperature T_c K	Specific Volume $\bar{v}_c\, m^3 / kg-mole$
Air	---	37.7	132.8	0.083
Ammonia	NH_2	112.8	405.8	0.073
Argon	A	44.7	151.0	0.075
Carbon dioxide	CO_2	73.8	304.2	0.094
Carbon monoxide	CO	35.0	133.0	0.093
Freon-12	CCl_2F_2	40.3	385.0	0.215
Helium	He	2.3	5.2	0.058
Hydrogen	H_2	13.0	33.2	0.065
Nitrogen	N_2	33.9	126.1	0.090
Oxygen	O-$_2$	50.6	154.5	0.075
Sulphurdioxide	SO_2	78.8	430.5	0.0123
Steam	H_2O	220.9	647.3	0.056

And following table gives a more detailed information from TEST [15]:



Material Properties Useful for the Real Gas Model

Substance	Formula	Molar Mass	Critical-Point Properties		
			Temperature	Pressure	Volume
		$\bar{M}$	T_{cr}	p_{cr}	v_{cr}
		kg/kmol	K	MPa	m³/kmol
Air	--	28.97	132.5	3.77	0.0883
Ammonia	NH3	17.03	405.5	11.28	0.0724
Argon	Ar	39.948	151	4.86	0.0749
Benzene	C6H6	78.115	562	4.92	0.2603
Bromine	Br2	159.808	584	10.34	0.1355
n-Butane	C4H10	58.124	425.2	3.8	0.2547
Carbon Dioxide	CO2	44.01	304.2	7.39	0.0943
Carbon Monoxide	CO	28.011	133	3.5	0.093
Carbon Tetrachloride	CCl4	153.82	556.4	4.56	0.2759
Chlorine	Cl2	70.906	417	7.71	0.1242
Chloroform	CHCl3	119.38	536.6	5.47	0.2403
Dichlorodifluoromethane (R-12)	CCl2F2	120.91	384.7	4.01	0.2179
Dichlorofluoromethane (R-21)	CHCl2F	102.92	451.7	5.17	0.1973
Ethane	C2H6	30.07	305.5	4.48	0.148
Ethyl-Alcohol	C2H5OH	46.07	516	6.38	0.1673
Ethylene	C2H4	28.054	282.4	5.12	0.1242
Helium	He	4.003	5.3	0.23	0.0578
n-Hexane	C6H14	86.179	507.9	3.03	0.3677
Hydrogen (normal)	H2O	2.016	33.3	1.3	0.0649
Krypton	Kr	83.8	209.4	5.5	0.0924
Methane	CH4	16.043	191.1	4.64	0.0993
Methyl alcohol	CH3OH	32.042	513.2	7.95	0.118

Methyl chloride	CH3Cl	50.488	416.3	6.68	0.143
Neon	Ne	20.183	44.5	2.73	0.0417
Nitrogen	N2	28.013	126.2	3.39	0.0899
Nitrous oxide	N2O	44.013	309.7	7.27	0.0961
Oxygen	O2	31.999	154.8	5.08	0.078
Propane	C3H8	44.097	370	4.26	0.1998
Propylene	C3H6	42.081	365	4.62	0.181
Sulfur dioxide	SO2	64.063	430.7	7.88	0.1217
Tetrafluoroethane (R-134a)	CF3CH2F	102.03	374.3	4.067	0.1847
Trichlorofluoromethane (R-11)	CCl3F	137.37	471.2	4.38	0.2478
Water	H2O	18.015	647.3	22.09	0.0568
Xenon	Xe	131.3	289.8	5.88	0.1186

Table 9.2

If values of Z determined from experiments for various gases are plotted against P_R and T_R, following plot is obtained:

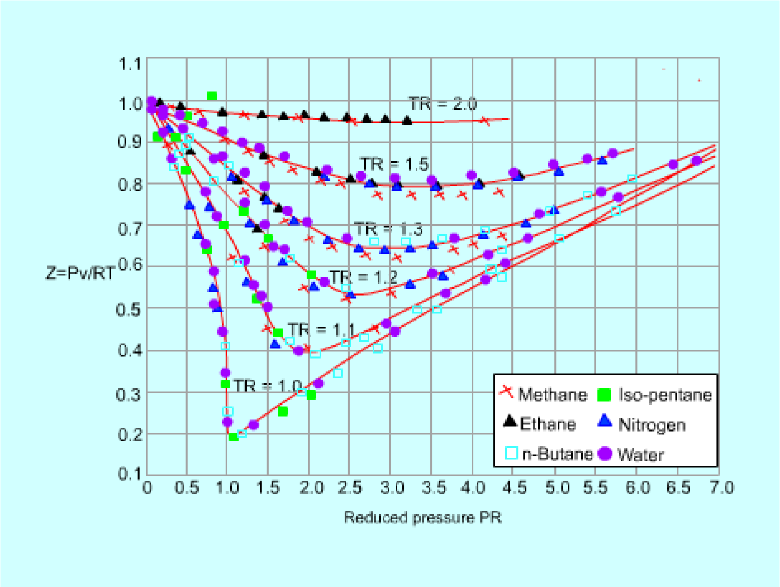


Fig. 9.5 Z values for various gases [7]

It is noted that 'Z factor is approximately the same for all gases at the same reduced pressure and temperature'. This is known as the ***principle of corresponding states***.

In problem solving, generally, we use the Lee-Kesler compressibility chart, based on ideal fluid assumption:

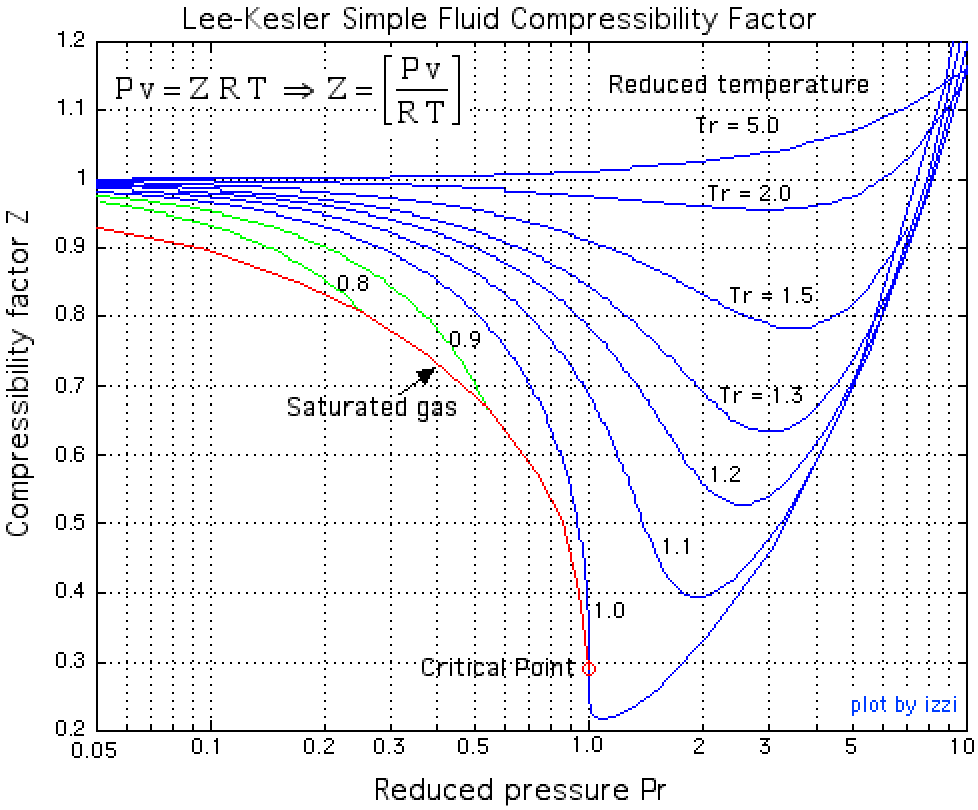


Fig. 9.6 Lee-Kesler compressibility chart [8]

We note the following from the generalized compressibility chart:

(i) At very low pressures, i.e. at $P_R << 1$, gases behave like an ideal gas irrespective of temperature

(ii) At high temperatures, i.e. at $T_R > 2$, ideal gas behavior can be assumed irrespective of pressure, except at very high pressures of $P_R >> 1$

(iii) Deviation from ideal gas behavior is most pronounced in the region near the critical point.

9.6 Equations of state for 'Real gases':

Several equations of state have been proposed in an attempt to predict P-V-T behavior of substances over a wider range of pressures and temperatures. We shall present a few of them below:

9.6.1 Van der Waal's equation of state:

This is one of the earliest attempts (1873) to increase the range of applicability of ideal gas equation by inserting factors to take into account the intermolecular attractions and the finite volume occupied by the molecules in a real gas. It is of the following form:

$$\left(P+\frac{a}{v^{2}}\right)\cdot(v-b)=R\cdot T \qquad ......(4.10)$$

Here, the term (a/v^2) accounts for the intermolecular attraction and the term b accounts for the volume occupied by the molecules. The constants a and b are given *in terms of critical properties* as follows:

$$a=\frac{27\cdot R^{2}\cdot T_{cr}}{64\cdot P_{cr}} \quad \text{and} \quad b=\frac{R\cdot T_{cr}}{8\cdot P_{cr}} \qquad ....(4.11)$$

To express Van der Waals equation in terms of mole basis, replace v by vbar and R by R_u in the above equations.

a and b can thus be calculated from the critical properties of a given gas.

Values of a and b for some common fluids are given below [17]

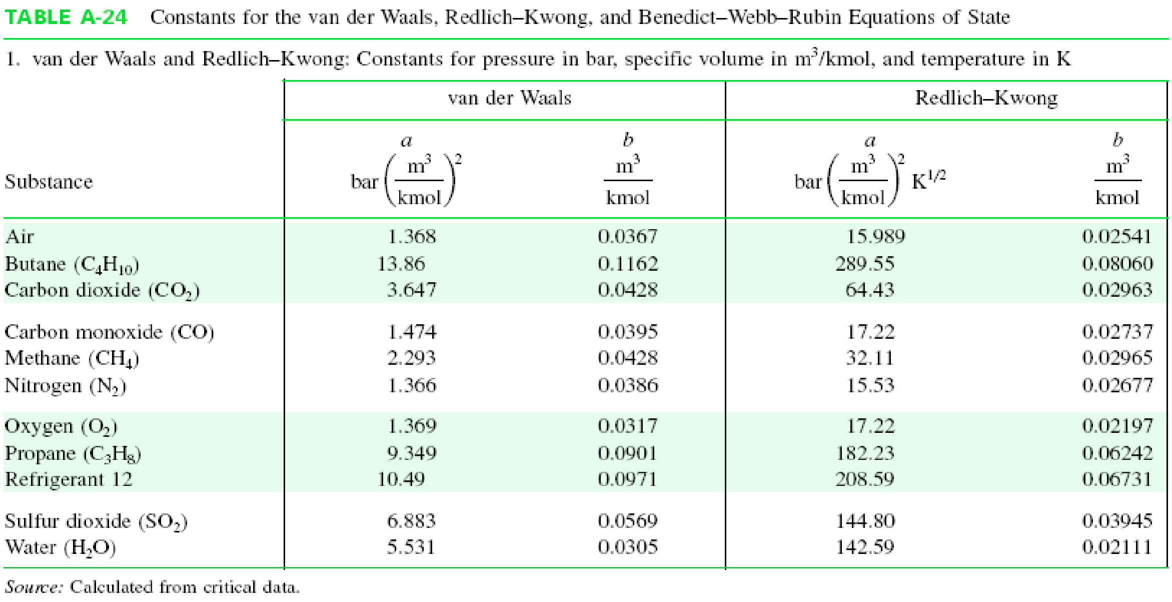


TABLE A-24 Constants for the van der Waals, Redlich–Kwong, and Benedict–Webb–Rubin Equations of State

1. van der Waals and Redlich–Kwong: Constants for pressure in bar, specific volume in m^3/kmol, and temperature in K

Substance	van der Waals a $\text{bar}\left(\frac{m^3}{kmol}\right)^2$	van der Waals b $\frac{m^3}{kmol}$	Redlich–Kwong a $\text{bar}\left(\frac{m^3}{kmol}\right)^2 K^{1/2}$	Redlich–Kwong b $\frac{m^3}{kmol}$
Air	1.368	0.0367	15.989	0.02541
Butane (C_4H_{10})	13.86	0.1162	289.55	0.08060
Carbon dioxide (CO_2)	3.647	0.0428	64.43	0.02963
Carbon monoxide (CO)	1.474	0.0395	17.22	0.02737
Methane (CH_4)	2.293	0.0428	32.11	0.02965
Nitrogen (N_2)	1.366	0.0386	15.53	0.02677
Oxygen (O_2)	1.369	0.0317	17.22	0.02197
Propane (C_3H_8)	9.349	0.0901	182.23	0.06242
Refrigerant 12	10.49	0.0971	208.59	0.06731
Sulfur dioxide (SO_2)	6.883	0.0569	144.80	0.03945
Water (H_2O)	5.531	0.0305	142.59	0.02111

Source: Calculated from critical data.

Van der Waal's constants for a few gases and liquids are given below:

	a **(L^{2}bar/mol^2)**	***b*** **(L/mol)**
Acetic acid	17.82	0.1068
Acetic anhydride	20.16	0.1263
Acetone	14.09	0.0994
Acetonitrile	17.81	0.1168
Acetylene	4.448	0.05136
Ammonia	4.225	0.03707
Argon	1.363	0.03219
Benzene	18.24	0.1154
Bromobenzene	28.94	0.1539
Butane	14.66	0.1226
Carbon dioxide	3.640	0.04267
Carbon disulfide	11.77	0.07685
Carbon monoxide	1.505	0.03985
Carbon tetrachloride	19.7483	0.1281
Chlorine	6.579	0.05622
Chlorobenzene	25.77	0.1453
Chloroethane	11.05	0.08651
Chloromethane	7.570	0.06483
Cyanogen	7.769	0.06901
Cyclohexane	23.11	0.1424

Diethyl ether	17.61	0.1344
Diethyl sulfide	19.00	0.1214
Dimethyl ether	8.180	0.07246
Dimethyl sulfide	13.04	0.09213
Ethane	5.562	0.0638
Ethanethiol	11.39	0.08098
Ethanol	12.18	0.08407
Ethyl acetate	20.72	0.1412
Ethylamine	10.74	0.08409
Fluorobenzene	20.19	0.1286
Fluoromethane	4.692	0.05264
Freon	10.78	0.0998
Germanium tetrachloride	22.90	0.1485
Helium	0.03457	0.0237
Hexane	24.71	0.1735
Hydrogen	0.2476	0.02661
Hydrogen bromide	4.510	0.04431
Hydrogen chloride	3.716	0.04081
Hydrogen selenide	5.338	0.04637
Hydrogen sulfide	4.490	0.04287
Iodobenzene	33.52	0.1656
Krypton	2.349	0.03978
Mercury	8.200	0.01696
Methane	2.283	0.04278
Methanol	9.649	0.06702
Neon	0.2135	0.01709
Nitric oxide	1.358	0.02789
Nitrogen	1.408	0.03913
Nitrogen dioxide	5.354	0.04424
Nitrous oxide	3.832	0.04415
Oxygen	1.378	0.03183
Pentane	19.26	0.146
Phosphine	4.692	0.05156
Propane	8.779	0.08445
Silane	4.377	0.05786
Silicon tetrafluoride	4.251	0.05571
Sulfur dioxide	6.803	0.05636
Tin tetrachloride	27.27	0.1642
Toluene	24.38	0.1463
Water	5.536	0.03049
Xenon	4.250	0.05105

Table 9.3 Van der Waals constants for a few gases and volatile liquids [10]
Source: Weast. R.C. (Ed.), *Handbook of Chemistry and Physics (53rd Edn.)*, Cleveland: Chemical Rubber Co., 1972.

Units:

1 J·m^3/mol^2 = 1 m^6·Pa/mol^2 = 10 L^2·bar/mol^2
1 L^{2}atm/mol^2 = 101 325 J·m^3/kmol^2 = 101 325 Pa·m^6/kmol^2
1 dm^3/mol = 1 L/mol = 1 m^3/kmol (where kmol is kilomoles = 1000 moles)

In terms of ‘reduced pressure, volume and temp:

If we define:

$P_r = \frac{P}{P_c}$ ....reduced pressure

$v_r = \frac{v}{v_c}$ ...reduced sp. volume

$T_r = \frac{T}{T_c}$ ....reduced temperature

Then, Van der Waal's eqn. can be written as:

$$\left(P_r + \frac{3}{v_r^{\,2}}\right)\cdot\left(v_r - \frac{1}{3}\right) = \frac{8}{3}\cdot T_r$$

Note that this eqn. does not contain gas const. R or the constants a and b.

Though Van der Waals equation represents an early attempt to improve the range of ideal gas equation, its range is still very limited.

9.6.2 Beattie – Bridgeman equation of state:

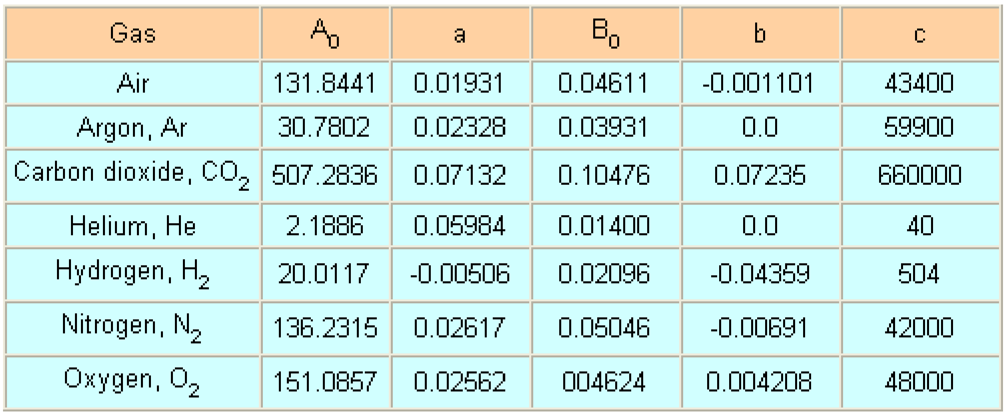
This equation, proposed in 1928, takes the following form:

$$P = \frac{R_u T}{\overline{v}^2}\left(1 - \frac{c}{\overline{v}T^3}\right)(\overline{v} + B) - \frac{A}{\overline{v}^2} \quad \text{where}$$

$$A = A_0\left(1 - \frac{a}{\overline{v}}\right) \quad B = B_0\left(1 - \frac{b}{\overline{v}}\right) \quad ....(4.12)$$

This equation is reasonably *accurate for densities up to less than about 2.5 times the density at the critical point.*

Values of constants in Beattie-Bridgeman equation for a few substances are given below:



Gas	A_0	a	B_0	b	c
Air	131.8441	0.01931	0.04611	-0.001101	43400
Argon, Ar	30.7802	0.02328	0.03931	0.0	59900
Carbon dioxide, CO_2	507.2836	0.07132	0.10476	0.07235	660000
Helium, He	2.1886	0.05984	0.01400	0.0	40
Hydrogen, H_2	20.0117	-0.00506	0.02096	-0.04359	504
Nitrogen, N_2	136.2315	0.02617	0.05046	-0.00691	42000
Oxygen, O_2	151.0857	0.02562	004624	0.004208	48000

Table 9.4 Values of constants in Beattie-Bridgeman equation [7]

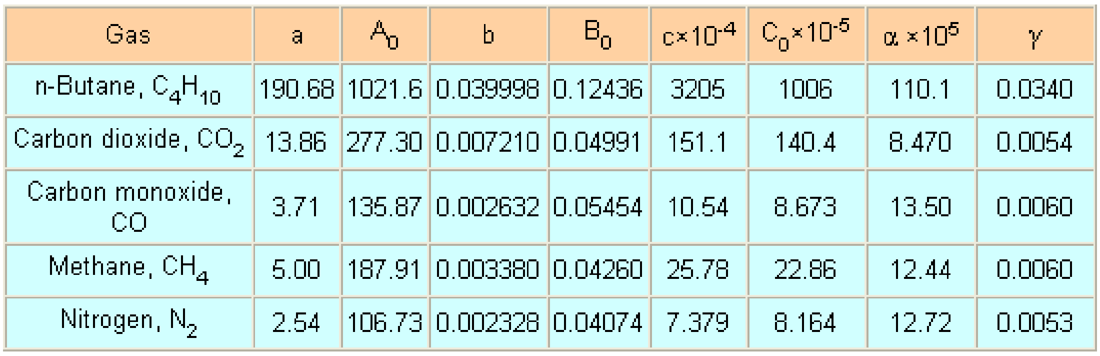
While using the above Table, note that P is in kPa, $\bar{V}$ is in m^3/kmol, T is in K and R_u is equal to 8.314 (kPa-m^3)/(kmol-K).

9.6.3 Benedict–Webb–Rubin (BWR) equation of state (1940):

In this equation number of constants is raised to 8. BWR equation is of following form:

$$P = \frac{R_u T}{\bar{v}} + \left(B_0 R_u T - A_0 - \frac{C_0}{T^2}\right)\frac{1}{\bar{v}^2} + \frac{bR_u T - a}{\bar{v}^3} + \frac{a\alpha}{\bar{v}^6} + \frac{c}{\bar{v}^3 T^2}\left(1 + \frac{\gamma}{\bar{v}^2}\right)e^{-\gamma/\bar{v}^2} \qquad \text{.....(4.13)}$$

Constants in eqn. (4.13) are given in the following Table:



Gas	a	A_0	b	B_0	$c \times 10^{-4}$	$C_0 \times 10^{-5}$	$\alpha \times 10^5$	γ
n-Butane, C_4H_{10}	190.68	1021.6	0.039998	0.12436	3205	1006	110.1	0.0340
Carbon dioxide, CO_2	13.86	277.30	0.007210	0.04991	151.1	140.4	8.470	0.0054
Carbon monoxide, CO	3.71	135.87	0.002632	0.05454	10.54	8.673	13.50	0.0060
Methane, CH_4	5.00	187.91	0.003380	0.04260	25.78	22.86	12.44	0.0060
Nitrogen, N_2	2.54	106.73	0.002328	0.04074	7.379	8.164	12.72	0.0053

Table 9.5 Values of constants in BWR equation [7]

Here, note that P is in kPa, $\bar{v}$ is in m^3/kmol, T is in K and R_u is 8.314 (kPa-m^3)/(kmol-K).

BWR equation is accurate at densities up to 2.5 times the density at the critical point.

In 1962, Strobridge improved this equation further by raising the number of constants to 16. It is therefore, more suitable for computer analysis.

9.6.4 Redlich – Kwong equation of state [5]:

$$P = \frac{RT}{V_m - b} - \frac{a}{\sqrt{T}\,V_m\,(V_m + b)} \qquad \text{....(4.14)}$$

where

$$a = \frac{0.42748\,R^2\,T_c^{2.5}}{p_c} \qquad \text{....(4.15)}$$

$$b = \frac{0.08662\,R\,T_c}{p_c} \qquad \text{.....(4.16)}$$

Here, R is the Universal gas constant = 8.314472 J/mol.K. V_m is the molar volume, i.e. volume of 1 mole of liquid or gas; P_c is the pressure at the critical point; V_c is the molar volume at the critical point. R-K equation performs poorly for liquid phase. It is suitable for gas phase calculation when $P_R < (T_R/2)$.

9.6.5 Peng-Robinson equation of state (1976) [5]:

This equation is most widely used in chemical engineering thermodynamics. It gives better prediction of liquid states as compared to other equations of state. This equation of state requires three inputs per compound: T_c, P_c and the acentric factor ω. This equation has the following form:

$$P = \frac{RT}{V_m - b} - \frac{a\,\alpha}{V_m^2 + 2bV_m - b^2} \qquad \text{....(4.17)}$$

where

$$a = \frac{0.45724\,R^2\,T_c^2}{p_c} \qquad \text{....(4.18)}$$

$$b = \frac{0.07780\,R\,T_c}{p_c} \qquad \text{......(4.19)}$$

$$\alpha = \left(1 + \left(0.37464 + 1.54226\,\omega - 0.26992\omega^2\right)\left(1 - T_r^{0.5}\right)\right)^2 \qquad \text{.....(4.20)}$$

and,

$$T_r = \frac{T}{T_c} \qquad \text{.....(4.21)}$$

Also, Universal gas constant R = 8.314472 J/mol.K. V_m is the molar volume, i.e. volume of 1 mole of liquid or gas; P_c is the pressure at the critical point; V_c is the molar volume at the critical point.

The Peng-Robinson equation is *particularly useful* for all calculations of all fluid properties in *Natural gas processes*. Further, this equation has reasonable accuracy near the critical point; therefore, it is suitable to calculate the compressibility factors and liquid density.

9.6.6 Virial equation of state [5]:

All the above equations of state depend on measured properties of fluids. But, the virial equation of state is derived directly from statistical mechanics. It is of following form:

$$\frac{\boldsymbol{P}\, V_m}{RT} = 1 + \frac{B}{V_m} + \frac{C}{V_m^2} + \frac{D}{V_m^3} + \dots \qquad \text{......(4.22)}$$

And,

$$B = -V_c \qquad \text{.....(4.23)}$$

$$C = \frac{V_c^2}{3} \qquad \text{.....(4.24)}$$

Here, R is the Universal gas constant = 8.314472 J/mol.K. V_m is the molar volume, i.e. volume of 1 mole of liquid or gas; P_c is the pressure at the critical point; V_c is the molar volume at the critical point. Accuracy can be increased by increasing the number of terms in eqn. (4.22).

9.7 Internal energy (u) and enthalpy (h) of an Ideal gas:

Joule's Law: "Specific internal energy of a gas is a function of temp only and is independent of both pressure and volume"

i.e. u = f(T) only.

And, for enthalpy:

h = u + P * v = u + R * T

i.e. h = f(T) only.

9.8 Specific heats of Ideal gases:

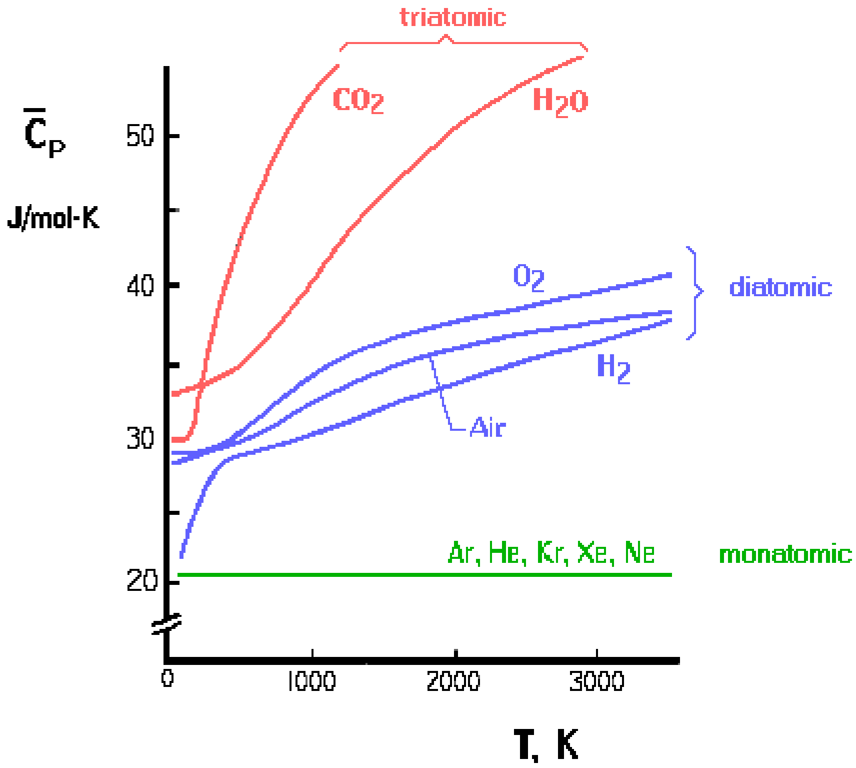
For an Ideal gas:

$$c_v = \frac{du}{dT} \qquad \text{..sp.heat at const. vol....for any process}$$

$$c_p = \frac{dh}{dT} \qquad \text{..sp.heat at const. pressure..}$$

$$c_p - c_v = R \qquad \text{...where R is Gas constant.}$$

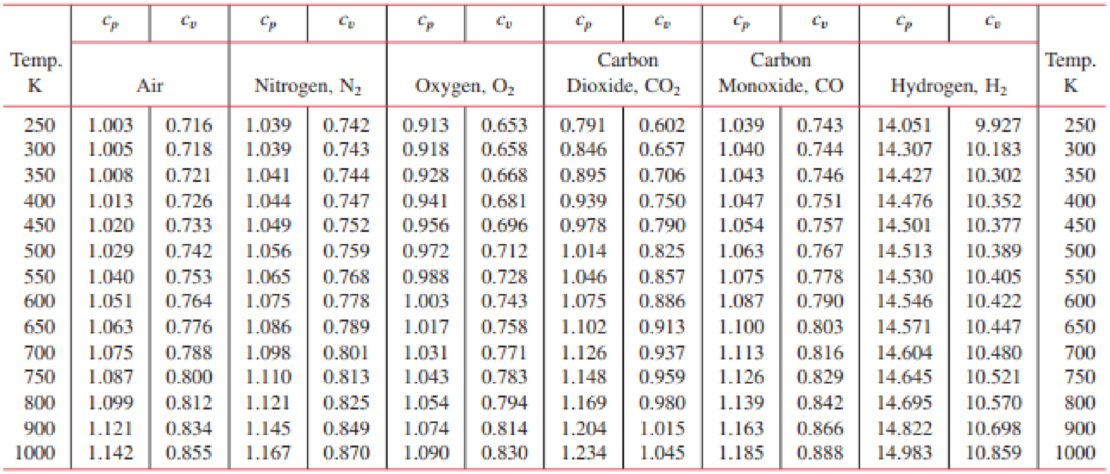
Isobaric sp. heats for several gases [16]:



Sp. heats of Ideal gas are functions of temp only.

Ideal gas sp. heats of some common gases are presented below in a Table, easy to use [17]:

Table T-10 Ideal Gas Specific Heats of Some Common Gases (kJ/kg · K)



Temp. K	Air		Nitrogen, N_2		Oxygen, O_2		Carbon Dioxide, CO_2		Carbon Monoxide, CO		Hydrogen, H_2		Temp. K
	c_p	c_v	c_p	c_v	c_p	c_v	c_p	c_v	c_p	c_v	c_p	c_v	
250	1.003	0.716	1.039	0.742	0.913	0.653	0.791	0.602	1.039	0.743	14.051	9.927	250
300	1.005	0.718	1.039	0.743	0.918	0.658	0.846	0.657	1.040	0.744	14.307	10.183	300
350	1.008	0.721	1.041	0.744	0.928	0.668	0.895	0.706	1.043	0.746	14.427	10.302	350
400	1.013	0.726	1.044	0.747	0.941	0.681	0.939	0.750	1.047	0.751	14.476	10.352	400
450	1.020	0.733	1.049	0.752	0.956	0.696	0.978	0.790	1.054	0.757	14.501	10.377	450
500	1.029	0.742	1.056	0.759	0.972	0.712	1.014	0.825	1.063	0.767	14.513	10.389	500
550	1.040	0.753	1.065	0.768	0.988	0.728	1.046	0.857	1.075	0.778	14.530	10.405	550
600	1.051	0.764	1.075	0.778	1.003	0.743	1.075	0.886	1.087	0.790	14.546	10.422	600
650	1.063	0.776	1.086	0.789	1.017	0.758	1.102	0.913	1.100	0.803	14.571	10.447	650
700	1.075	0.788	1.098	0.801	1.031	0.771	1.126	0.937	1.113	0.816	14.604	10.480	700
750	1.087	0.800	1.110	0.813	1.043	0.783	1.148	0.959	1.126	0.829	14.645	10.521	750
800	1.099	0.812	1.121	0.825	1.054	0.794	1.169	0.980	1.139	0.842	14.695	10.570	800
900	1.121	0.834	1.145	0.849	1.074	0.814	1.204	1.015	1.163	0.866	14.822	10.698	900
1000	1.142	0.855	1.167	0.870	1.090	0.830	1.234	1.045	1.185	0.888	14.983	10.859	1000

Source: Tables T-10 are adapted from K. Wark, *Thermodynamics*, 4th ed., McGraw-Hill, New York, 1983, as based on "Tables of Thermal Properties of Gases," NBS Circular 564, 1955.

Generally, variation of sp. heats for different ideal gases are expressed as *third order polynomials in T*, and are available in Thermodynamics Text books / handbooks.

As an example:

cp_bar = a + b * T + c * T^2 + d * T^3

where T is in Kelvin, cp_bar in kJ/kmol.K

And a, b, c and d for some gases are [1]:

Substance	a	b	c	d
Air	**28.11**	**0.1967E-2**	**0.4802E-5**	**-1.966E-9**
N2	**28.9**	**-0.1571E-2**	**0.8081E-5**	**-2.873E-9**
O2	**25.48**	**1.520E-2**	**-0.7155E-5**	**1.312E-9**
CO2	**22.26**	**5.981E-2**	**-3.501E-5**	**7.469E-9**
CO	**28.16**	**0.1675E-2**	**0.5372E-5**	**-2.222E-9**
H2	**29.11**	**-0.1916E-2**	**0.4003E-5**	**-0.8704E-9**
Water vapor	**32.24**	**0.1923E-2**	**1.055E-5**	**-3.595E-9**
Ammonia (NH3)	**27.568**	**2.5630E-2**	**0.99072E-5**	**-6.6909E-9**
Methane (CH4)	**19.89**	**5.024E-2**	**1.269E-5**	**-11.01E-9**

9.9 Some Processes with Ideal gases: (See Chapter 4)

9.9.1 Work:

Work = Force x distance, N.m (= 1 Joule)

Work is a 'path function' i.e. an inexact differential.

9.9.2 pdV- work or displacement work:

$$dW = p \cdot dV$$

$$W_{12} = \int_{V1}^{V2} p \, dV$$ ....Integration performed on a quasi-static path

9.9.3 pdV- work in various quasi-static processes:

(a). Constant pressure (isobaric) process:

$$W_{12} = p \cdot (V2 - V1)$$

(b). Constant volume (isochoric) process:

$$W_{12} = 0$$

(c). For a process in which pV = const....Isothermal process:

$$W_{12} = p1 \cdot V1 \cdot \ln\left(\frac{p1}{p2}\right)$$

(d). For a process in which pV^{γ} = const....reversible adiabatic or isentropic process:

$$W_{12} = \frac{p1 \cdot V1 - p2 \cdot V2}{\gamma - 1} = \frac{R \cdot (T1 - T2)}{\gamma - 1} = \frac{p1 \cdot V1}{n - 1} \cdot \left[1 - \left(\frac{p2}{p1}\right)^{\frac{\gamma - 1}{\gamma}}\right]$$

Also, for a perfect gas:

$$p \cdot v = R \cdot T$$

And for isentropic process, pv^{γ} = const., we have:

$$T \cdot v^{\gamma-1} = \text{constant}$$

$$\frac{p2}{p1} = \left(\frac{v1}{v2}\right)^{\gamma}$$

$$\frac{T2}{T1} = \left(\frac{v1}{v2}\right)^{\gamma-1}$$

$$\frac{T2}{T1} = \left(\frac{p2}{p1}\right)^{\frac{\gamma-1}{\gamma}}$$

(e). For a process in which pV^n = const....polytropic process:

$$W_{12} = \frac{p1 \cdot V1 - p2 \cdot V2}{n-1} = \frac{p1 \cdot V1}{n-1} \cdot \left[1 - \left(\frac{p2}{p1}\right)^{\frac{n-1}{n}}\right]$$

i.e. $$W_{12} = \frac{R \cdot (T1 - T2)}{n-1}$$

Also: for a polytropic process:

$$\frac{p2}{p1} = \left(\frac{v1}{v2}\right)^n$$

$$\frac{T2}{T1} = \left(\frac{v1}{v2}\right)^{n-1}$$

$$\frac{T2}{T1} = \left(\frac{p2}{p1}\right)^{\frac{n-1}{n}}$$

For a perfect gas:

$$p \cdot v = R \cdot T \qquad du = cv \cdot dT$$

$$\gamma = \frac{c_p}{c_v} \qquad c_p - c_v = R$$

i.e. $$c_v = \frac{R}{\gamma - 1}$$

Then, heat transfer during a polytropic process (for a perfect gas):

$$Q = (u2 - u1) + W = c_v \cdot (T2 - T1) + R \cdot (T1 - T2)$$

Simplifying, we get:

$$Q_{poly} = \frac{\gamma - n}{\gamma - 1} \cdot \frac{R \cdot (T1 - T2)}{n-1}$$

i.e. $$Q_{poly} = \frac{\gamma - n}{\gamma - 1} \cdot W_{poly}$$

Polytropic sp. heat:

Polytr. sp. heat: $$c_n = c_v \cdot \frac{\gamma - n}{1 - n}$$

9.10 Properties of Mixtures of Ideal gases [18]:

9.10.1 Dalton's Law:

The pressure of a mixture of gases is equal to the sum of the partial pressures of the constituents.

The partial pressure of each constituent is that pressure which the gas would exert if it occupied alone that volume occupied by the mixture at the same temperature.

Considering a mixture of two Ideal gases A and B:

$m = m_A + m_B$ and,

$p = p_A + p_B$ ...by Dalton's Law

For a mixture of i no. of ideal gases:

$$m = m_A + m_B + m_C + ... + m_i$$

$$p = p_A + p_B + p_C + ... + p_i$$

Or,

$$m = \Sigma\, m_i$$

and,

$$p = \Sigma\, p_i$$

9.10.2 Gibbs-Dalton Law:

The internal energy, enthalpy and entropy of a gaseous mixture are respectively equal to the sums of the internal energies, enthalpies and entropies of the constituents.

Each constituent has that internal energy, enthalpy and entropy which it could have if it occupied alone that volume occupied by the mixture at the temperature of the mixture.

i.e. we have:

$$m \cdot u = m_A \cdot u_A + m_B \cdot u_B + \ldots\ldots\ldots\ldots$$

$$m \cdot h = m_A \cdot h_A + m_B \cdot h_B + \ldots\ldots\ldots\ldots\ldots\ldots$$

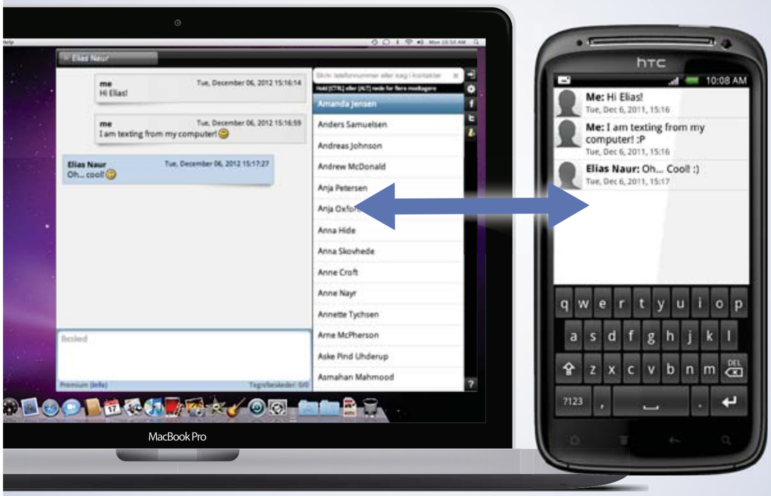
$$m \cdot s = m_A \cdot s_A + m_B \cdot s_B + \ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

Or,

$$m.u = \Sigma\, m_i * u_i$$

$$m.h = \Sigma\, m_i * h_i$$

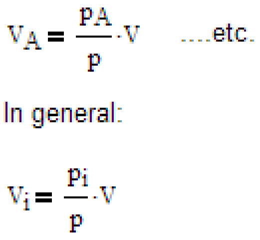
$$m.s = \Sigma\, m_i * s_i$$



9.10.3 Volumetric analysis of a gas mixture:

Consider a volume V of a gaseous mixture at a temp T consisting of three constituents A, B and C. Let each of the constituents be compressed to the total pressure p of the mixture and let the temp remain constant. The partial volumes occupied by the constituents will then be V_A, V_B and V_C.

And, we get:



$$V_A = \frac{p_A}{p} \cdot V \qquad \text{....etc.}$$

In general:

$$V_i = \frac{p_i}{p} \cdot V$$

i.e. Σ Vi = Σ (p_i * V) / p = (V / P) * Σ p_i

But, p = Σ p_i

Therefore: Σ Vi = V

Thus, **"volume of a mixture of gases is equal to the sum of the volumes of the individual constituents when each exists alone at the pressure and temp of mixture."** … This is known **as Amagat's Law.**

Remember:

n = m / M where

n is the no. of moles, m = mass of gas, and M = molecular weight of gas

Avogadro's Law: "number of moles of any gas is proportional to the volume of the gas at a given pressure and temperature".

So, total number of moles in a vessel containing a mixture of gases must equal the sum of the moles of the individual constituents.

i.e.

$$n = n_A + n_B + n_C + ..$$

i.e. n = Σ n_i

9.10.4 Apparent Molecular weight and Gas constant:

If a gas mixture, with total number of moles n, occupies a total volume of V, at a temperature T, then:

$p * V = R_u * T * \Sigma n_i$

i.e. $p * V = n * R_u * T$ where R_u is the Universal gas const.

Apparent mol. weight is defined as: $M = m / n$

where, m = the mass of the mixture, and n = no. of moles in the mixture

Apparent Gas constant for the mixture is defined as $R = R_u / M$

It can be assumed that the mixture of perfect gases behaves like a perfect gas and obeys the perfect gas laws.

Apparent gas constant of mixture in terms of individual gas constants:

$$R = \Sigma (mi / m)*R_i$$

where (mi / m) = mass fraction of constituent i

Also note that:

$$\frac{p_i}{p} = \frac{n_i}{n} = \frac{V_i}{V}$$

i.e. Molar analysis is identical with the volumetric analysis, and both are equal to the ratio of partial pressure to the total pressure.

Also:

$M = \Sigma (n_i / n) .M_i$

And,

$M = 1 / \Sigma (m_{fi} / M_i)$

where m_{fi} is the mass fraction of species i, M_i is its mol. wt.

9.10.5 Sp. heats of a Gas mixture:

$c_v = \Sigma\ (m_i / m).\ c_{vi}$, and

$c_p = \Sigma\ (m_i / m).\ c_{pi}$

$R = c_p - c_v = \Sigma\ (m_i / m).\ R_i$ …. gives for the mixture

For the mixture, we can also write:

$\gamma = c_p / c_v$

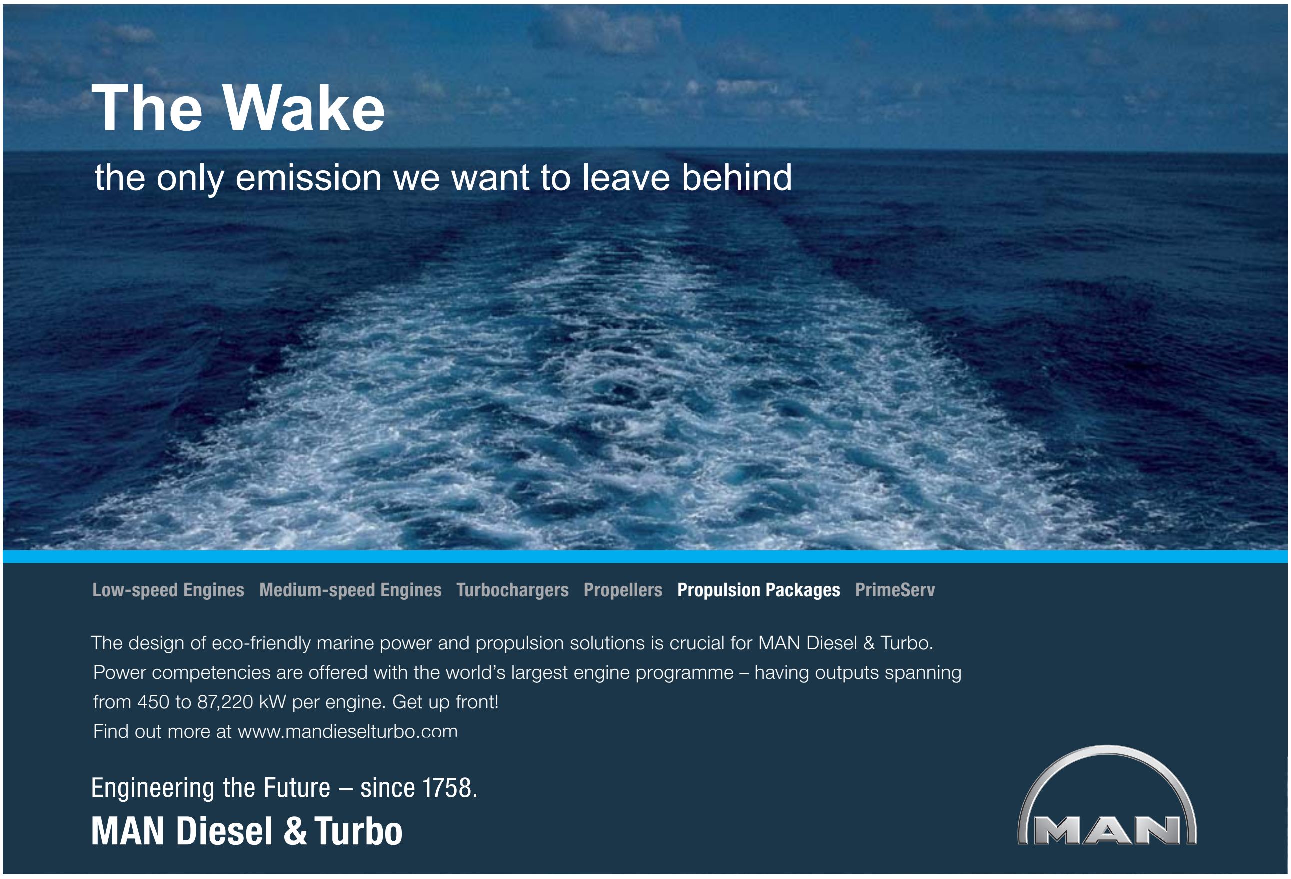
$c_p = \gamma.\ R / (\gamma - 1)$

$c_v = R / (\gamma - 1)$

Molar sp. heats:

$C_p = M.\ c_p$

$C_v = M.\ c_v$



$C_p - C_v = M.\ R = R_u$ … the Universal Gas const.

Also,

$U = n.\ C_v.\ T$ and,

$H = n.\ C_p\ T$

And,

$C_v = \Sigma\ (n_i / n).C_{vi}$

$C_p = \Sigma\ (n_i / n).C_{pi}$

9.10.6 Mixing of two Ideal gases at same P and T [Ref: 2]:

Let a mass m_A of ideal gas A at a given P and T be mixed with m_B of ideal gas B at the same P and T, such that the final ideal gas mixture is also at P and T. Then, entropy change for the process is:

$$\Delta S_{mix} = -m_A \cdot R_A \cdot \ln(y_A) - m_B \cdot R_B \cdot \ln(y_B)$$

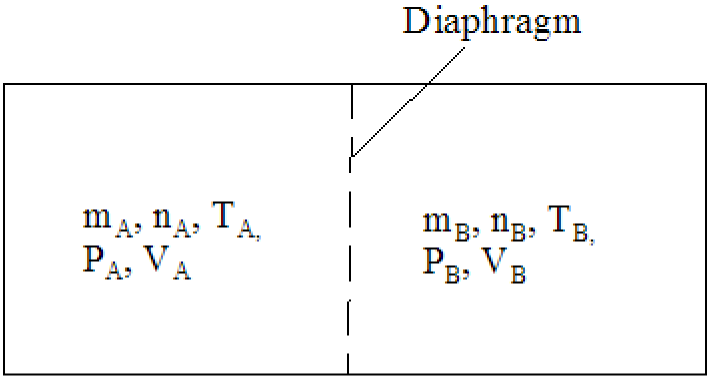
i.e. $$\Delta S_{mix} = -n_A \cdot R_u \cdot \ln(y_A) - n_B \cdot R_u \cdot \ln(y_B)$$

Note that increase in entropy depends only on the no. of moles of component gases and is *independent* of the composition of the gas.

9.10.7 Adiabatic mixing of two Ideal gases: [Ref: 18]:

Two cases are considered:

1. Two compartments, separated by a membrane contain two ideal gases A and B, one in each compartment.



Now, the membrane is removed and the gases mix:

Mixture of Gases A and B

$m = m_A + m_B,$
$V = V_A + V_B,$
$n = n_A + n_B$
P, T

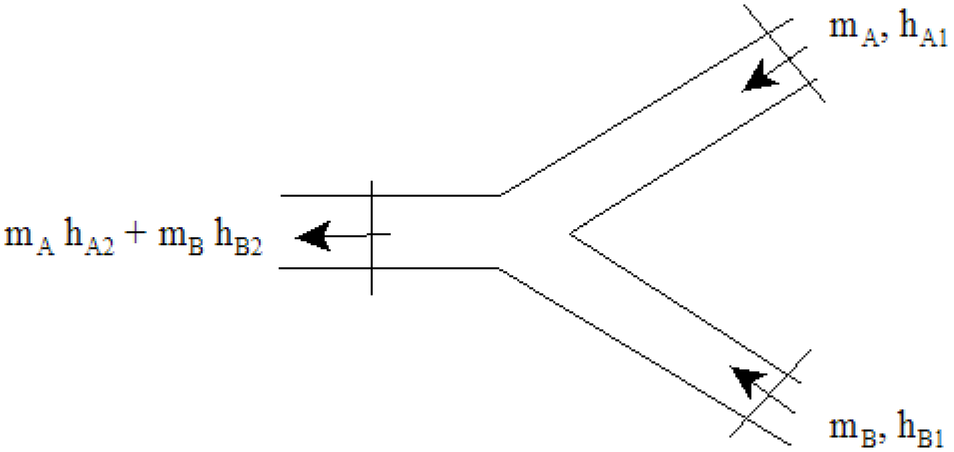
The process is equivalent to free expansion of each gas. So, **equating the total internal energies before and after mixing,** we get:

$$U_1 = n_A \cdot Cv_A \cdot T_A + n_B \cdot Cv_B \cdot T_B$$

$$U_2 = \left(n_A \cdot Cv_A + n_B \cdot Cv_B\right) \cdot T$$

and, $$T = \frac{n_A \cdot Cv_A \cdot T_A + n_B \cdot Cv_B \cdot T_B}{n_A \cdot Cv_A + n_B \cdot Cv_B}$$

2. If two streams of fluid meet to form a common stream in **steady flow**, we apply **steady flow energy eqn** to the mixing section. Neglecting the changes in P.E. and K.E. we get:



$$m_A \cdot h_{A1} + m_B \cdot h_{B1} + Q = m_A \cdot h_{A2} + m_B \cdot h_{B2} + W$$

For adiabatic flow, Q = 0, Also W = 0. Then, we get:

$$m_A \cdot h_{A1} + m_B \cdot h_{B1} = m_A \cdot h_{A2} + m_B \cdot h_{B2}$$

Now, h = cp. T. Therefore:

$$m_A \cdot cp_A \cdot T_A + m_B \cdot cp_B \cdot T_B = m_A \cdot cp_A \cdot T + m_B \cdot cp_B \cdot T$$

and, $$T = \frac{m_A \cdot cp_A \cdot T_A + m_B \cdot cp_B \cdot T_B}{m_A \cdot cp_A + m_B \cdot cp_B}$$

T is the temp after mixing.

In terms of moles of gases:

$$T = \frac{n_A \cdot Cp_A \cdot T_A + n_B \cdot Cp_B \cdot T_B}{n_A \cdot Cp_A + n_B \cdot Cp_B}$$

where $Cp = M \cdot cp$ and,

$M = \frac{m}{n}$ and $n \cdot Cp = m \cdot cp$

==

9.11 Problems solved with Mathcad:

Prob. 9.1 Sp. vol. of CO2 at 120 C is 1.2 m^3/kg. Determine the pressure exerted by CO2 (i) by Ideal gas eqn. (ii) by Van der Waals eqn. [VTU – Jan. 2004]

Mathcad Solution:

Data:

$R_u := 8314.4$ J/kg.mole.K $m := 1$ kg $T := 120 + 273$ K

$V := 1.2$ m3 $M := 44$ Mol. wt of CO2

Calculations:

(i) By Ideal gas eqn.:

$R := \frac{R_u}{M}$ i.e. $R = 188.964$ J.kg.K

Therefore: $p := \frac{m \cdot R \cdot T}{V}$ Pa

i.e. $p = 6.189 \times 10^4$ **Pa.... Ans.**

(ii) By Van der Waals eqn.:

We have he Van der Waal's constants for CO2:

$a = 3.647$ bar.(m^3/kmol)^2 = 364700 Pa.(m^3/kmol)^2

$b = 0.0428$ m^3/lmol

i.e. For CO2:

$a := 364700$ Pa.(m^3/kmol)^2 $b := 0.0428$ m^3/lmol

$$vbar := \frac{V}{\left(\frac{m}{M}\right)} \qquad vbar = 52.8$$ m3/kg.mol

i.e. For CO2:

$a := 364700$ Pa.(m^3/kmol)^2 $b := 0.0428$ m^3/lmol

$$vbar := \frac{V}{\left(\frac{m}{M}\right)} \qquad vbar = 52.8$$ m3/kg.mol

$$pVW := \frac{R_u \cdot T}{vbar - b} - \frac{a}{vbar^2}$$ **....Van der waal's eqn. for pressure**

i.e. $pVW = 6.18 \times 10^4$ **Pa.....Pressure as per Van der Waal's eqn....Ans.**

==

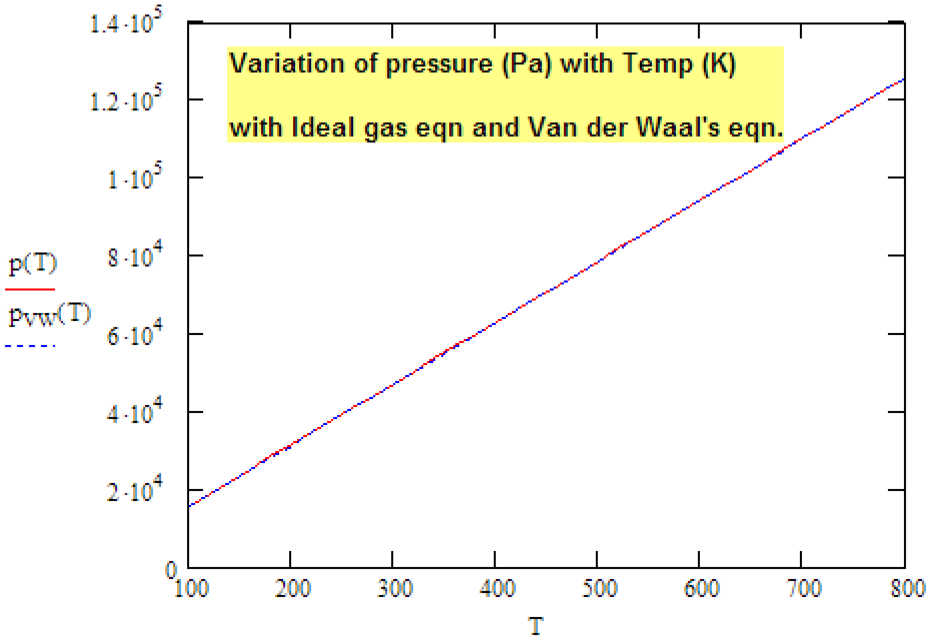
In addition:

Plot the variation of p with T as T varies from 100 K to 800 K, using Ideal gas eqn and Van der Waal's eqn:

$$p(T) := \frac{m \cdot R \cdot T}{V}$$ ....define p as a function of T

$$pVW(T) := \frac{R_u \cdot T}{vbar - b} - \frac{a}{vbar^2}$$ ....define pVW as a function of T

$T := 100, 120 .. 800$ ...define a range variable T



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Prob.9.2. Determine the pressure exerted by CO2 in a container of 1.5 m^3 capacity when it contains 6 kg at 27 C (i) by Ideal gas eqn. (ii) by Van der Waals eqn, (iii) by Beattie Bridgman eqn.

Mathcad Solution:

Data:

$R_u := 8314.4$ J/kg.mole.K $m := 6$ kg $T := 300$ K $V := 1.5$ m3

$M := 44$ Mol. wt of CO2

Calculations:

(i) By Ideal gas eqn.:

$R := \frac{R_u}{M}$ i.e. $R = 188.964$ J/kg.K

$p := \frac{m \cdot R \cdot T}{V}$ Pa i.e. $p = 2.268 \times 10^5$ **Pa....Pressure by Ideal gas eqn.... Ans**

(ii) By Van der Waals eqn.:

For CO2: $a := 364700$ Pa.(m^3/kmol)^2 $b := 0.0428$ m^3/kmol

$$vbar := \frac{V}{\left(\frac{m}{M}\right)} \qquad vbar = 11 \quad \text{m3/kg.mol}$$

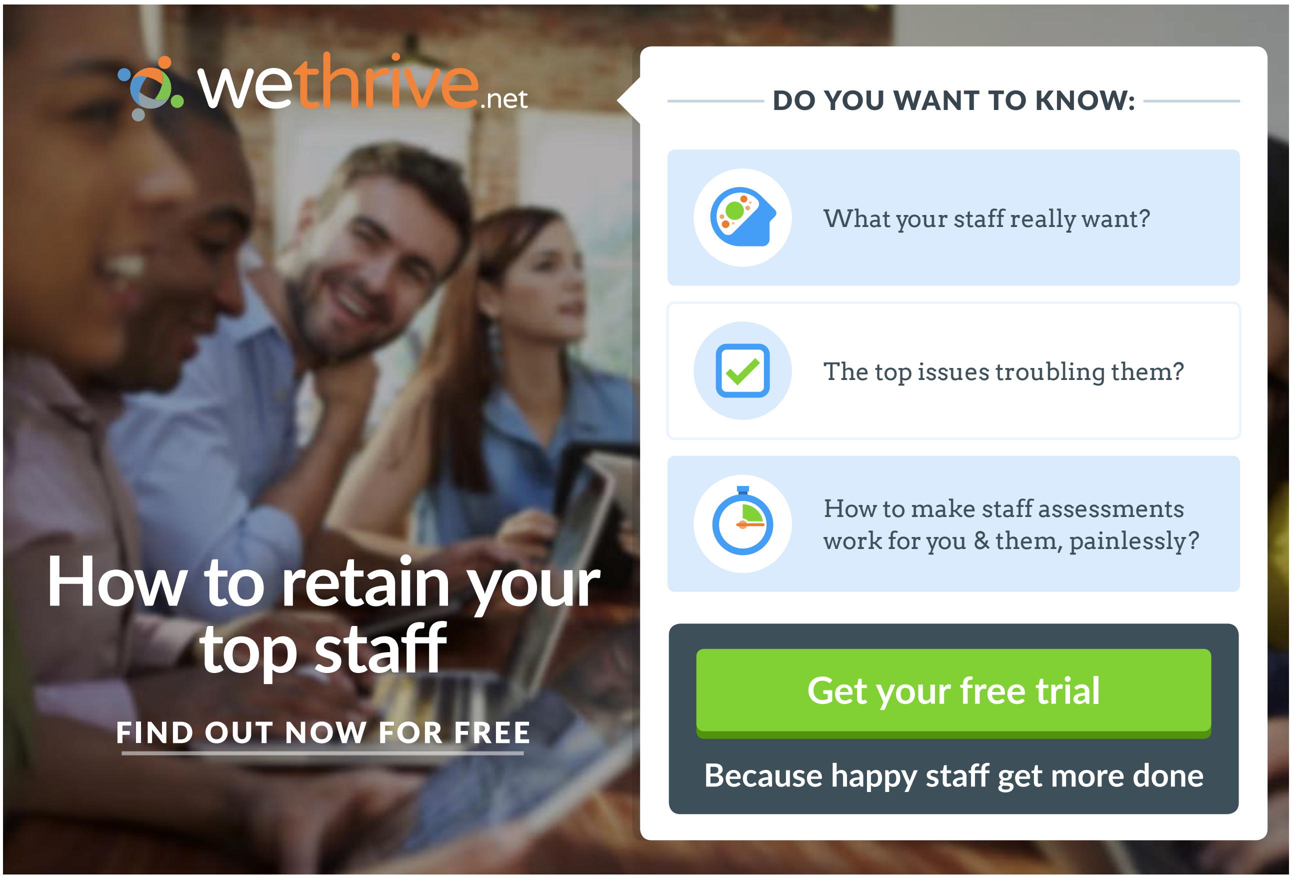
$$pvw := \frac{R_u \cdot T}{vbar - b} - \frac{a}{vbar^2}$$ ....Van der Waals eqn.

i.e. $pvw = 2.246 \times 10^5$ **Pa....Pressure by Van der Waal's eqn.... Ans**

(iii) By Beattie Bridgeman eqn.:

For CO2 we have:

$aa := 0.07132$ $bb := 0.07235$ $cc := 66 \cdot 10^4$ $A_0 := 507.2836$ $B_0 := 0.10476$



$A := A_0 \cdot \left(1 - \frac{aa}{vbar}\right)$ $\quad A = 503.995$

$B := B_0 \cdot \left(1 - \frac{bb}{vbar}\right)$ $\quad B = 0.104$

$\varepsilon := \frac{cc}{\left(vbar \cdot T^3\right)}$ $\quad \varepsilon = 2.222 \times 10^{-3}$

$$pBB := \frac{R_u \cdot T \cdot (1 - \varepsilon)}{vbar^2} \cdot (vbar + B) - \frac{A}{vbar^2}$$ ...Beattie Bridgeman eqn.

i.e. $pBB = 2.284 \times 10^5$ **Pa....Pressure by Beattie Bridgeman eqn.... Ans.**

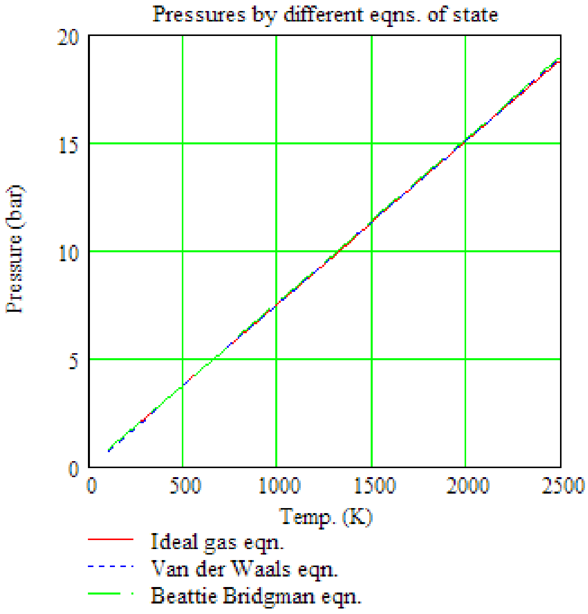
To draw a graph of p for various T:

$T := 100, 200 .. 2500$ ....define a range variable

$$p_{ideal}(T) := \frac{m \cdot R \cdot T}{V}$$ ....Ideal gas eqn.

$$pVW(T) := \frac{R_u \cdot T}{vbar - b} - \frac{a}{vbar^2}$$ ....Van der Waals eqn.

$$pBB(T) := \frac{R_u \cdot T \cdot (1 - \varepsilon)}{vbar^2} \cdot (vbar + B) - \frac{A}{vbar^2}$$ ...Beattie Bridgeman eqn.



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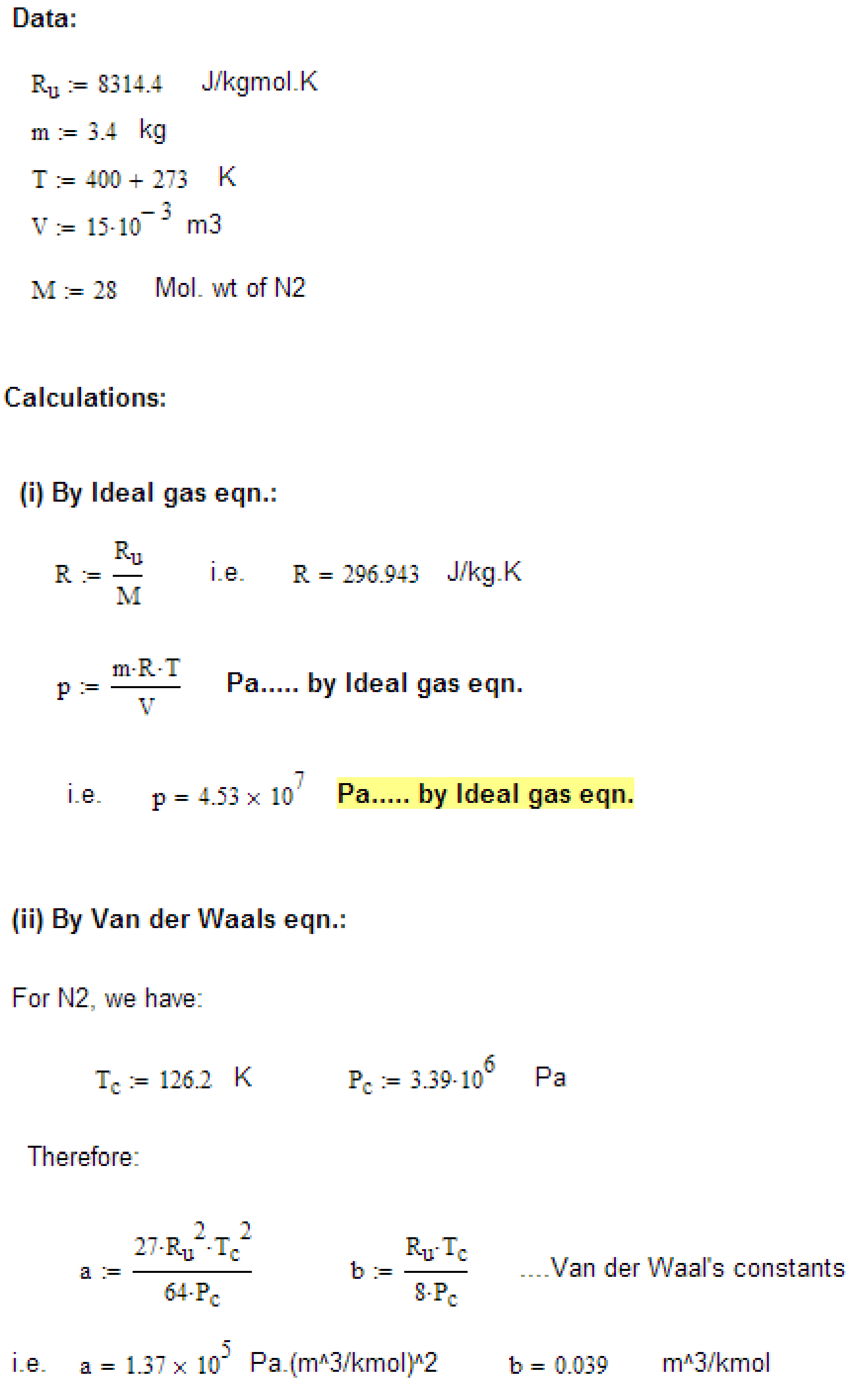
Prob.9.3. Determine the pressure in a steel vessel having a volume of 15 L and containing 3.4 kg of nitrogen at 400 C using: (i) Ideal gas eqn. (ii) Van der Waals eqn. [VTU – Feb. 2002]

Mathcad Solution:



Data:

$R_u := 8314.4$ J/kgmol.K

$m := 3.4$ kg

$T := 400 + 273$ K

$V := 15 \cdot 10^{-3}$ m3

$M := 28$ Mol. wt of N2

Calculations:

(i) By Ideal gas eqn.:

$R := \frac{R_u}{M}$ i.e. $R = 296.943$ J/kg.K

$p := \frac{m \cdot R \cdot T}{V}$ **Pa..... by Ideal gas eqn.**

i.e. $p = 4.53 \times 10^{7}$ **Pa..... by Ideal gas eqn.**

(ii) By Van der Waals eqn.:

For N2, we have:

$T_c := 126.2$ K $P_c := 3.39 \cdot 10^{6}$ Pa

Therefore:

$a := \frac{27 \cdot R_u^{2} \cdot T_c^{2}}{64 \cdot P_c}$ $b := \frac{R_u \cdot T_c}{8 \cdot P_c}$ ....Van der Waal's constants

i.e. $a = 1.37 \times 10^{5}$ Pa.(m^3/kmol)^2 $b = 0.039$ m^3/kmol

$vbar := \frac{V}{\left(\frac{m}{M}\right)}$ $vbar = 0.124$ m3/kg.mol

$pvw := \frac{R_u \cdot T}{vbar - b} - \frac{a}{vbar^2}$ ...Van der Waal's eqn.

$pvw = 5.698 \times 10^7$ **Pa..... by Vqan der Waals eqn.**

Compressibility factor:

$Z := \frac{pvw \cdot V}{R \cdot T}$ ...by definition of Z

i.e. $Z = 4.277$ **....Ans**

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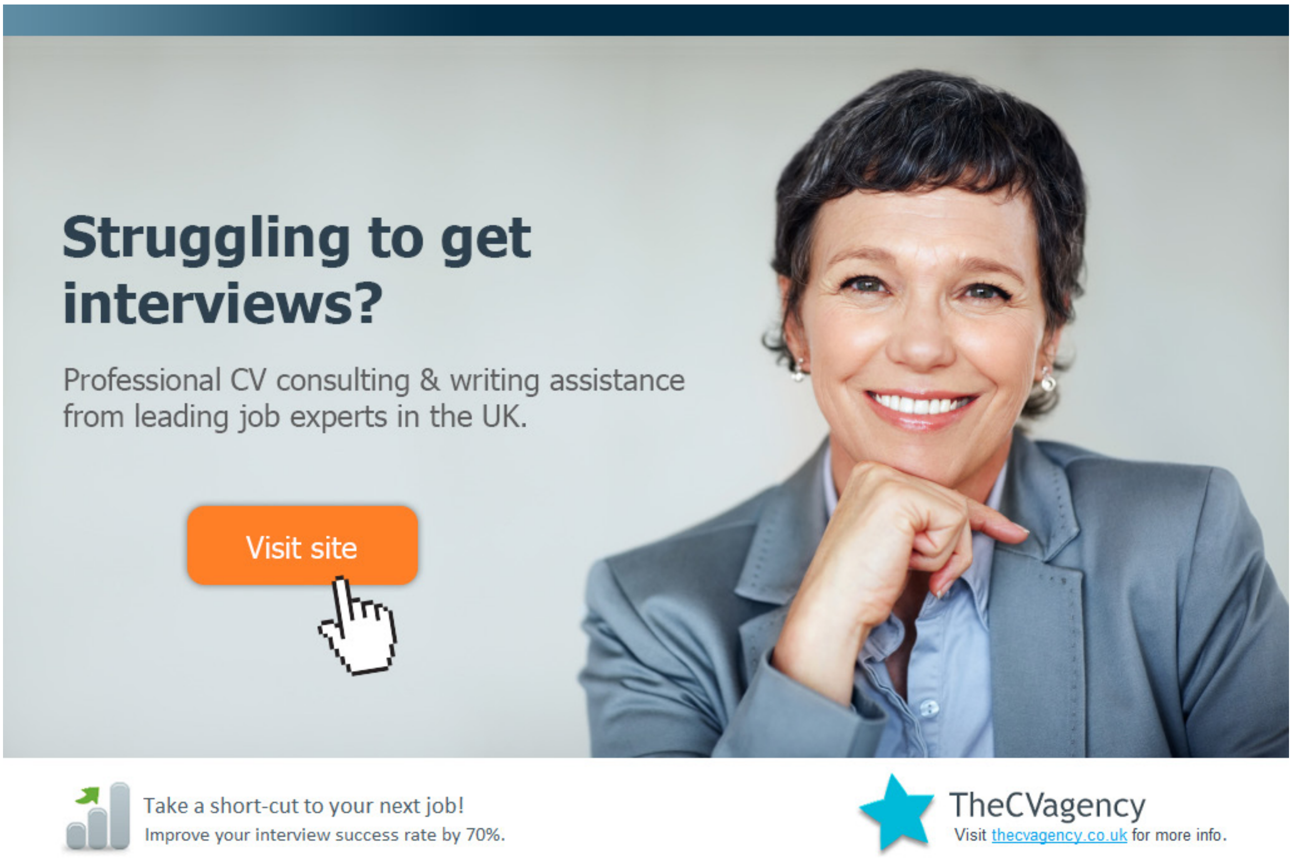


Prob.9.4. Pressure and temp. of a mixture of 3 kg of N2 and 5 kg of CO2 are 3 bar and 20 C respectively. For the mixture, determine the following:(i) mole fraction of each component (ii) Avg. Mol. wt. and specific gas constant (iii) partial pressures and partial volumes of CO2 and N2, and (iv) volume & density of the mixture.

Mathcad Solution:

Data:

$m_{N2} := 3$ kg $\quad M_{N2} := 28$ ...Mol. wt. of N2

$m_{CO2} := 5$ kg $\quad M_{CO2} := 44$ ...Mol. wt. of CO2

$p := 3 \cdot 10^5$ Pa $\quad R_u := 8314.4$ J/kg.mole.K

$T := 25 + 273$ K

Calculations:

(i) Mole fractions:

$n_{N2} := \dfrac{m_{N2}}{M_{N2}} \quad n_{N2} = 0.107$ ...No. of moles of N2

$n_{CO2} := \dfrac{m_{CO2}}{M_{CO2}} \quad n_{CO2} = 0.114$ ...No. of moles of CO2

$n := n_{CO2} + n_{N2} \quad n = 0.221$ ..Total no. of moles

$y_{CO2} := \dfrac{n_{CO2}}{n} \quad y_{CO2} = 0.515$ **....Mole fraction of O2....Ans.**

$y_{N2} := \dfrac{n_{N2}}{n} \quad y_{N2} = 0.485$ **....Mole fraction of N2....Ans.**

(ii) Avg. Mol. wt.:

$m_m := m_{CO2} + m_{N2}$ ....total mass

$M_m := \frac{m_m}{n}$ $M_m = 36.235$ ....Avg. Mol. wt. of mixture....Ans.

(iii) Specific gas constant:

$R_m := \frac{R_u}{M_m}$ $R_m = 229.456$ J/kg.K....Specific gas constant....Ans.

Alternatively: $R_{mix} := \left(\frac{m_{CO2}}{m_m}\right)\cdot\left(\frac{R_u}{M_{CO2}}\right) + \left(\frac{m_{N2}}{m_m}\right)\cdot\left(\frac{R_u}{M_{N2}}\right)$ $R_{mix} = 229.456$ **....verified.**

(iv) Partial pressures and partial Volumes and Density:

$p_{N2} := y_{N2}\cdot p$ $p_{N2} = 1.456 \times 10^5$ Pa....Ans.

$p_{CO2} := y_{CO2}\cdot p$ $p_{CO2} = 1.544 \times 10^5$ Pa....Ans.

$V = V_{CO2} + V_{N2}$ ...Mixture vol....by Amagat's Law...at same P & T as mixture

$V_{CO2} := m_{CO2}\cdot\frac{R_u}{M_{CO2}}\cdot\frac{T}{p}$ i.e $V_{CO2} = 0.939$ m3....partial vol. of CO2

$V_{N2} := m_{N2}\cdot\frac{R_u}{M_{N2}}\cdot\frac{T}{p}$ i.e $V_{N2} = 0.885$ m3....partial vol. of N2

Therefore,

$V := V_{CO2} + V_{N2}$ ....total volume

i.e. $V = 1.823$ m3...Mixture vol...Ans.

Verify: $V = \frac{(m\cdot R\cdot T).mix}{p} = \frac{(m_{CO2} + m_{N2})\cdot R_m\cdot T}{p} = 1.823$ ...verified.

Density: $\frac{m_{CO2} + m_{N2}}{V} = 4.387$ kg/m3....Ans.

==

Prob. 9.5. (a) The above mixture is heated at const. vol. from 25 C to 40 C. Find change in int. energy, enthalpy and entropy of mixture.

(b) if the heating is performed at const. pr. to the same temp. find the change in int. energy, enthalpy and entropy of mixture.

Given: Cp of N2 = 1.04 kJ/kg.K and Cp of CO2 = 0.755 kJ/kg.K

Mathcad Solution:

Data:

$Cp_{N2} := 1.04$ kJ/kg.K

$Cp_{CO2} := 0.755$ kJ/kg.K

$T_1 := 298$ K $T_2 := 313$ K

Calculations:

(i) Sp. heats of mixture:

$m_m := m_{CO2} + m_{N2}$ i.e. $m_m = 8$ kg....mass of mixture

Then:

$$Cp_{mix} := \frac{(m_{CO2} \cdot Cp_{CO2} + m_{N2} \cdot Cp_{N2})}{m_m}$$

i.e. $Cp_{mix} = 0.862$ **kJ/kg.K....Ans.**

And,

$$Cv_{CO2} := Cp_{CO2} - \frac{R_u \cdot 10^{-3}}{M_{CO2}}$$

i.e. $Cv_{CO2} = 0.566$ kJ/kg.K

$$Cv_{N2} := Cp_{N2} - \frac{R_u \cdot 10^{-3}}{M_{N2}}$$

i.e. $Cv_{N2} = 0.743$ kJ/kg.K

And:

$$Cv_{mix} := \frac{(m_{CO2} \cdot Cv_{CO2} + m_{N2} \cdot Cv_{N2})}{m_m}$$

i.e. $Cv_{mix} = 0.632$ **kJ/kg.K....Ans.**

(ii) Changes in int. energy, enthalpy & entropy of mixture:

$$\Delta U := m_m \cdot Cv_{mix} \cdot (T_2 - T_1)$$

i.e. $\Delta U = 75.89$ **kJ....Ans.**

$\Delta H := m_m \cdot Cp_{mix} \cdot (T_2 - T_1)$

i.e. $\Delta H = 103.425$ **kJ....Ans.**

$\Delta S := m_m \cdot Cv_{mix} \cdot \ln\left(\frac{T_2}{T_1}\right)$ kJ/K....for const. vol. process

i.e. $\Delta S = 0.248$ **kJ/K.....for const. vol. process..Ans.**

(b) Changes in int. energy, enthalpy & entropy of mixture, for const. pressure process:

$\Delta U := m_m \cdot Cv_{mix} \cdot (T_2 - T_1)$

i.e. $\Delta U = 75.89$ **kJ....Ans....same as earlier..**

$\Delta H := m_m \cdot Cp_{mix} \cdot (T_2 - T_1)$

i.e. $\Delta H = 103.425$ **kJ....Ans.....same as earlier..**

$\Delta S := m_m \cdot Cp_{mix} \cdot \ln\left(\frac{T_2}{T_1}\right)$ kJ/K....for const. pressure process

i.e. $\Delta S = 0.339$ **kJ/K....for const. pressure process..Ans.**

==

Prob.9.6. A mixture of Ideal gases contains 3 kg of N2 and 5 kg of CO2. The partial pressure of CO2 in the mixture is 155 kPa. Find: (i) partial pressure of N2 (ii) Gas const. for the mixture, and (iii) Mol. wt. of the mixture . [VTU – Jan. 2006]

Mathcad Solution:

Data:

$m_{N2} := 3$ kg $M_{N2} := 28$

$m_{CO2} := 5$ kg $M_{CO2} := 44$

$p_{CO2} := 155$ kPa $R_u := 8314.4$ J/kg.mole.K

Calulations:

(i) Mole fractions:

$n_{CO2} := \frac{m_{CO2}}{M_{CO2}}$ i.e. $n_{CO2} = 0.114$ ...No. of moles of CO2

$n_{N2} := \frac{m_{N2}}{M_{N2}}$ i.e. $n_{N2} = 0.107$ ...No. of moles of N2

$n := n_{CO2} + n_{N2}$ i.e. $n = 0.221$ ..Total no. of moles

$y_{CO2} := \frac{n_{CO2}}{n}$ i.e. $y_{CO2} = 0.515$ **....Mole fraction of CO2....Ans.**

$y_{N2} := \frac{n_{N2}}{n}$ i.e. $y_{N2} = 0.485$ **....Mole fraction of N2....Ans.**

Therefore, $P_{tot} := \frac{p_{CO2}}{y_{CO2}}$ i.e. $P_{tot} = 301.143$ **kPa.....Ans.**

And, $p_{N2} := y_{N2} \cdot P_{tot}$ i.e. $p_{N2} = 146.143$ **kPa ... Ans.**

(ii) Avg. Mol. wt.:

$M_m := \frac{m_{CO2} + m_{N2}}{n}$ i.e. $M_m = 36.235$ **....Avg. Mol. wt. of mixture....Ans.**

(iii) Specific gas constant:

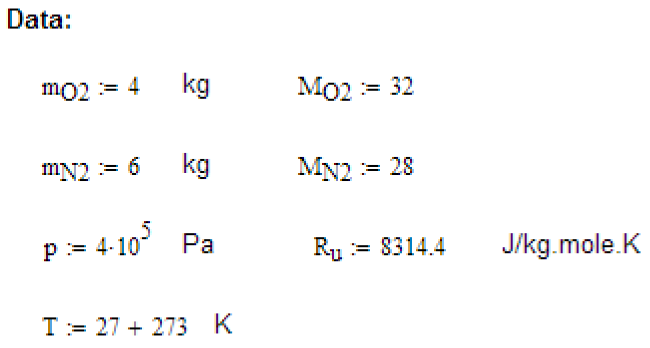
$$R_m := \frac{R_u}{M_m}$$

i.e. $R_m = 229.456$ **J/kg.K....Specific gas constant....Ans.**

==

Prob.9.7. Pressure and temperature of a mixture of 4 kg of O2 and 6 kg of N2 are 4 bar and 27 C respectively. For the mixture, determine the following: (i) mole fraction of each component (ii) Avg. Mol. wt. (iii) specific gas constant (iv) volume and density. [VTU – Jan. 2005]

Mathcad Solution:



Data:

$m_{O2} := 4$ kg $\quad M_{O2} := 32$

$m_{N2} := 6$ kg $\quad M_{N2} := 28$

$p := 4 \cdot 10^5$ Pa $\quad R_u := 8314.4$ J/kg.mole.K

$T := 27 + 273$ K

Calculations:

(i) Mole fractions:

$n_{O2} := \frac{m_{O2}}{M_{O2}}$ i.e. $n_{O2} = 0.125$ ...No. of moles of O2

$n_{N2} := \frac{m_{N2}}{M_{N2}}$ i.e. $n_{N2} = 0.214$ ...No. of moles of N2

$n := n_{O2} + n_{N2}$ i.e. $n = 0.339$ ..Total no. of moles

$y_{O2} := \frac{n_{O2}}{n}$ i.e. $y_{O2} = 0.368$ **....Mole fraction of O2....Ans.**

$y_{N2} := \frac{n_{N2}}{n}$ i.e. $y_{N2} = 0.632$ **....Mole fraction of N2....Ans.**

(ii) Avg. Mol. wt.:

$M_m := \frac{m_{O2} + m_{N2}}{n}$ i.e. $M_m = 29.474$ **....Avg. Mol. wt. of mixture....Ans.**

(iii) Specific gas constant:

$R_m := \frac{R_u}{M_m}$ i.e. $R_m = 282.096$ **..J/kg.K .... Ans.**

(iv) Volume and Density:

$V = V_{O2} + V_{N2}$ **...Mixture vol....by Amagat's Law...at same P & T as mixture**

$V_{O2} := m_{O2} \cdot \frac{R_u}{M_{O2}} \cdot \frac{T}{p}$ i.e. $V_{O2} = 0.779$ m3....partial vol. of O2

$V_{N2} := m_{N2} \cdot \frac{R_u}{M_{N2}} \cdot \frac{T}{p}$ i.e. $V_{N2} = 1.336$ m3....partial vol. of N2

Therefore,

$V := V_{O2} + V_{N2}$ ...mixture volume

i.e. $V = 2.116$ **m3...Mixture vol...Ans.**

Density:

$\frac{m_{O2} + m_{N2}}{V} = 4.727$ **kg/m3....Ans.**

==

Prob.9.8. A gaseous mixture consists of 1 kg of O2 and 2 kg of N2 at a pressure of 150 kPa and temp of 20 C. For the mixture, determine the following:(i) specific gas constant (ii) Avg. Mol. wt. (iii) sp. heats Cp and Cv (iv) change in entropy of the mixture if the mixture is heated at constant volume to a temp. of 100 C. Given: Cv of N2 = 0.743 kJ/kg.K and Cv of O2 = 0.65 kJ/kg.K. [VTU – July, 2004]

Mathcad Solution:

Data:

$m_{O2} := 1$ kg $M_{O2} := 32$

$m_{N2} := 2$ kg $M_{N2} := 28$

$p := 150 \cdot 10^3$ Pa $R_u := 8314.4$ J/kg.mole.K

$T_1 := 20 + 273$ K $T_2 := 100 + 273$ K

$Cv_{O2} := 0.65$ kJ/kg.K $Cv_{N2} := 0.743$ kJ/kg.K

Calculations:

(i) Mole fractions:

$n_{O2} := \frac{m_{O2}}{M_{O2}}$ i.e. $n_{O2} = 0.031$ ...No. of moles of O2

$n_{N2} := \frac{m_{N2}}{M_{N2}}$ i.e. $n_{N2} = 0.071$ ...No. of moles of N2

$n := n_{O2} + n_{N2}$ i.e. $n = 0.103$ ..Total no. of moles

$y_{O2} := \frac{n_{O2}}{n}$ i.e. $y_{O2} = 0.304$ ....Mole fraction of O2....Ans.

$y_{N2} := \frac{n_{N2}}{n}$ i.e. $y_{N2} = 0.696$ ....Mole fraction of N2....Ans.

(ii) Avg. Mol. wt.:

$M_m := \frac{m_{O2} + m_{N2}}{n}$ i.e. $M_m = 29.217$ ....Avg. Mol. wt. of mixture....Ans.

(iii) Specific gas constant:

$R_m := \frac{R_u}{M_m}$ i.e. $R_m = 284.57$ J/kg.K....Specific gas constant....Ans.

(iv) Sp. heats of mixture:

$m_m := m_{O2} + m_{N2}$ i.e. $m_m = 3$ kg....mass of mixture

$Cv_{mix} := \frac{(m_{O2} \cdot Cv_{O2} + m_{N2} \cdot Cv_{N2})}{m_m}$ i.e. $Cv_{mix} = 0.712$ **kJ/kg.K....Ans.**

$Cp_{O2} := Cv_{O2} + \frac{R_u \cdot 10^{-3}}{M_{O2}}$ i.e. $Cp_{O2} = 0.91$ kJ/kg.K

$Cp_{N2} := Cv_{N2} + \frac{R_u \cdot 10^{-3}}{M_{N2}}$ i.e. $Cp_{N2} = 1.04$ kJ/kg.K

$Cp_{mix} := \frac{(m_{O2} \cdot Cp_{O2} + m_{N2} \cdot Cp_{N2})}{m_m}$ i.e. $Cp_{mix} = 0.997$ **kJ/kg.K....Ans.**

(v) Change in entropy:

$\Delta S := m_m \cdot \left(Cv_{mix} \cdot \ln\left(\frac{T_2}{T_1}\right)\right)$ ....at const. volume

i.e. $\Delta S = 0.516$ **kJ/K....Ans.**

===

Prob.9.9. Pressure and temperature of a mixture of 1 kg of O2 and 2 kg of N2 are 150 kPa and 20 C respectively. If the mixture is heated at constant pressure to a temp. of 100 C, determine the following: (i) change in enthalpy (ii) change in entropy (iii) change in int. energy.

Given: Cv of N2 = 0.743 kJ/kg.K and Cv of O2 = 0.65 kJ/kg.K. [VTU – Jan, 2005]

Mathcad Solution:

Data:

$m_{O2} := 1$ kg $\qquad M_{O2} := 32$

$m_{N2} := 2$ kg $\qquad M_{N2} := 28$

$p := 150 \cdot 10^{3}$ Pa $\qquad R_u := 8314.4$ J/kg.mole.K

$T_1 := 20 + 273$ K $\qquad T_2 := 100 + 273$ K

$Cv_{O2} := 0.65$ kJ/kg.K $\qquad Cv_{N2} := 0.743$ kJ/kg.K

Calculations:

(i) Sp. heats of mixture:

$m_m := m_{O2} + m_{N2}$ i.e. $m_m = 3$ kg....mass of mixture

$$Cv_{mix} := \frac{\left(m_{O2} \cdot Cv_{O2} + m_{N2} \cdot Cv_{N2}\right)}{m_m}$$ i.e. $Cv_{mix} = 0.712$ **kJ/kg.K....Ans.**

$$Cp_{O2} := Cv_{O2} + \frac{R_u \cdot 10^{-3}}{M_{O2}}$$ i.e. $Cp_{O2} = 0.91$ kJ/kg.K

$$Cp_{N2} := Cv_{N2} + \frac{R_u \cdot 10^{-3}}{M_{N2}}$$ i.e. $Cp_{N2} = 1.04$ kJ/kg.K

$$Cp_{mix} := \frac{\left(m_{O2} \cdot Cp_{O2} + m_{N2} \cdot Cp_{N2}\right)}{m_m}$$ i.e. $Cp_{mix} = 0.997$ **kJ/kg.K....Ans.**

(ii) Change in enthalpy:

$\Delta H := m_m \cdot Cp_{mix} \cdot \left(T_2 - T_1\right)$ i.e. $\Delta H = 239.177$ **kJ....Ans.**

(iii) Change in entropy:

$$\Delta S := m_m \cdot \left(Cp_{mix} \cdot \ln\left(\frac{T_2}{T_1}\right)\right)$$ ....at const. pressure

i.e. $\Delta S = 0.722$ **kJ/K....Ans.**

(iv) Change in internal energy:

$$\Delta U := m_m \cdot Cv_{mix} \cdot (T_2 - T_1)$$

i.e. $\Delta U = 170.88$ **kJ....Ans.**

==

Prob.9.10. Neon, with Mol. wt :M=20.183, and critical properties: Tc = 44.5 K, pc = 2.73 MPa, Vc= 0.0416 m3/kg.mol. Reading from compressibility chart for a reduced pressure pr = 2 and reduced temp Tr = 1.3, the compressibility factor is Z=0.7. Find corresponding sp. vol., pressure, temp and reduced

Data:

$M := 20.183$ $T_c := 44.5$ K $p_c := 2.73 \cdot 10^3$ kPa $v_c := 0.0416$ m3/kmol

$p_r := 2$ $T_r := 1.3$ $Z := 0.7$ $R_u := 8314$ J/kmol.K

Calculations:

$p := p_c \cdot p_r$ i.e. $p = 5.46 \times 10^3$ **kPa....Ans.**

$T := T_c \cdot T_r$ i.e. $T = 57.85$ **K....Ans.**

Now, $Z = \frac{v_{actual}}{v_{ideal}}$ and,

$$v_{ideal} := \frac{\frac{R_u}{M} \cdot T}{p \cdot 10^3}$$ i.e. $v_{ideal} = 4.365 \times 10^{-3}$ **m3/kg**

and, $v_{actual} := Z \cdot v_{ideal}$ i.e. $v_{actual} = 3.055 \times 10^{-3}$ **m3/kg...Ans.**

Reduced volume:

$v_r = \frac{v_{actual}}{v_c}$ i.e. $v_r := \frac{v_{actual} \cdot M}{v_c}$ ..volumes in m3/kg.mol

i.e. $v_r = 1.482$ **...Ans.**

==

Prob.9.11. Find increase in entropy when 2 kg of O2 at 60 C mixes with 6 kg of N2 at the same temp. The initial pressure of each constituent is 103 kPa and is the same as that of the mixture. [VTU – Jan. 2005]

Mathcad Solution:

Data:

$m_{O2} := 2$ kg $\quad M_{O2} := 32$

$m_{N2} := 6$ kg $\quad M_{N2} := 28$

$p := 103 \cdot 10^{3}$ Pa $\quad R_u := 8314.4$ J/kg.mole.K

$T_1 := 60 + 273$ K

Calculations:

(i) Mole fractions:

$n_{O2} := \frac{m_{O2}}{M_{O2}}$ i.e. $n_{O2} = 0.063$ ...No. of moles of O2

$n_{N2} := \frac{m_{N2}}{M_{N2}}$ i.e. $n_{N2} = 0.214$ ...No. of moles of N2

$n := n_{O2} + n_{N2}$ i.e. $n = 0.277$ ..Total no. of moles

$y_{O2} := \frac{n_{O2}}{n}$ i.e. $y_{O2} = 0.226$ **....Mole fraction of O2....Ans.**

$y_{N2} := \frac{n_{N2}}{n}$ i.e. $y_{N2} = 0.774$ **....Mole fraction of N2....Ans.**

(ii) Change in entropy:

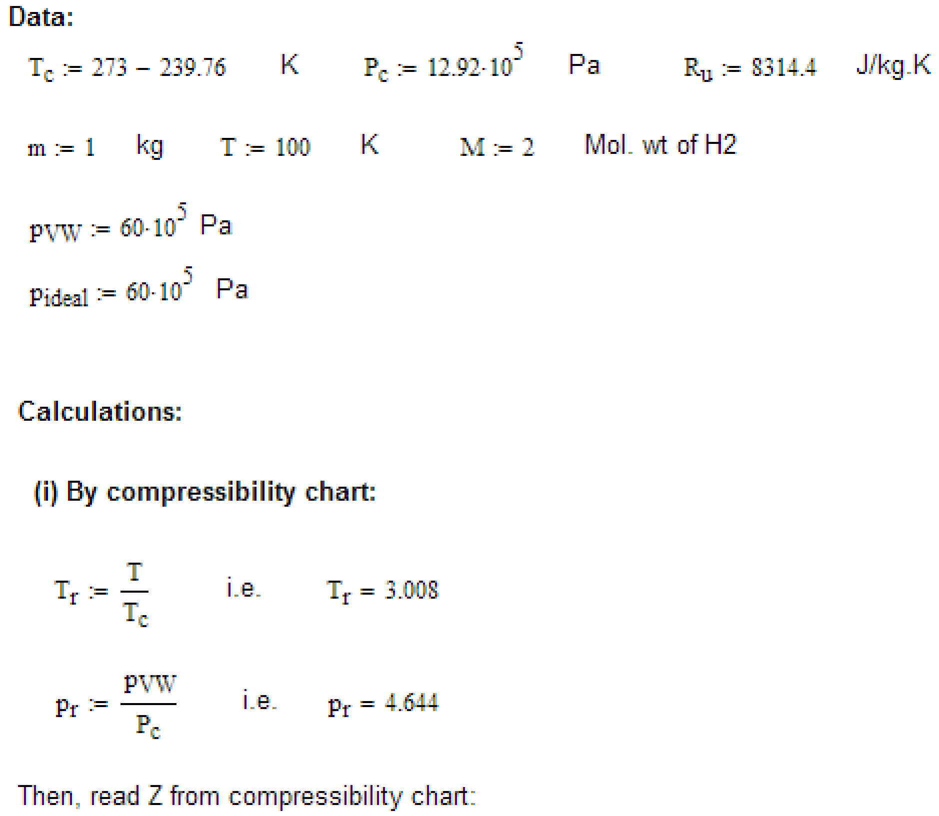
$$\Delta S := R_u \cdot \left(n_{O2} \cdot \ln\left(\frac{1}{y_{O2}}\right) + n_{N2} \cdot \ln\left(\frac{1}{y_{N2}}\right)\right)$$

i.e. $\Delta S = 1.229 \times 10^{3}$ **J/kg.mole.K......Ans.**

==

Prob.9.12. Determine the sp. vol. of H2 gas at 100 K, when its pressure is 60 bar, (i) by using compressibility chart (ii) by Van der Waals eqn. Values of critical properties Pc and Tc for H2 are given, and also the values of a and b in Van der Waals eqn. [VTU – Jan. 2004]

Mathcad Solution:



Data:

$T_c := 273 - 239.76$ K $\quad P_c := 12.92 \cdot 10^5$ Pa $\quad R_u := 8314.4$ J/kg.K

$m := 1$ kg $\quad T := 100$ K $\quad M := 2$ Mol. wt of H2

$p_{VW} := 60 \cdot 10^5$ Pa

$p_{ideal} := 60 \cdot 10^5$ Pa

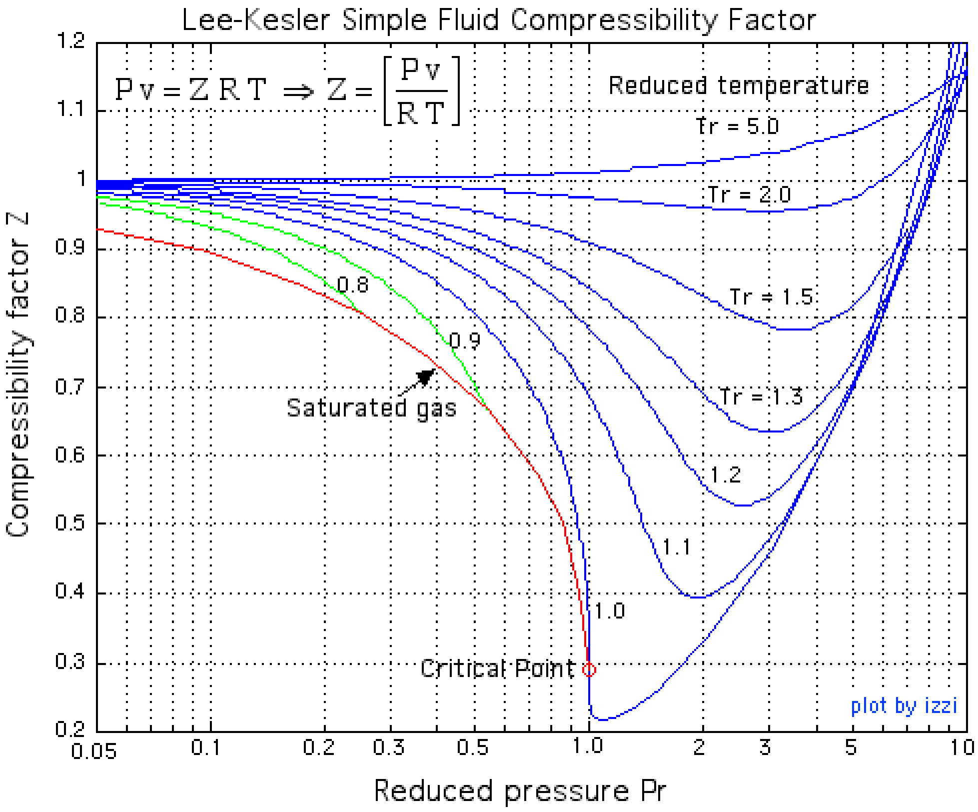
Calculations:

(i) By compressibility chart:

$T_r := \frac{T}{T_c}$ i.e. $T_r = 3.008$

$p_r := \frac{p_{VW}}{P_c}$ i.e. $p_r = 4.644$

Then, read Z from compressibility chart:


Lee-Kesler Simple Fluid Compressibility Factor
$Pv = ZRT \Rightarrow Z = \left[\frac{Pv}{RT}\right]$
Reduced temperature
Tr = 5.0
Tr = 2.0
Tr = 1.5
Tr = 1.3
1.2
1.1
1.0
0.8
0.9
Saturated gas
Critical Point
plot by izzi
Compressibility factor Z
Reduced pressure Pr
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.05
0.1
0.2
0.3
0.5
1.0
2
3
5
10

We get: $Z := 0.99$

For Ideal gas: $Z = \frac{p \cdot v}{R \cdot T}$ .....Then, v can be calculated.

Then: $v_{ideal} := \frac{Z \cdot \frac{R_u}{M} \cdot T}{p_{ideal}}$

i.e. $v_{ideal} = 0.069$ **m^3....sp.vol. according to Ideal gas Law ... Ans.**

(ii) By Van der Waals eqn.:

For H2: $a := 25105$ Nm^4/(kg.mol)^2

$b := 0.0262$ m^3/kg.mol

$pVW := 60 \cdot 10^5$ Pa

Use the Solve block of Mathcad to find vbar:

$vbar := 10$ .....guess value

Given

$$pVW = \frac{R_u \cdot T}{vbar - b} - \frac{a}{vbar^2}$$

$Find(vbar) = 0.141$

i.e. $vbar := 0.141$

Now,

$$vbar = \frac{V}{\left(\frac{m}{M}\right)}$$

Therefore, $V := vbar \cdot \frac{m}{M}$

i.e. $V = 0.071$ **m3.sp. vol. according to Van der Waals eqn.......Ans.**

===

Prob.9.13. Determine the compressibility factor for Oxygen at (i) 100 bar and -75 C, and (ii) 5 bar and 35 C.

Mathcad Solution:

Data:

For O2, we have the critical properties:

$T_c := 154.88$ K $\qquad P_c := 50.6$ bar $\qquad R_u := 8314.4$ J/kg.K

Calculations:

Case 1: P = 100 bar, T = -75 C:

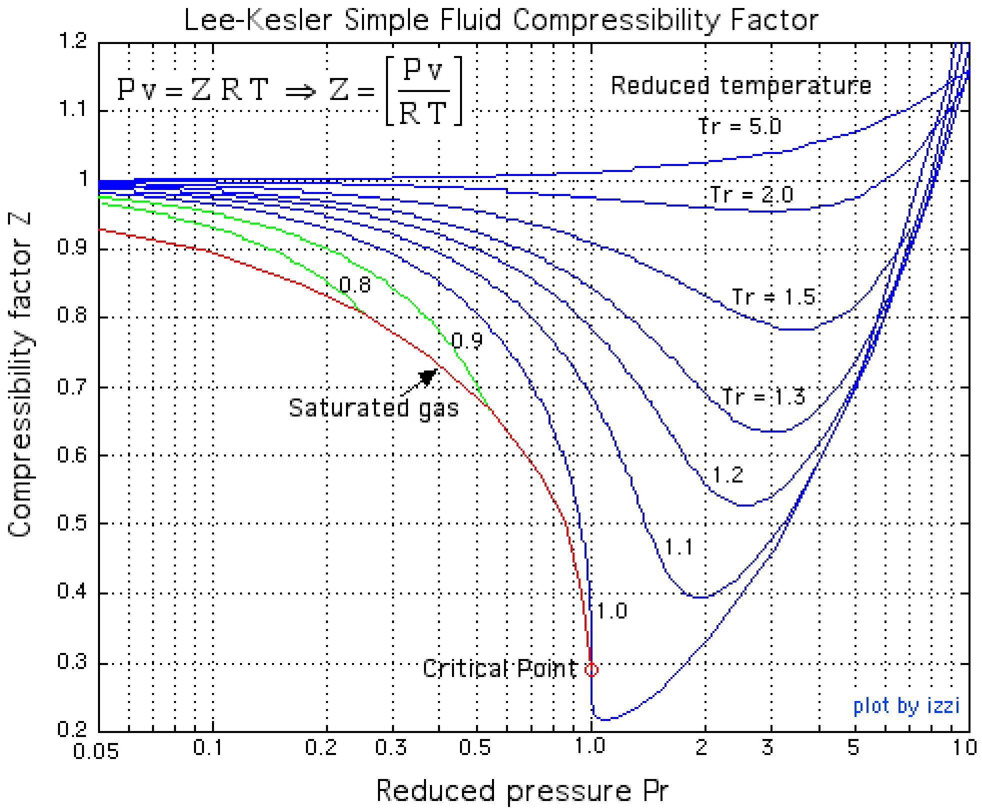
For this case, reduced pressure and reduced temp:

$T := -75 + 273$ K $\qquad P := 100$ bar

$p_r := \frac{P}{P_c}$ i.e. $p_r = 1.976$

$T_r := \frac{T}{T_c}$ i.e. $T_r = 1.278$

Now, from compressibility chart, read the value of Z, the compressibility factor:


Lee-Kesler Simple Fluid Compressibility Factor
$Pv = ZRT \Rightarrow Z = \left[\frac{Pv}{RT}\right]$
Reduced temperature
Tr = 5.0
Tr = 2.0
Tr = 1.5
Tr = 1.3
1.2
1.1
1.0
0.8
0.9
Saturated gas
Critical Point
plot by izzi
Compressibility factor Z
Reduced pressure Pr
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.05
0.1
0.2
0.3
0.5
1.0
2
3
5
10

We get: $Z = 0.7$ **...compressibility factor ... Ans.**

Case 2: P = 5 bar, T = 35 C

For this case, reduced pressure and reduced temp:

For this case, reduced pressure and reduced temp:

$T := 35 + 273$ K $\quad P := 5$ bar

$p_r := \frac{P}{P_c}$ i.e. $p_r = 0.099$

$T_r := \frac{T}{T_c}$ i.e. $T_r = 1.989$

Now, from compressibility chart, read the value of Z, the compressibility factor:

We get: $Z = 1$ ..approx. **...compressibility factor ... Ans.**

i.e. at low pressures and high temps, real gas eqn approaches ideal gas eqn.

===

Prob.9.14. One kg.mol of CO2 undergoes a reversible, non-flow isothermal compression from 0.2 m^3/kg to 0.05 m^5/kg, and the initial temp is 40 C. If the gas obeys Van der Waals eqn, determine the work done and the final pressure.

Mathcad Solution:

Data:

Critical properties for CO2:

$T_c := 304.2$ K $\quad P_c := 73.8 \cdot 10^5$ Pa $\quad R_u := 8314.4$ J/kg.mol.K

$T := 40 + 273$ K $\quad M := 44$ ...Mol. wt. of CO2 sp. volumes:

$v_1 := 0.2 \cdot M$ i.e. $v_1 = 8.8$ m^3/kg.mol

$v_2 := 0.05 \cdot M$ i.e. $v_2 = 2.2$ m^3/kg.mol

Van der Waals constants for CO2:

$a := 364700$ Pa.(m^3/kmol)^2

$b := 0.0428$ m^3/kmol

Van der Waals eqn:

$$\left(p + \frac{a}{v^2}\right) \cdot (v - b) = R_u \cdot T$$

i.e. $p(v) := \dfrac{R_u \cdot T}{v - b} - \dfrac{a}{v^2}$ ...define pressure as a function of sp. volume, v.

(i) Therefore, Work done, W:

$$W := \int_{v_1}^{v_2} p(v)\, dv$$

i.e. $W = -3.522 \times 10^6$ **J/kg.mol ...... Ans.**

Note: the negative sign indicates that work is done on the CO2.

Note also the ease with which this integration is done in Mathcad.

(ii) Final pressure, P2:

$P2 := p(v_2)$ ...using the function for pressure, written above

i.e. $P2 = 1.131 \times 10^6$ **Pa = 11.31 bar .... Ans.**

===

9.12 Problems solved with EES:

“**Prob. 9.15.** An ideal gas cycle consisting of 3 processes uses Argon (M = 40) as working substance. Process 1-2 is a reversible adiabatic process from 0.014 m^3, 700 kPa and 280 C to 0.056 m^3. Process 2-3 is a reversible isothermal process. Process 3-1 is an isobaric process. Sketch the cycle on P-v and T-s diagrams, and find: (i) the work transfer in process 1-2, (ii) work transfer in process 2-3, (iii) net work output from the cycle (assume gamma = 1.67), and (iv) change in enthalpy for each process. [VTU – July 2004]:”

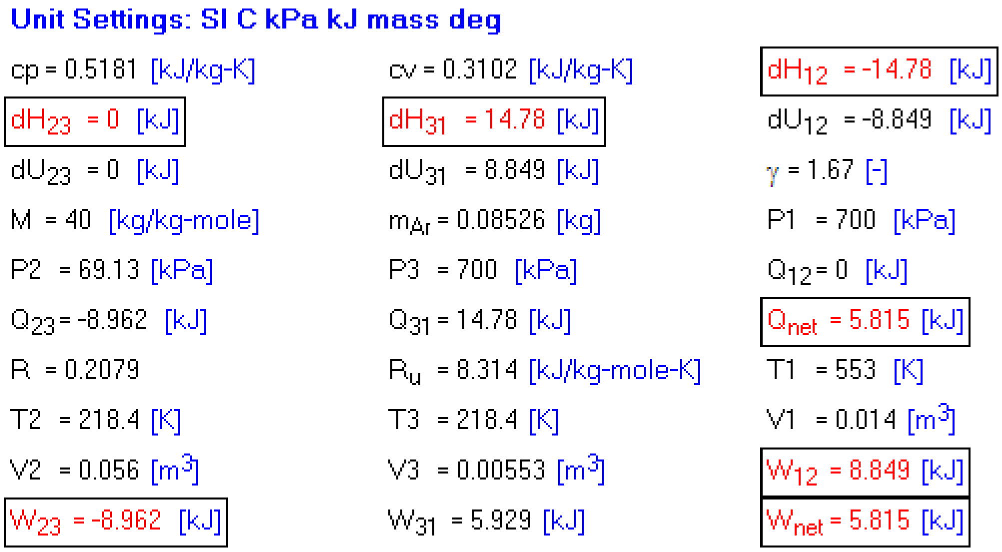
EES Solution:

“Data:”

M = 40 “... Mol. wt. of Argon”
R_u = 8.314 “kJ/kg.mol -K”
R = R_u / M “kJ/kg.K .... Gas const. for Argon”
V1 = 0.014"m^3”
P1 = 700 “kPa”
T1 = 280 + 273 “K”
V2 = 0.056 “m^3”
T2 = T3 “...Process 2-3 is Isothermal”

```
Q_12 = 0 “...Process 1-2 is adiabatic”
P3 = P1 “Process 3-1 is isobaric”
gamma = 1.67

“Calculations:”

cp / cv = gamma “...by definition gamma = cp / cv”
cp – cv = R “Gas constant”
m_Ar = (P1 * V1) / (R * T1) “kg ... mass of Argon”

“Process 1-2:”

P1 * V1^gamma = P2 * V2^gamma “...finds P2”
P1 * V1 / T1 = P2 * V2 / T2 “...finds T2”
W_12 = (P1 * V1 – P2 * V2) / (gamma -1) “kJ”
Q_12 = dU_12 + W_12 “....finds dU_12, change in int. energy during Process 1-2”

“Process 2-3”

W_23 = m_Ar * R * T2 * ln (V3 / V2) “kJ”
dU_23 = 0 “...since Isothermal”
Q_23 = W_23 + dU_23 “kJ”
P2 * V2 = P3 * V3 “...finds V3”

“Process 3-1:”

W_31 = P3 * (V1 – V3) “kJ ... work in process 3-1”
Q_31 = dU_31 + W_31"kJ .... heat transfer in process 3-1”
dU_31 = m_Ar * cv * (T1 – T3) “kJ...change in int. energy during 3-1”
W_net = W_12 + W_23 + W_31"kJ.... net work output”

“Check:”

Q_net = Q_12 + Q_23 + Q_31"...for a closed cycle 1-2-3, this should be equal to W_net”

“Changes in enthalpy for each process:”

dH_12 = m_Ar * cp * (T2 – T1) “kJ”
dH_23 = 0 “kJ .... since T2 = T3”
dH_31 = m_Ar * cp * (T1 – T3) “kJ”
```

Results:



Unit Settings: SI C kPa kJ mass deg

cp = 0.5181 [kJ/kg-K]

cv = 0.3102 [kJ/kg-K]

dH_{12} = -14.78 [kJ]

dH_{23} = 0 [kJ]

dH_{31} = 14.78 [kJ]

dU_{12} = -8.849 [kJ]

dU_{23} = 0 [kJ]

dU_{31} = 8.849 [kJ]

γ = 1.67 [-]

M = 40 [kg/kg-mole]

m_{Ar} = 0.08526 [kg]

P1 = 700 [kPa]

P2 = 69.13 [kPa]

P3 = 700 [kPa]

Q_{12} = 0 [kJ]

Q_{23} = -8.962 [kJ]

Q_{31} = 14.78 [kJ]

Q_{net} = 5.815 [kJ]

R = 0.2079

R_u = 8.314 [kJ/kg-mole-K]

T1 = 553 [K]

T2 = 218.4 [K]

T3 = 218.4 [K]

V1 = 0.014 [m^3]

V2 = 0.056 [m^3]

V3 = 0.00553 [m^3]

W_{12} = 8.849 [kJ]

W_{23} = -8.962 [kJ]

W_{31} = 5.929 [kJ]

W_{net} = 5.815 [kJ]

Thus:

Work transfer in process 1-2 = W_12 = 8.849 kJ … Ans.

Work transfer in process 2-3 = W_23 = – 8.962 kJ … negative sign showing that work is done *on* the gas …Ans.

Net work output from the cycle = W_net = 5.815 kJ …. Ans.

Check: W_net = Q_net = 5.815 kJ ….O.K.

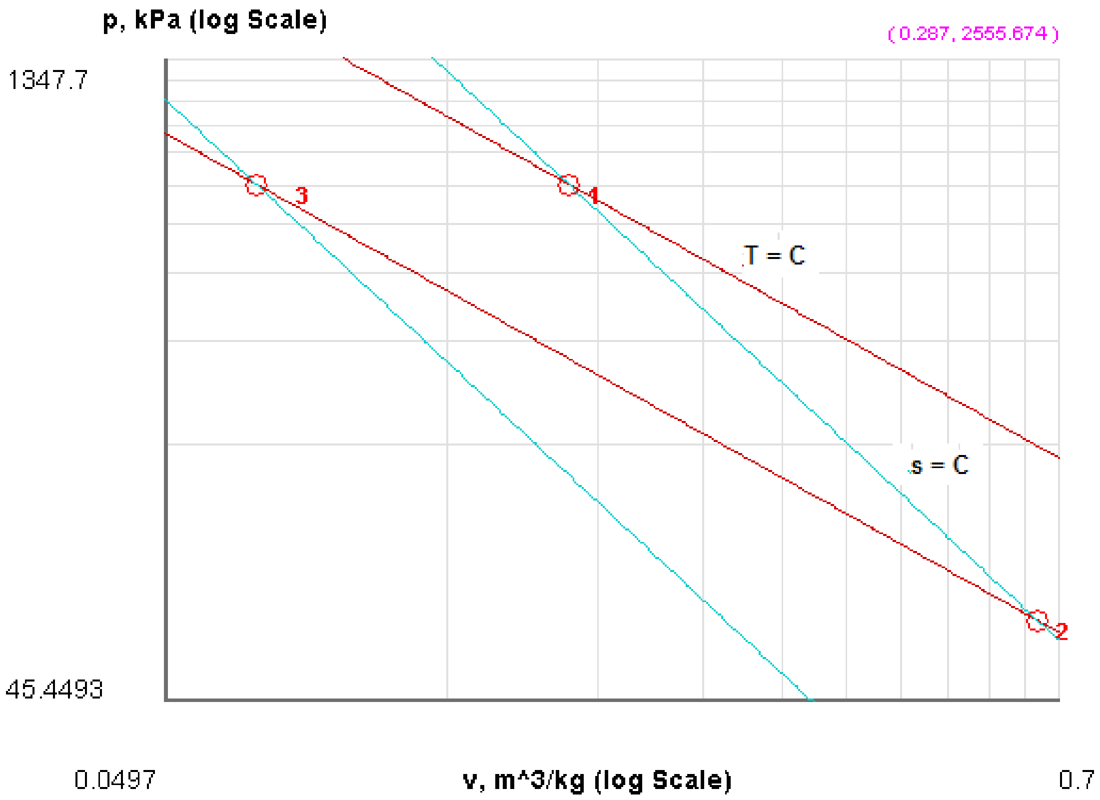
Changes in enthalpy:

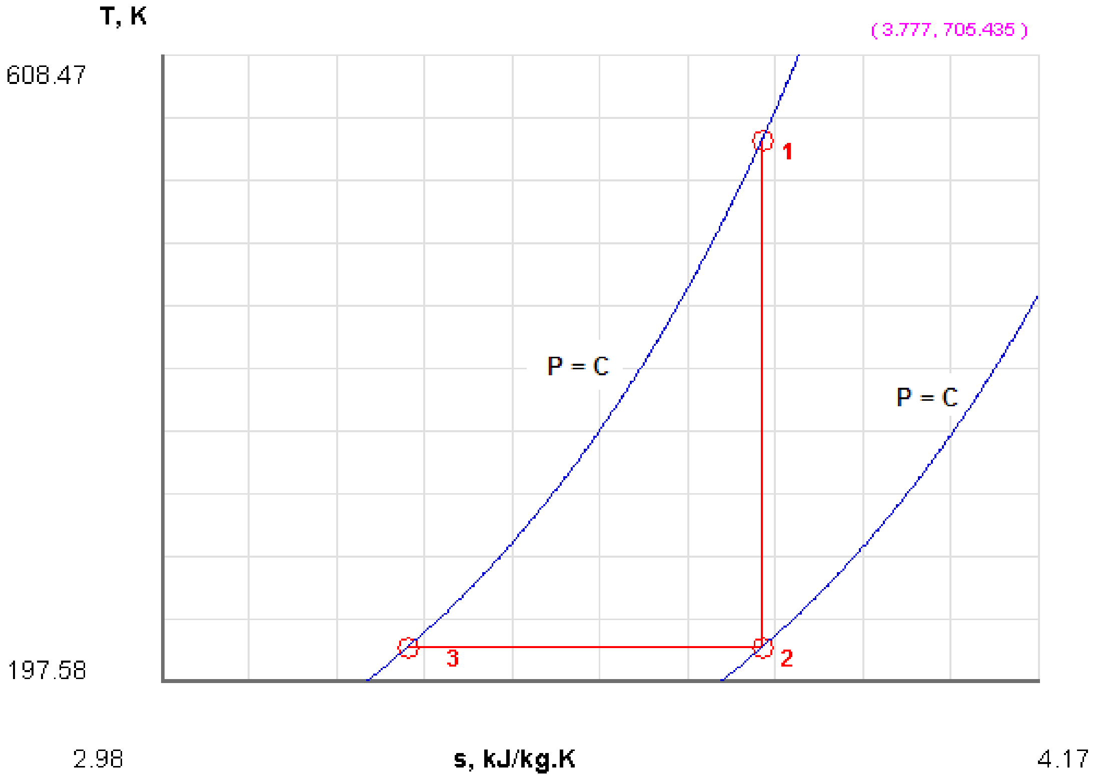
Process 1-2: dH_12 = -14.78 kJ … Ans.

Process 2-3: dH_23 = 0 kJ … Ans.

Process 3-1: dH_31 = 14.78 kJ … Ans.

Plot the cycle on P-v and T-s diagrams (from TEST):





==

“**Prob.9.16.** Determine the pressure exerted by CO2 in a container of 1.5 m3 capacity when it contains 4 kg at 30 C (i) using Ideal gas eqn. (ii) using Van der Waal’s eqn, and (iii) using Beattie-Bridgeman eqn.”

EES Solution:

Following are the three Equations of State:

Ideal Gas eqn:

$$p_{ideal} = mass \cdot R \cdot \frac{T}{V} \quad Pa$$

Van der Waal’s eqn:

$$p_{VW} = \frac{R_u \cdot T}{\bar{v} - b} - \frac{a}{\bar{v}^2} \quad Pa$$

Beattie Bridgeman eqn:

$$p_{BB} = \frac{R_u \cdot T \cdot (1 - \varepsilon)}{\bar{v}^2} \cdot (\bar{v} + BBB) - \frac{AAA}{\bar{v}^2} \quad Pa$$

Constants in the above three eqns. are given below:

```
"Data:"

R_u = 8314.4"J/kg.mol.K"

M = 44"Mol. wt."

V = 1.5"m3"

mass = 4.0"kg"

T = 303 "K"

a = 3.647E05 "Nm^4/kgmol^2....const. in Van der Waal's  eqn."

b = 0.0428"m3/kgmol....const. in Van der Waal's  eqn."

epsilon = cc / (v_bar * T^3)"..factor in Beattie Bridgeman eqn."

AAA = A_0 * (1-aa / v_bar)".factor A in Beattie Bridgeman eqn."

BBB = B_0 * (1- bb / v_bar)"..factor B. in Beattie Bridgeman eqn."

A_0 = 507.2836"..const. in Beattie Bridgeman eqn."

aa = 0.07132"..const. in Beattie Bridgeman eqn."

B_0 = 0.10476"..const. in Beattie Bridgeman eqn."

bb = 0.07235"..const. in Beattie Bridgeman eqn."

cc = 66E04"..const. in Beattie Bridgeman eqn."

"---------------------------"

"(i) Ideal gas eqn.:"

R = R_u / M"...specific gas constant"

p_ideal = mass * R * T/V "Pa"
```

“(ii) Van der Waal’s eqn.:”

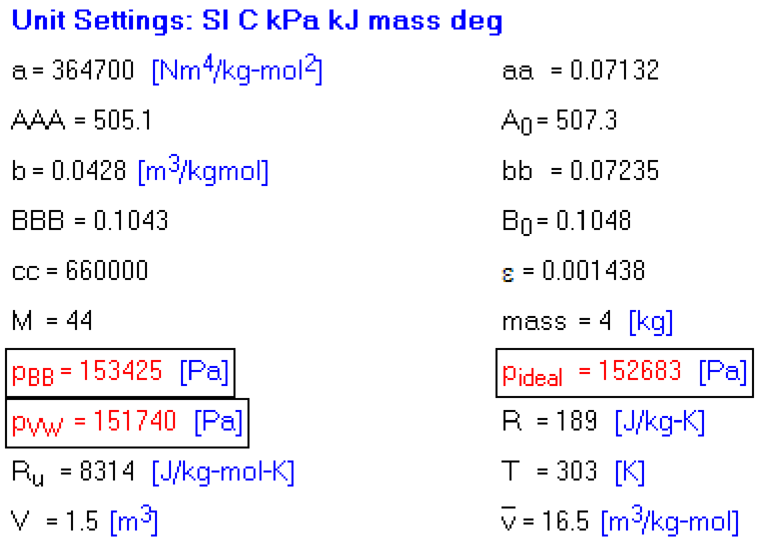
v_bar = V / (mass/M) “m3/kgmole....molar volume”

p_VW = ((R_u * T) / (v_bar – b)) – (a / v_bar^2) “Pa”

“(iii) Beattie Bridgeman eqn.:”

p_BB = ((R_u * T * (1 – epsilon)) / (v_bar)^2) * (v_bar + BBB) – AAA / (v_bar)^2 “Pa”

Results:



```
Unit Settings: SI C kPa kJ mass deg
a = 364700  [Nm4/kg-mol2]          aa  = 0.07132
AAA = 505.1                        A0 = 507.3
b = 0.0428 [m3/kgmol]              bb  = 0.07235
BBB = 0.1043                       B0 = 0.1048
cc = 660000                        ε = 0.001438
M  = 44                            mass  = 4  [kg]
pBB = 153425  [Pa]                 pideal  = 152683  [Pa]
pVW  = 151740  [Pa]                R  = 189  [J/kg-K]
Ru  = 8314  [J/kg-mol-K]           T  = 303  [K]
V  = 1.5 [m3]                      v̄ = 16.5 [m3/kg-mol]
```

Thus:

Pressure as per Ideal Gas eqn. = p_ideal = 152683 Pa …. Ans.

Pressure as per Van der Waals eqn. = p_VW = 151740 Pa …. Ans.

Pressure as per Beattie Bridgeman eqn. = p_BB = 153425 Pa …. Ans.

===

"**Prob.9.17.** A cylinder 0.01 m^3 volume is filled with 0.727 kg of n-octane (C8H18) at 427.85 K. Assuming that n-octane obeys the Van der Waals eqn of state, calculate the pressure of the gas in the cylinder. Take constants a and b as 3.789 Pa (m^3/mol)^2 and 2.37 E-04 m^3/mol respectively. [VTU – Dec. 2008–Jan. 2009]"

EES Solution:

"Data:"

R_u = 8314.4"J/kg.mol.K"

M = 114.232"Mol. wt."

V = 0.01"m3"

mass = 0.727"kg.."

T = 427.85 "K"

a = 3.789E05 "Nm^4/kgmol^2....const. in Van der Waal's eqn."

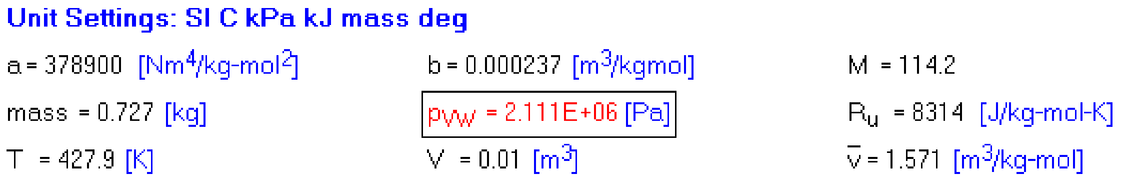
b = 2.37E-04"m3/kgmol....const. in Van der Waal's eqn."

"Van der Waal's eqn.:"

v_bar = V / (mass/M) "m3/kgmol....molar volume"

p_VW = ((R_u * T) / (v_bar – b)) – (a / v_bar^2) "Pa"

Results:



Unit Settings: SI C kPa kJ mass deg

a = 378900 [Nm^4/kg-mol^2]	b = 0.000237 [m^3/kgmol]	M = 114.2
mass = 0.727 [kg]	$\boxed{p_{VW} = 2.111E+06\ [Pa]}$	R_u = 8314 [J/kg-mol-K]
T = 427.9 [K]	V = 0.01 [m^3]	$\bar{v}$ = 1.571 [m^3/kg-mol]

Thus:

Pressure = p_VW = 21.11E05 Pa = 21.11 bar …. Ans.

===

"**Prob.9.18.** If the above gas undergoes an isothermal compression to a volume of 0.005 m^3, find out the final pressure, and change in entropy."

EES Solution:

"Data:"

R_u = 8314.4"J/kg.mol.K"

M = 114.232"Mol. wt."

R = R_u / M "J/kg.K..Gas const. for n-octane"

V1 = 0.01"m3 ... initial volume"

mass = 0.727"kg.."

T = 427.85 “K”

a = 3.789E05 “Nm^4/kgmol^2....const. in Van der Waal’s eqn.”

b = 2.37E-04“m3/kgmol....const. in Van der Waal’s eqn.”

“Initial pressure:”

v1_bar = V1 / (mass/M) “m3/kgmole....molar volume”

p1_VW = ((R_u * T) / (v1_bar – b)) – (a / v1_bar^2) “Pa”

“Final pressure:”

V2 = 0.005 “m^3”

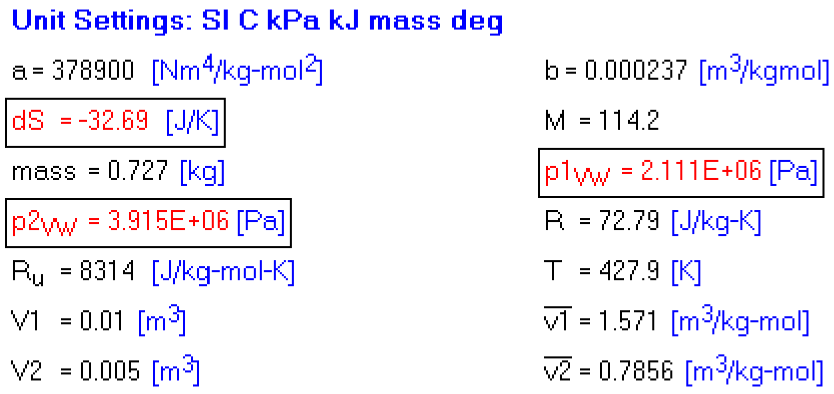
v2_bar = V2 / (mass/M) “m3/kgmole....molar volume”

p2_VW = ((R_u * T) / (v2_bar – b)) – (a / v2_bar^2) “Pa .... final pressure”

“Change in entropy: ... at constant T:”

dS = – mass * R * ln (p2_VW / p1_VW) “J/K”

Results:



Unit Settings: SI C kPa kJ mass deg

a = 378900 [$Nm^4/kg\text{-}mol^2$]
b = 0.000237 [$m^3/kgmol$]
dS = -32.69 [J/K]
M = 114.2
mass = 0.727 [kg]
$p1_{VW}$ = 2.111E+06 [Pa]
$p2_{VW}$ = 3.915E+06 [Pa]
R = 72.79 [J/kg-K]
R_u = 8314 [J/kg-mol-K]
T = 427.9 [K]
V1 = 0.01 [m^3]
$\overline{v1}$ = 1.571 [$m^3/kg\text{-}mol$]
V2 = 0.005 [m^3]
$\overline{v2}$ = 0.7856 [$m^3/kg\text{-}mol$]

Thus:

Final pressure = p2_VW = 3.915E06 Pa = 39.15 bar … Ans.

Change in entropy – dS = -32.69 J/K …entropy decreases in compression… Ans.

==

"**Prob.9.19.** If the temp of the gas in Prob.9.17 changes to 700 K, volume remaining constant at 0.01 m^3, find out the final pressure, and changes in enthalpy and entropy.

Given: sp. heat at constant pressure for n-octane is given by:

cp = C_0 + C_1 * theta + C_2 * theta^2 + C_3 * theta^3 , kJ/kg.K where

theta = T(Kelvin)/1000. Values of C_0, C_1, C_2 and C_3 are given below. (Ref:2)"

EES Solution:

"Data:"

R_u = 8314.4"J/kg.mol.K"

M = 114.232"Mol. wt."

R = R_u / M "J/kg.K..Gas const. for n-octane"

V1 = 0.01"m3 ... initial volume"

```
mass = 0.727"kg.."

T1 = 427.85 "K"

T2 = 700 "K"

a = 3.789E05 "Nm^4/kgmol^2....const. in Van der Waal's eqn."

b = 2.37E-04"m3/kgmol....const. in Van der Waal's  eqn."

"To find cp of n-octane:"

C_0 = -0.053
C_1 = 6.75
C_2 = -3.67
C_3 = 0.775

T_avg = (T1 + T2)/2 "…find the average temp."

theta = T_avg/1000 "...at an average temp"

cp = C_0 + C_1 * theta + C_2 * theta^2 + C_3 * theta^3 "kJ/kg.K … sp. heat ct const. pressure"

cp * 10^3 – cv = R "... finds cv in J/kg.K"

"Initial pressure:"

v1_bar = V1 / (mass/M) "m3/kgmole....molar volume"

p1_VW = ((R_u * T1) / (v1_bar – b)) – (a / v1_bar^2) "Pa"

"Final pressure:"

p2_VW = ((R_u * T2) / (v1_bar – b)) – (a / v1_bar^2) "Pa .... final pressure"

"Change in internal energy:"

dU = mass * cv * (T2 – T1) "J"
```

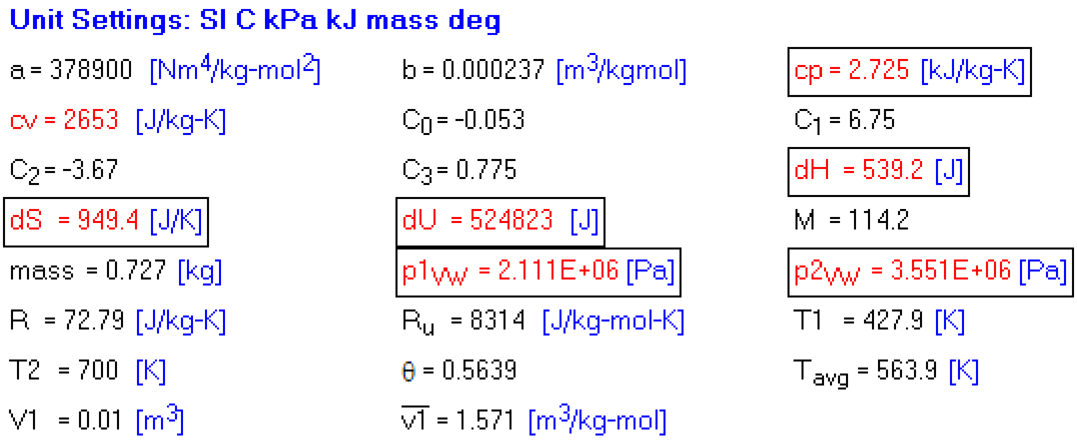
"Change in enthalpy:"

dH = mass * cp * (T2 – T1) "J"

"Change in entropy: ... at constant volume:"

dS = mass * cv * ln (T2/T1) "J/K"

Results:



```
Unit Settings: SI C kPa kJ mass deg

a = 378900  [Nm^4/kg-mol^2]     b = 0.000237 [m^3/kgmol]        cp = 2.725 [kJ/kg-K]
cv = 2653  [J/kg-K]             C0 = -0.053                     C1 = 6.75
C2 = -3.67                      C3 = 0.775                      dH  = 539.2 [J]
dS  = 949.4 [J/K]               dU  = 524823  [J]               M  = 114.2
mass  = 0.727  [kg]             p1VW  = 2.111E+06 [Pa]          p2VW  = 3.551E+06 [Pa]
R  = 72.79  [J/kg-K]            Ru  = 8314  [J/kg-mol-K]        T1  = 427.9  [K]
T2  = 700  [K]                  θ = 0.5639                      Tavg = 563.9  [K]
V1  = 0.01  [m^3]               v1 = 1.571  [m^3/kg-mol]
```

Thus:

Final pressure = p2_VW = 3.551E06 Pa = 35.51 bar … Ans.

cp = 2.725 kJ/kg.K … sp. heat at const. pressure.

cv = 2.653 kJ/kg.K … sp. heat at const. vol.

Change in internal energy = dU = 524.823 kJ … Ans.

Change in enthalpy = dH = 539.2 J …. Ans.

Change in entropy = dS = 949.4 J/K … Ans.

===

"**Prob.9.20.** A vessel of capacity 3 m^3 contains 1 kgmole of N2 at 90 C.

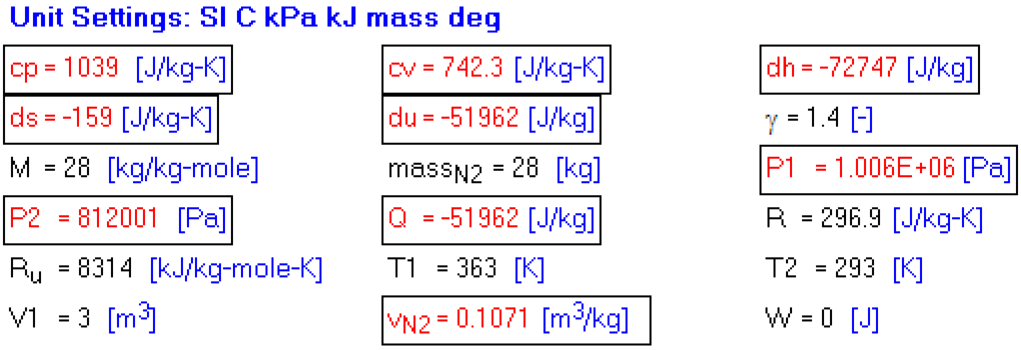
Calculate: (i) the pressure and sp. volume of the gas (ii) If the ratio of sp. heats is 1.4, obtain cp and cv (iii) Subsequently, the gas cools to atm. temp of 20 C; evaluate the final pressure of gas (iv) Evaluate the increase in sp. internal energy, the increase in sp. enthalpy, increase in sp. entropy and heat transfer. [VTU – Dec. 2009–Jan. 2010]:"

EES Solution:

```
"Data:"

M = 28 "... Mol. wt. of N2"

R_u = 8314 "J/kg.mol -K"

R = R_u / M "J/kg.K .... Gas const. for N2"

V1 = 3 "m^3"

T1 = 90 + 273 "K"

T2 = 20 + 273 "K"

gamma = 1.4 "...ratio of sp. heats"

mass_N2 = 28 "kg..mass of N2..since one kmol = M kg"
```

```
"Calculations:"

cp / cv = gamma "...by definition gamma = cp / cv"

cp – cv = R "...finds cp and cv "

mass_N2 = (P1 * V1) / (R * T1) "finds Pressure P1 of N2, in Pa"

"Therefore: sp. vol. of N2"

v_N2 = V1/mass_N2 "m^3/kg ... sp. vol. of N2"

"Pressure of gas when temp is T2 (=20 C):"

P1/ T1 = P2 / T2 "by Ideal gas Law at const. vol....finds P2"

"Increase in specific internal energy: i.e. for 1 kg"

du = cv * (T2 – T1) "J"

"Increase in sp. enthalpy:"

dh = cp * (T2 – T1) "J"

"Increase in sp. entropy: ... at const. vol."

ds= cv * ln (T2/T1) "J/K"

"Heat transfer:"

Q = dU + W ". J/kg ...by I Law"

W = 0 "...since it is a const. vol. process"
```

Results:



```
Unit Settings: SI C kPa kJ mass deg
cp = 1039  [J/kg-K]          cv = 742.3 [J/kg-K]         dh = -72747 [J/kg]
ds = -159 [J/kg-K]           du = -51962 [J/kg]          γ = 1.4 [-]
M  = 28  [kg/kg-mole]        massN2 = 28  [kg]           P1  = 1.006E+06 [Pa]
P2  = 812001  [Pa]           Q  = -51962 [J/kg]          R  = 296.9 [J/kg-K]
Ru  = 8314  [kJ/kg-mole-K]   T1  = 363  [K]              T2  = 293  [K]
V1  = 3  [m3]                vN2 = 0.1071  [m3/kg]       W = 0  [J]
```

Thus:

Pressure of gas = P1 = 10.06 bar , sp. vol. = v_N2 = 0.1071 m^3/kg …. Ans.

cp = 1039 J/kg.K and cv = 742.3 J/kg.K …. Ans.

Pressure of gas when temp is 20 C = P2 = 8.12 bar … Ans.

Change in sp. int. energy = du = -51962 J/kg … decrease since –ve,…. Ans.

Change in sp. enthalpy = dh = -72747 J/kg … decrease since –ve,…. Ans.

Change in sp. entropy = ds = -159 J/kg.K … decrease since –ve,…. Ans.

Heat transfer = Q = du = -51962 J/kg … decrease since –ve,…. Ans.

===

"**Prob. 9.21.** Find the gas constant and apparent molar mass of a mixture of 2 kg O2 and 3 kg of N2, given that universal gas constant is 8314.3 J/kgmol.K, molar masses of O2 and N2 are respectively 32 and 28. [VTU – July 2006]:"

EES Solution:

"Data:"

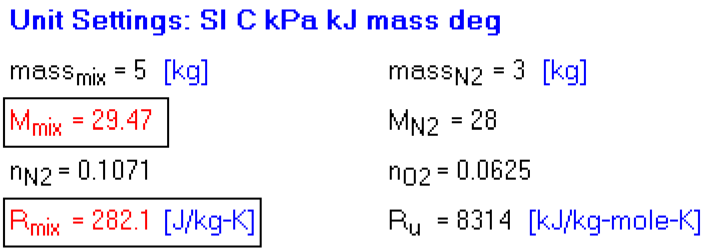
M_N2 = 28 "... Mol. wt. of N2"

M_O2 = 32 "... Mol. wt. of O2"

mass_N2 = 3 "kg...mass of N2"

```
mass_O2 = 2 "kg ... mass of O2"

R_u = 8314.3 "J/kg.mol -K"

"Calculations:"
mass_mix = mass_N2 + mass_O2

n_N2 = mass_N2 / M_N2 "...no. of moles of N2"

n_O2 = mass_O2 / M_O2 "...no. of moles of O2"

n_tot = n_N2 + n_O2 "...total no. of moles in mixture"

"Avg. Mol. wt."

M_mix = mass_mix / n_tot

"Sp. gas const. of mixture:"

R_mix = R_u / M_mix "J/kg.K .."
```

Results:



Unit Settings: SI C kPa kJ mass deg

$mass_{mix}$ = 5 [kg]
$mass_{N2}$ = 3 [kg]
$mass_{O2}$ = 2 [kg]
M_{mix} = 29.47
M_{N2} = 28
M_{O2} = 32
n_{N2} = 0.1071
n_{O2} = 0.0625
n_{tot} = 0.1696
R_{mix} = 282.1 [J/kg-K]
R_u = 8314 [kJ/kg-mole-K]

Thus:

Mol. wt. of mixture = M_mix = 29.47 …. Ans.

Gas const. of mixture = R_mix = 282.1 J/kg.K …. Ans.

==

"**Prob. 9.22.** A gaseous mixture consists of 1 kg of Oxygen and 2 kg of Nitrogen initially at a pressure of 150 kPa and temp of 20 C. It is heated at constant pressure until its temp reaches 100 C. Determine: (i) change in enthalpy, (ii) change in entropy and (iii) change in internal energy. Given: Cp of N2 = 1.04 kJ/kg.K and Cp of O2 = 0.922 kJ/kg.K [VTU – Jan.–Feb. 2005]:"

EES Solution:

"Data:"

M_N2 = 28 "... Mol. wt. of N2"

M_O2 = 32 "... Mol. wt. of O2"

mass_N2 = 2 "kg...mass of N2"

mass_O2 = 1 "kg ... mass of O2"

R_u = 8314.3 "J/kg.mol -K"

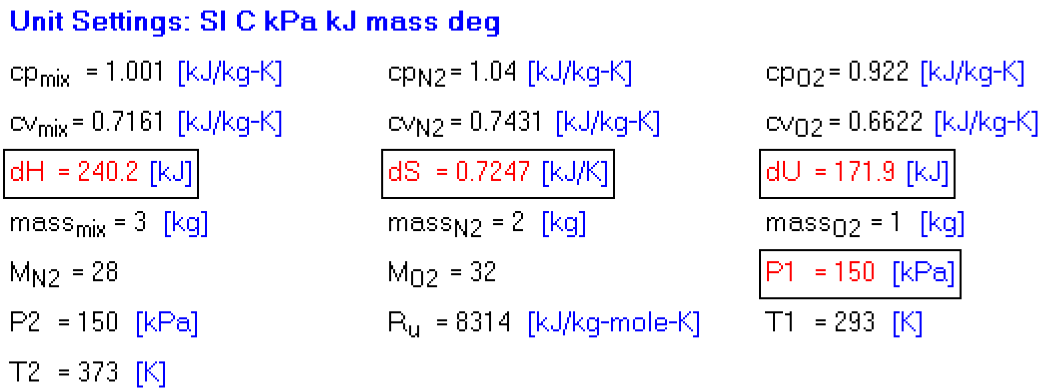
cp_O2 = 0.922 "kJ/kg.K"

cp_N2 = 1.04 "kJ/kg.K"

P1 = 150 "kPa ... initial pressure"

```
T1 = 20 + 273 “K ... initial temp.”

T2 = 100 + 273 “K ... final temp.”

P2 = P1 “...by data”

“Calculations:”
mass_mix = mass_N2 + mass_O2 “kg .... mass of mixture”

“Sp. heats of mixture:”

cp_mix = (mass_N2 * cp_N2 + mass_O2 * cp_O2) / (mass_N2 + mass_O2) “kJ/kg.K”

cv_N2 = cp_N2 – R_u * 10^(-3)/ M_N2 “kJ/kg.K”

cv_O2 = cp_O2 – R_u * 10^(-3)/ M_O2 “kJ/kg.K”

“Therefore: cv of mixture:”

cv_mix = (mass_N2 * cv_N2 + mass_O2 * cv_O2) / (mass_N2 + mass_O2) “kJ/kg.K”

“Change in enthalpy:”

dH = mass_mix * cp_mix * (T2 – T1) “kJ”

“Change in Int. energy:”

dU = mass_mix * cv_mix * (T2 – T1) “kJ”

“Change in entropy:”

dS = mass_mix * cp_mix * ln (T2 / T1) “kJ/K .... for constant pressure process”
```

Results:



```
Unit Settings: SI C kPa kJ mass deg

cpmix  = 1.001  [kJ/kg-K]      cpN2 = 1.04   [kJ/kg-K]          cpO2 = 0.922  [kJ/kg-K]
cvmix = 0.7161  [kJ/kg-K]      cvN2 = 0.7431  [kJ/kg-K]         cvO2 = 0.6622  [kJ/kg-K]
dH  = 240.2  [kJ]              dS  = 0.7247  [kJ/K]             dU  = 171.9  [kJ]
massmix = 3  [kg]              massN2 = 2  [kg]                 massO2 = 1  [kg]
MN2  = 28                      MO2  = 32                        P1  = 150  [kPa]
P2  = 150  [kPa]               Ru  = 8314  [kJ/kg-mole-K]       T1  = 293  [K]
T2  = 373  [K]
```

Thus:

Change in enthalpy = dH = 240.2 kJ … Ans.

Change in entropy = dS = 0.7247 kJ/K …. Ans.

Change in Int. energy = dU = 171.9 kJ … Ans.

==

“**Prob.9.23.** 0.1 m^3 of H2, initially at 1.2 MPa and 200 C, undergoes a reversible isothermal expansion to 0.1 MPa. Determine: (i) the work done during the process (ii) heat transferred, and (iii) the change in entropy of gas. Take R = 8.3143 kJ/kg.K, cp = 14.4 kJ/kg.K and Mol. wt = 2.016. [VTU – Dec. 2010]”

EES Solution:

```
“Data:”

M_H2 = 2.016 “... Mol. wt. of H2”

R_u = 8.3143 “J/kg.mol -K .... universal gas const.”

cp_H2 = 14.4 “kJ/kg.K .... sp. heat of H2 at const. pressure”

P1 = 1200 “kPa ... initial pressure”

V1 = 0.1 “m^3 ... initial volume”

T1 = 200 + 273 “K ... initial temp.”

T2 = T1 “K ... final temp .... since isothermal expansion.”

P2 = 100 “kPa...final pressure”

“Calculations:”

R_H2 = R_u / M_H2 “kJ/kg.K .... gas const. for H2”

mass_H2 = (P1 * V1) / (R_H2 * T1) “kg .... mass of H2”

“To find final volume, V2:”

P1* V1 = P2 * V2 “ at const. temp .... finds V2”

“Work done, W:”

W = R_H2 * T1 * ln (V2 / V1) “kJ ... work done”

“Change in Int. energy:”

dU = 0 “kJ .... since temp is constant”
```

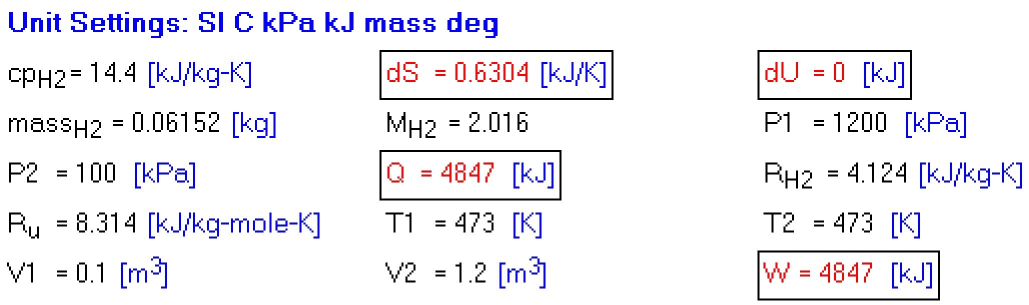
"Therefore: heat transferred:"

Q = dU + W "kJ .... by I Law for the process"

"Change in entropy:"

dS = mass_H2 * R_H2 * ln (V2/V1) "kJ/K .... for isothermal process"

Results:



Unit Settings: SI C kPa kJ mass deg

```
cpH2 = 14.4 [kJ/kg-K]          dS = 0.6304 [kJ/K]      dU = 0 [kJ]
massH2 = 0.06152 [kg]          MH2 = 2.016             P1 = 1200 [kPa]
P2 = 100 [kPa]                 Q = 4847 [kJ]           RH2 = 4.124 [kJ/kg-K]
Ru = 8.314 [kJ/kg-mole-K]      T1 = 473 [K]            T2 = 473 [K]
V1 = 0.1 [m3]                  V2 = 1.2 [m3]           W = 4847 [kJ]
```

Thus:

Work done = W = 4847 kJ …work done by the gas, so +ve… Ans.

Heat transferred = Q = 4847 kJ …heat supplied, since +ve …. Ans.

Change in entropy = dS = 0.6304 kJ/K …. Ans.

==

"**Prob.9.24.** Determine the pressure of water vapor at 350 C and 0.03524 m^3/kg, using (i) ideal gas eqn (ii) generalized compressibility chart. Take for water vapor: R = 0.4615 kJ/kg.K. [VTU – Dec. 2010]"

EES Solution:

"Data:"

T1 = 350 + 273 "K"

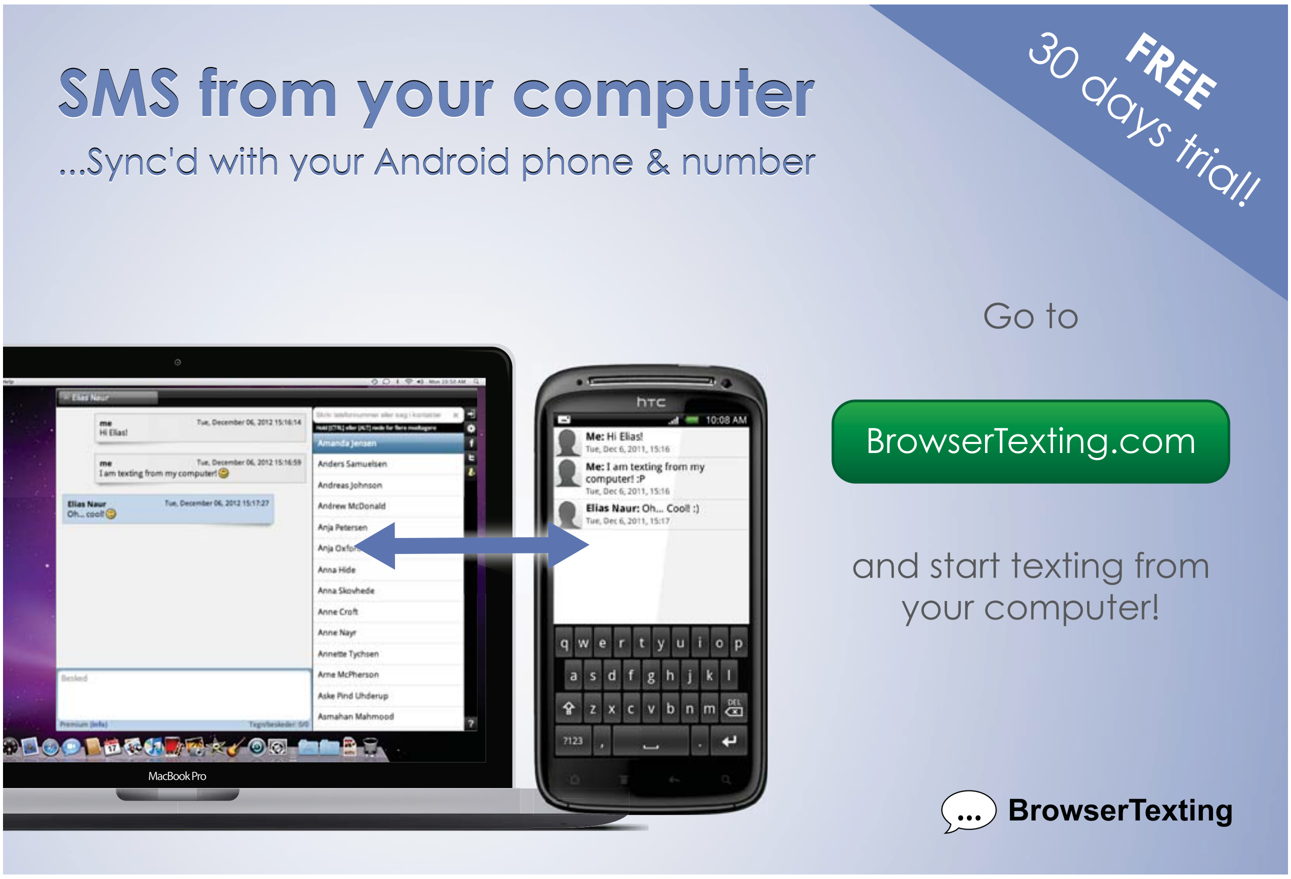
V1 = 0.03524 "m^3"

mass = 1 "kg"

R_H2O = 0.4615 "kJ/kg.K"

M_H2O = 18 "..Mol. wt. of H2O"

```
“(i) Using Ideal gas eqn.:”

P1 *V1 = mass * R_H2O * T1 “... finds P1 in kPa”

“(ii) Using compressibility chart:”

“We have for Water vapor:”

P_c = 22090 “kPa,”

T_c = 647.3 “K”

“Now:”

“P = (Z* R *T / v). and

p_r = p / p_c = Z * R * T / (p_c * v) = A * Z.”

A = R_H2O * T1 / ( P_c * V1)

“We get: A = 0.3693
```

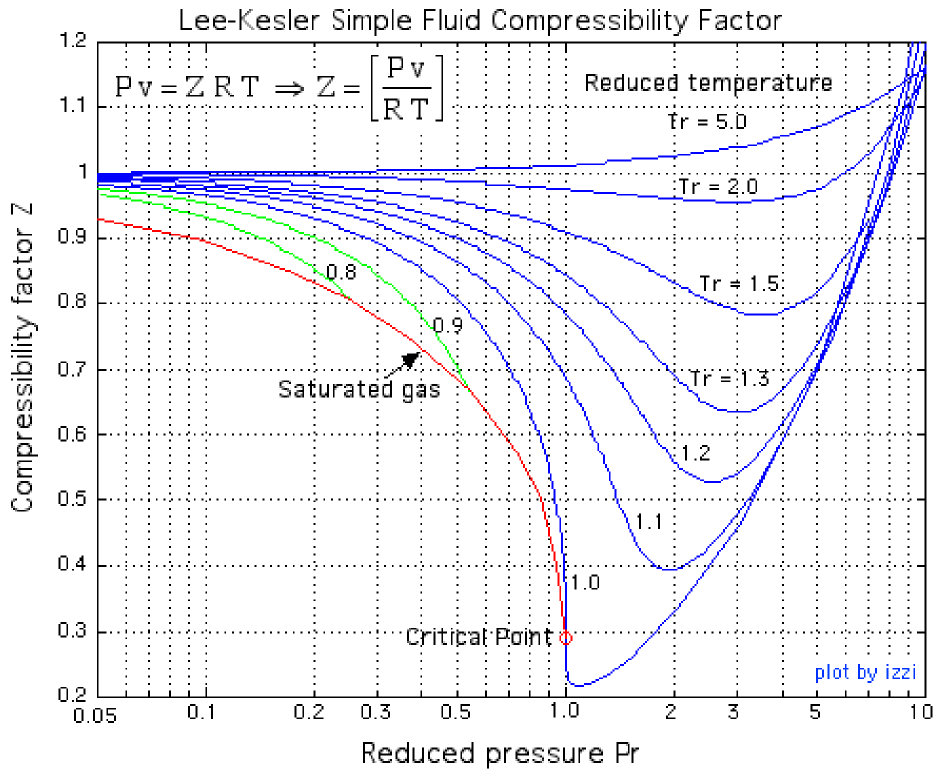


i.e. P_r = 0.3693 * Z"

T_r = T1 / T_c "...reduced temp."

"We get T_r = 0.9625"

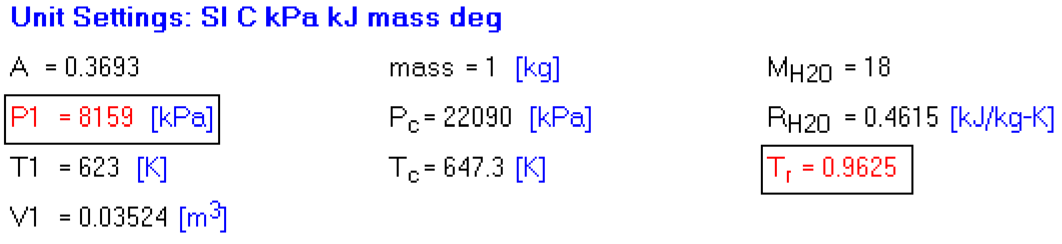
"Now, go to the Generalized compressibility chart and by *trial and error*, find Pr and Z on Tr = 0.9625 line:



We get: Pr = 0.34, Z = 0.84"

"i.e. P = 0.34 * P_c = 7510 kPa."

Results:


Unit Settings: SI C kPa kJ mass deg

A = 0.3693
P1 = 8159 [kPa]
T1 = 623 [K]
V1 = 0.03524 [m^3]

mass = 1 [kg]
P_c = 22090 [kPa]
T_c = 647.3 [K]

M_{H2O} = 18
R_{H2O} = 0.4615 [kJ/kg-K]
T_r = 0.9625

Thus:

Pressure according to Ideal gas eqn = P1 = 8158 kPa …. Ans.

Pressure from generalized compressibility chart, = 7510 kPa … Ans.

==

"**Prob.9.25.** A vessel of 1.5 m^3 volume containing oxygen at 8 bar and 50 C is connected to another vessel of 3.5 m^3 volume containing CO at 1 bar and 25 C. A connecting valve is opened and the gases mix adiabatically. Calculate: (i) final temp and pressure of the mixture, and (ii) change in entropy of the system. Take for O2: Cv = 21.07 kJ/mole.K, for CO, Cv = 20.86 kJ/mole.K"

EES Solution:

"Data:"

P_O2 = 8E05 "Pa"

P_CO = 1E05 "Pa"

V_O2 = 1.5 "m^3"

R_u = 8314"J/kg.mole.K"

T_O2 = 50+273 "K"

T_CO = 25+273 "K"

V_CO = 3.5 "m^3"

Cv_O2 = 21.07"kJ/mole.K"

CV_CO = 20.86 "kJ/mole.K"

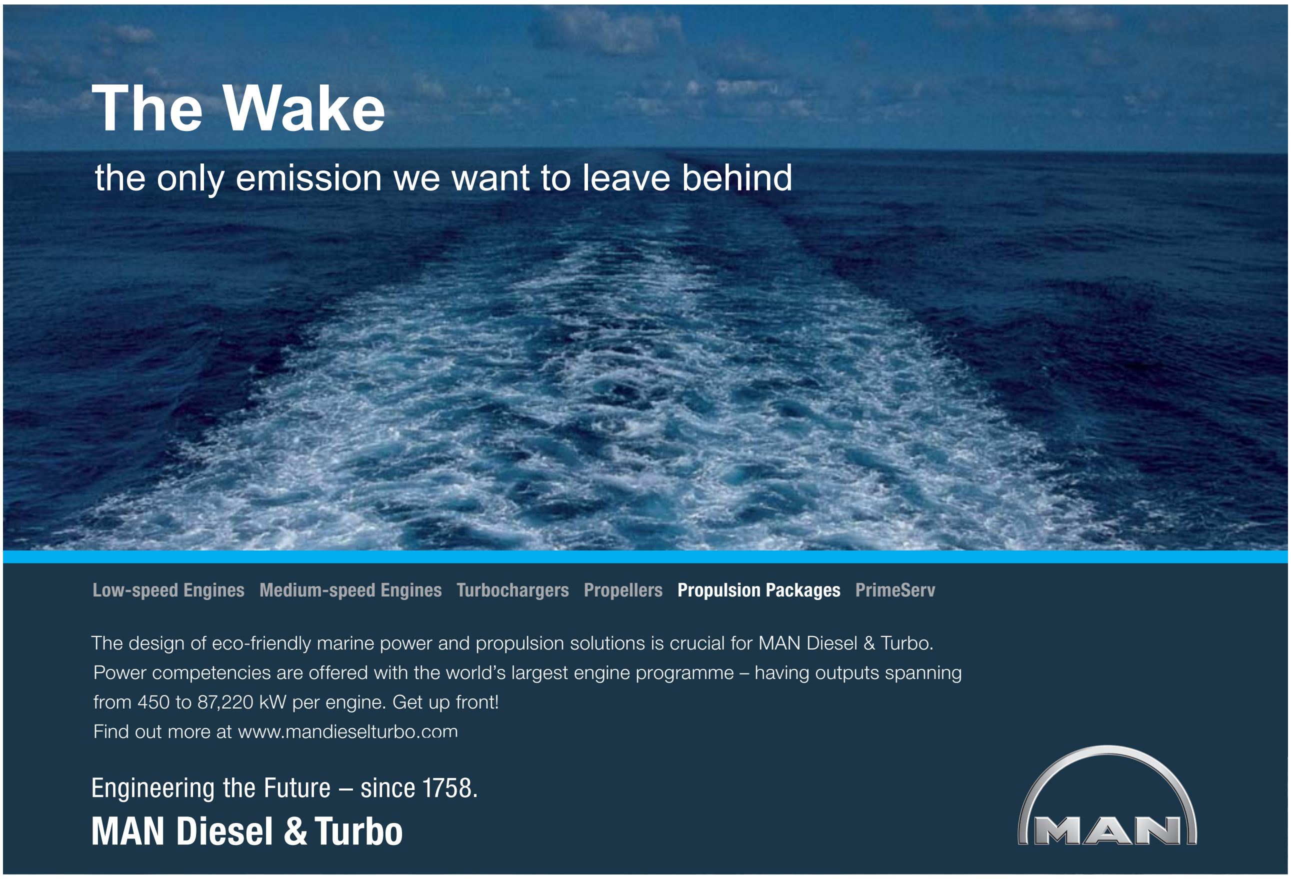
"Calculations:"

"No. of moles:"

n_O2 = (P_O2 * V_O2) / (R_u * T_O2) "...no. of moles of O2"

n_CO = (P_CO * V_CO) / (R_u * T_CO) "...no. of moles of CO"

```
"Final temp and pressure:"

U1 = n_O2 * Cv_O2 * T_O2 + n_CO * Cv_CO * T_CO "kJ ...initial int. energy"

U2 = T_f * ( n_O2 * Cv_O2 + n_CO * Cv_CO) "kJ ... final int. energy, where T_f is the final mixture temp"

"But, U1 = U2 for this case:"

U1 = U2 "...determines mixture temp T_f"

"Then, final, mixture pressure, P_f:"

P_f = ((n_O2 + n_CO) * R_u * T_f ) / (V_O2 + V_CO) "Pa...final, mixture pressure"

V_f = V_O2 + V_CO "...final vol. of mixture"

"Changes in entropy:"

"For O2:"

dS_O2 = n_O2 * Cv_O2 * ln(T_f / T_O2) + n_O2 * R_u*10^(-3) * ln(V_f / V_O2)"kJ/K"
```



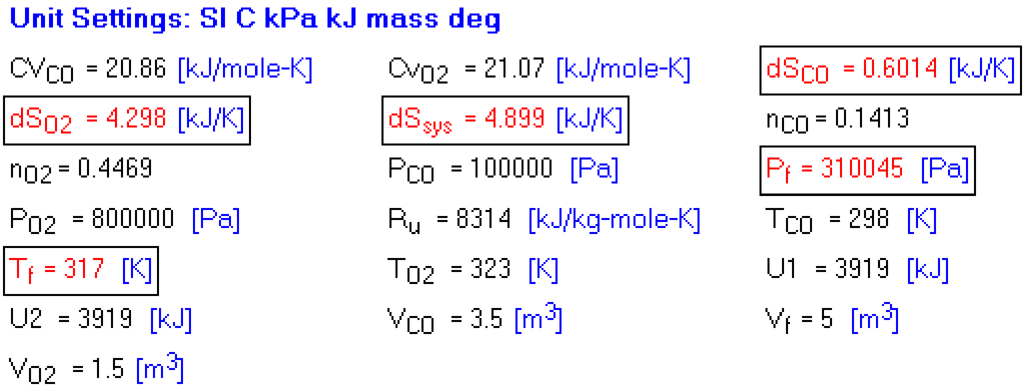
"For CO:"

dS_CO = n_CO * Cv_CO * ln(T_f / T_CO) + n_CO * R_u *10^(-3)* ln(V_f / V_CO)"kJ/K"

"Total change in entropy for the system:"

dS_sys = dS_O2+dS_CO "kJ/K"

Results:



Unit Settings: SI C kPa kJ mass deg

CV_{CO} = 20.86 [kJ/mole-K]
Cv_{O2} = 21.07 [kJ/mole-K]
dS_{CO} = 0.6014 [kJ/K]
dS_{O2} = 4.298 [kJ/K]
dS_{sys} = 4.899 [kJ/K]
n_{CO} = 0.1413
n_{O2} = 0.4469
P_{CO} = 100000 [Pa]
P_f = 310045 [Pa]
P_{O2} = 800000 [Pa]
R_u = 8314 [kJ/kg-mole-K]
T_{CO} = 298 [K]
T_f = 317 [K]
T_{O2} = 323 [K]
U1 = 3919 [kJ]
U2 = 3919 [kJ]
V_{CO} = 3.5 [m^3]
V_f = 5 [m^3]
V_{O2} = 1.5 [m^3]

Thus:

Final temp of mixture = T_f = 317 K … Ans.

Final pressure of mixture = P_f = 310045 Pa = 3.1 bar … Ans.

Entropy change for O2 = dS_O2 = 4.298 kJ/K … Ans.

Entropy change for CO = dS_CO = 0.6014 kJ/K … Ans.

Entropy change for the system = dS_sys = 4.899 kJ/K .. Ans.

===

"**Prob.9.26.** 4 kg of CO2 at 40 C and 1.5 bar are mixed with 8 kg of N2 at 150 C and 1 bar to form a mixture at a final pressure of 0.8 bar. The process occurs adiabatically in a steady flow apparatus. Calculate: (i) the final temp of mixture, and (ii) change in entropy.

Take: cp for CO2 = 0.85 kJ/kg.K and cp for N2 = 1.04 kJ/kg.K”

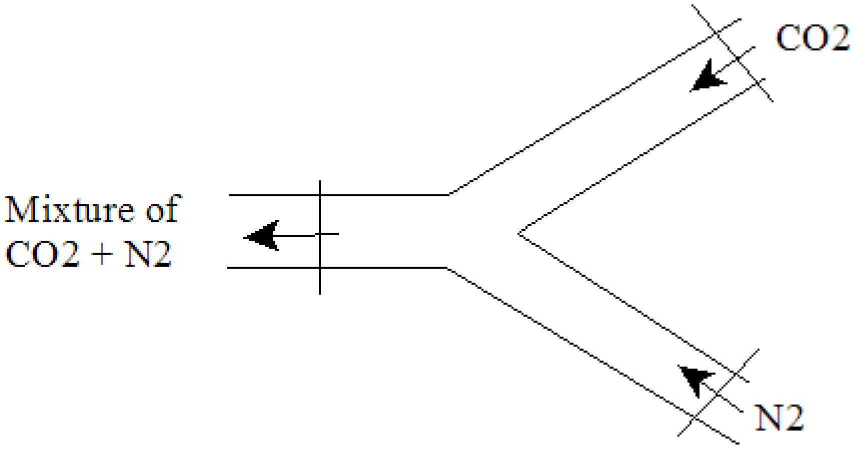


Fig.Prob.9.26

EES Solution:

“Data:”

P1_CO2 = 1.5E05 “Pa”

m1_CO2 = 4 “kg”

T1_CO2 = 40 + 273 “K”

P1_N2= 1E05 “Pa”

m1_N2 = 8 “kg”

T1_N2 = 150 + 273 “K”

P_f = 0.8E05“Pa”

R_u = 8314“J/kg.mole.K”

cp_CO2 = 0.85“kJ/kg.K”

cp_N2 = 1.04 “kJ/kg.K”

M_CO2 = 44 “...Mol. wt. of CO2”

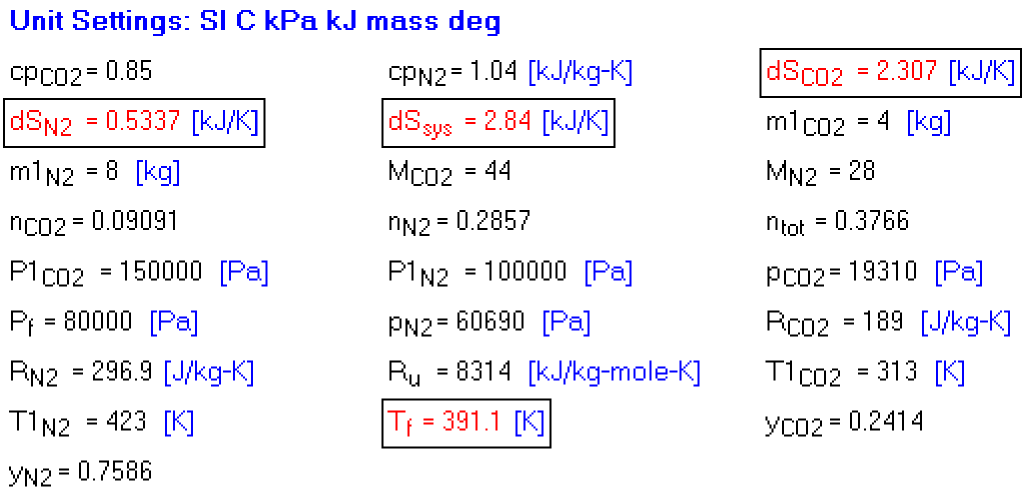
M_N2 = 28 “...Mol.wt. of N2”

```
“Calculations:”

“No. of moles of CO2 and N2:”

n_CO2 = m1_CO2 / M_CO2 “..no. of moles of CO2”

n_N2 = m1_N2 / M_N2 “.no. of moles of N2”

n_tot = n_CO2 + n_N2 “...total no. of moles”

y_CO2 = n_CO2 / n_tot “...mole fraction of CO2”

y_N2 = n_N2 / n_tot “...mole fraction of N2”

p_CO2 = y_CO2 * P_f “..Pa ... partial pressure of CO2 in final mixture”

p_N2 = y_N2 * P_f “..Pa ... partial pressure of N2 in final mixture”

R_CO2 = R_u / M_CO2 “J/kg.K ... Gas const. for CO2”

R_N2 = R_u / M_N2 “J/kg.K ... Gas const. for N2”

“Final temp is calculated by applying the steady flow energy eqn.:”

“Here Q = 0 and W = 0.

Therefore:”

m1_CO2 * cp_CO2 * T1_CO2 + m1_N2 * cp_N2 * T1_N2 = m1_CO2 * cp_CO2 * T_f + m1_N2 * cp_N2 * T_f “...finds final temp, T_f”

“Changes in entropy:”

“For CO2:”

dS_CO2 = m1_CO2 * (cp_CO2 * ln (T_f / T1_CO2)) – m1_CO2 * R_CO2 *10^(-3) * ln(p_CO2 / P1_CO2)"kJ/K”

“For N2:”

dS_N2 = m1_N2 * (cp_N2 * ln (T_f / T1_N2)) – m1_N2 * R_N2 * 10^(-3) * ln(p_N2 / P1_N2)“kJ/K”
```

"For the system of (CO2 + N2):"

dS_sys = dS_CO2 + dS_N2 "kJ/K"

Results:



Unit Settings: SI C kPa kJ mass deg

$cp_{CO2} = 0.85$ $\quad$ $cp_{N2} = 1.04$ [kJ/kg-K] $\quad$ $\boxed{dS_{CO2} = 2.307 \text{ [kJ/K]}}$

$\boxed{dS_{N2} = 0.5337 \text{ [kJ/K]}}$ $\quad$ $\boxed{dS_{sys} = 2.84 \text{ [kJ/K]}}$ $\quad$ $m1_{CO2} = 4$ [kg]

$m1_{N2} = 8$ [kg] $\quad$ $M_{CO2} = 44$ $\quad$ $M_{N2} = 28$

$n_{CO2} = 0.09091$ $\quad$ $n_{N2} = 0.2857$ $\quad$ $n_{tot} = 0.3766$

$P1_{CO2} = 150000$ [Pa] $\quad$ $P1_{N2} = 100000$ [Pa] $\quad$ $p_{CO2} = 19310$ [Pa]

$P_f = 80000$ [Pa] $\quad$ $p_{N2} = 60690$ [Pa] $\quad$ $R_{CO2} = 189$ [J/kg-K]

$R_{N2} = 296.9$ [J/kg-K] $\quad$ $R_u = 8314$ [kJ/kg-mole-K] $\quad$ $T1_{CO2} = 313$ [K]

$T1_{N2} = 423$ [K] $\quad$ $\boxed{T_f = 391.1 \text{ [K]}}$ $\quad$ $y_{CO2} = 0.2414$

$y_{N2} = 0.7586$

Thus:

Final temp of mixture = T_f = 391.1 K … Ans.

Entropy change for CO2 = dS_CO2 = 2.307 kJ/K … Ans.

Entropy change for N2 = dS_N2 = 0.5337 kJ/K … Ans.

Entropy change for the system = dS_sys = 2.84 kJ/K .. Ans.

==

9.13 Problems solved with TEST:

Prob.9.27. An ideal gas cycle consisting of 3 processes uses Argon (M = 40) as working substance. Process 1-2 is a reversible adiabatic process from 0.014 m^3, 700 kPa and 280 C to 0.056 m^3. Process 2-3 is a reversible isothermal process. Process 3-1 is an isobaric process. Sketch the cycle on P-v and T-s diagrams, and find: (i) the work transfer in process 1-2, (ii) work transfer in process 2-3, (iii) net work output from the cycle (assume gamma = 1.67), and (iv) change in enthalpy for each process. [VTU – July 2004]

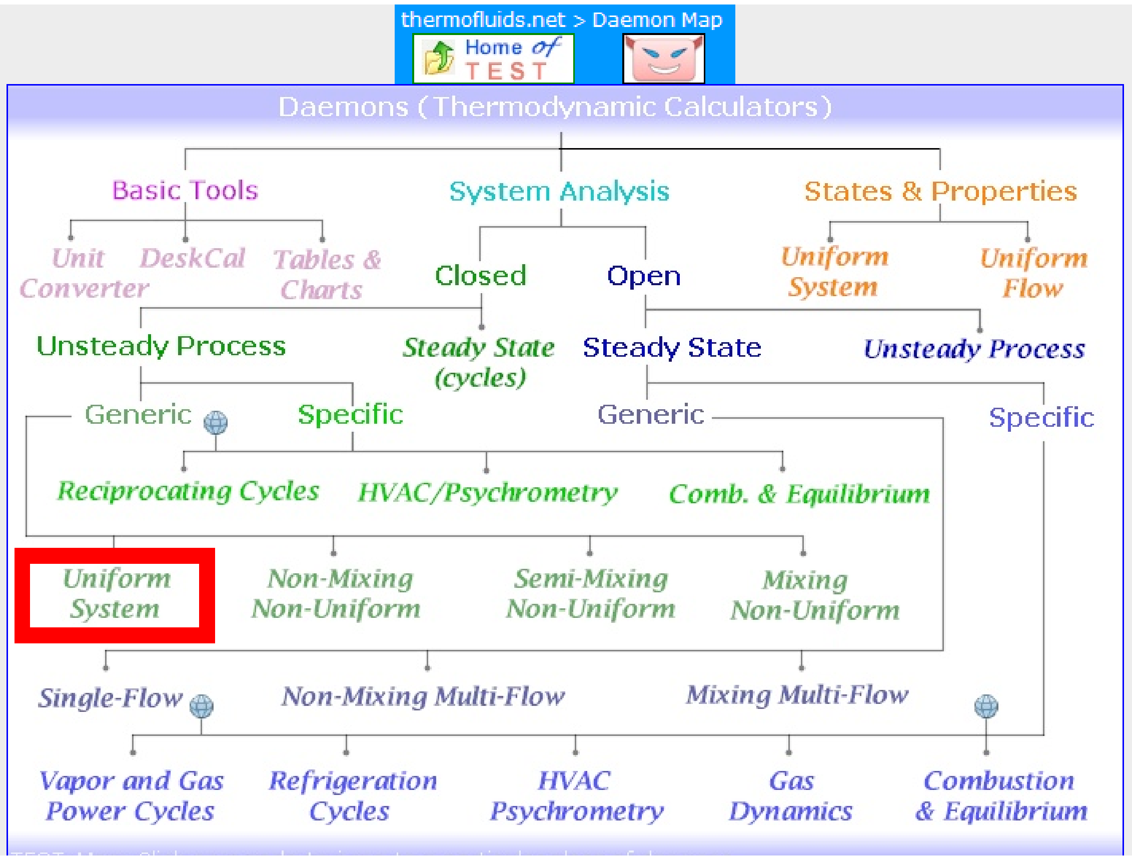
This problem is the same as Prob.9.15, which was solved with EES.

But, see how easily it is solved in TEST:

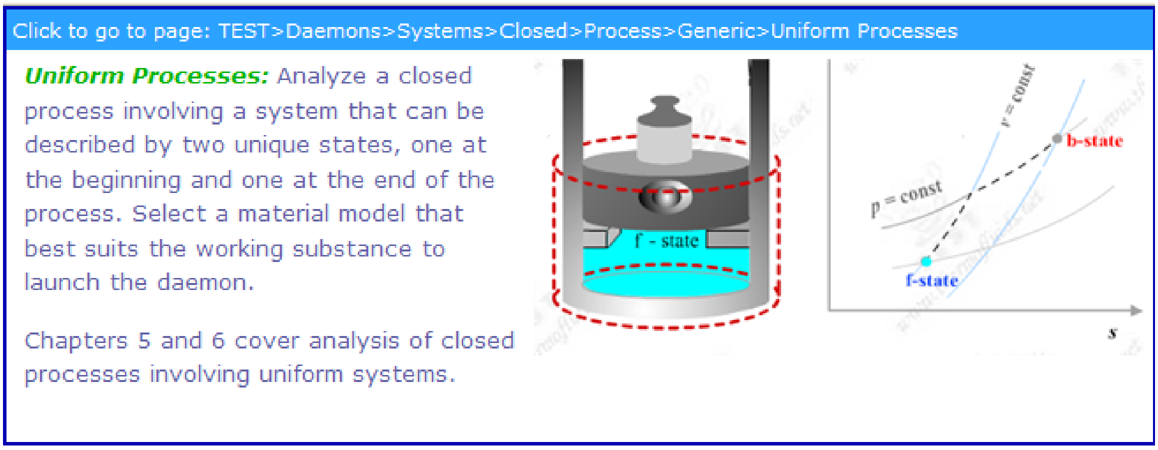
TEST Solution:

Following are the steps:

1. After going to TEST, in the Daemon tree choose System Analysis – Colsed _Uniform System:



Hovering the mouse pointer over *Uniform System* brings up the following explanatory pop-up:

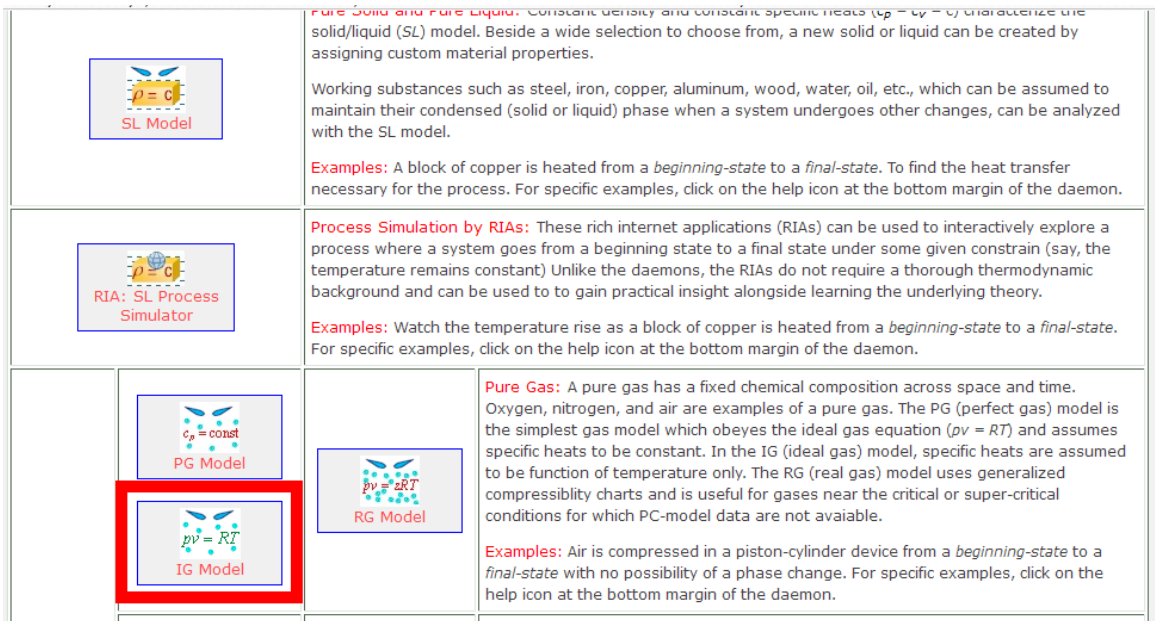


Click to go to page: TEST>Daemons>Systems>Closed>Process>Generic>Uniform Processes

Uniform Processes: Analyze a closed process involving a system that can be described by two unique states, one at the beginning and one at the end of the process. Select a material model that best suits the working substance to launch the daemon.

Chapters 5 and 6 cover analysis of closed processes involving uniform systems.

2. For Material model, select Ideal Gas (IG) Model, as shown below:



Pure Solid and Pure Liquid: Constant density and constant specific heats ($c_p = c_v = c$) characterize the solid/liquid (*SL*) model. Beside a wide selection to choose from, a new solid or liquid can be created by assigning custom material properties.

Working substances such as steel, iron, copper, aluminum, wood, water, oil, etc., which can be assumed to maintain their condensed (solid or liquid) phase when a system undergoes other changes, can be analyzed with the SL model.

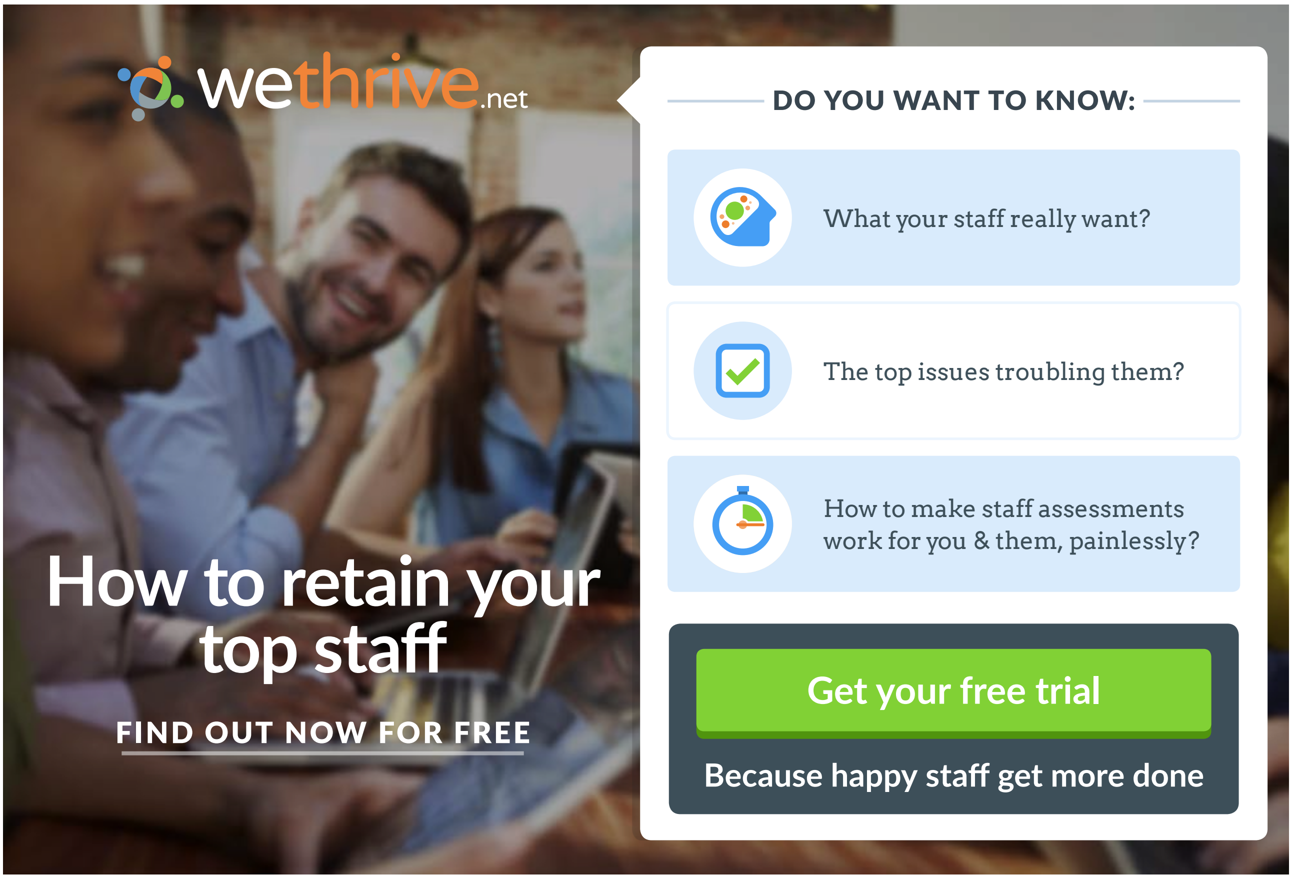
Examples: A block of copper is heated from a *beginning-state* to a *final-state*. To find the heat transfer necessary for the process. For specific examples, click on the help icon at the bottom margin of the daemon.

Process Simulation by RIAs: These rich internet applications (RIAs) can be used to interactively explore a process where a system goes from a beginning state to a final state under some given constrain (say, the temperature remains constant) Unlike the daemons, the RIAs do not require a thorough thermodynamic background and can be used to to gain practical insight alongside learning the underlying theory.

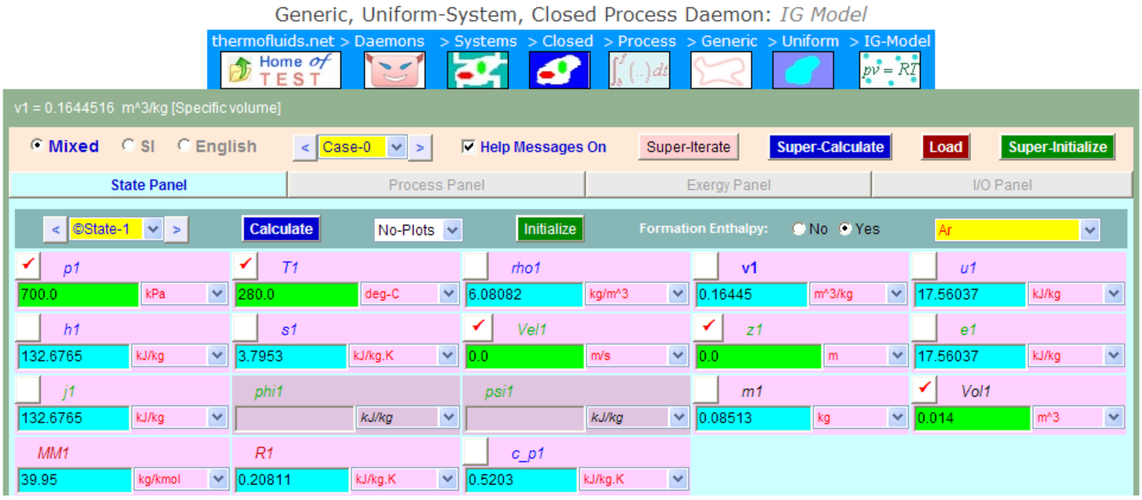
Examples: Watch the temperature rise as a block of copper is heated from a *beginning-state* to a *final-state*. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Gas: A pure gas has a fixed chemical composition across space and time. Oxygen, nitrogen, and air are examples of a pure gas. The PG (perfect gas) model is the simplest gas model which obeys the ideal gas equation ($pv = RT$) and assumes specific heats to be constant. In the IG (ideal gas) model, specific heats are assumed to be function of temperature only. The RG (real gas) model uses generalized compressiblity charts and is useful for gases near the critical or super-critical conditions for which PC-model data are not avaiable.

Examples: Air is compressed in a piston-cylinder device from a *beginning-state* to a *final-state* with no possibility of a phase change. For specific examples, click on the help icon at the bottom margin of the daemon.



3. Choose Argon for the substance, enter p1, T1, Vol1 for State 1. Hit Enter. Remaining properties are calculated immediately. We get:



v1 = 0.1644516 m^3/kg [Specific volume]

● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

State-1 | No-Plots | Formation Enthalpy: ○ No ● Yes | Ar

☑ p1: 700.0 kPa
☑ T1: 280.0 deg-C
☐ rho1: 6.08082 kg/m^3
☐ v1: 0.16445 m^3/kg
☐ u1: 17.56037 kJ/kg
☐ h1: 132.6765 kJ/kg
☐ s1: 3.7953 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: 17.56037 kJ/kg
☐ j1: 132.6765 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: 0.08513 kg
☑ Vol1: 0.014 m^3
MM1: 39.95 kg/kmol
R1: 0.20811 kJ/kg.K
☐ c_p1: 0.5203 kJ/kg.K

4. For State 2, enter s2 = s1 (since isentropic), Vol2 and m2 = m1. Hit Enter. We get:

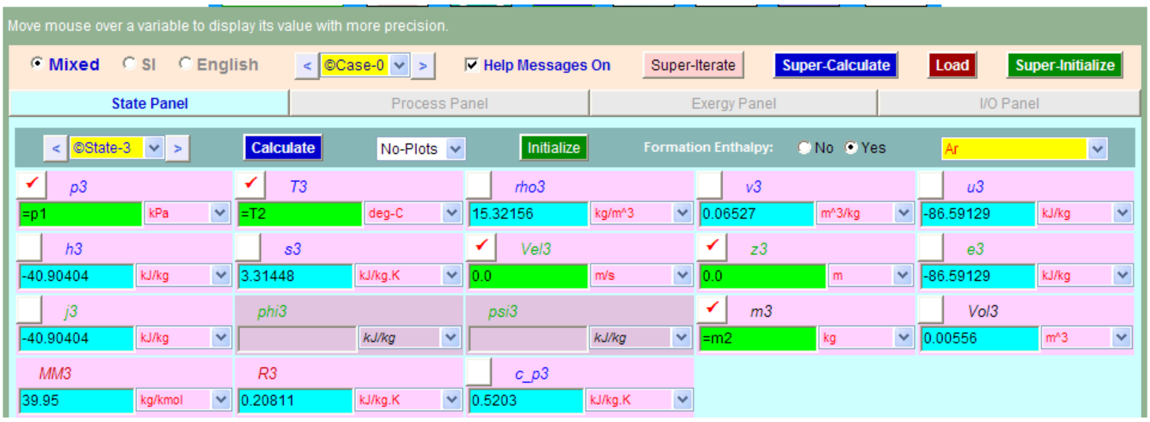
Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

State-2 | No-Plots | Formation Enthalpy: ○ No ● Yes | Ar

☐ p2: 69.45394 kPa
☐ T2: -53.61601 deg-C
☐ rho2: 1.5202 kg/m^3
☐ v2: 0.65781 m^3/kg
☐ u2: -86.59129 kJ/kg
☐ h2: -40.90404 kJ/kg
☑ s2: =s1 kJ/kg.K
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
☐ e2: -86.59129 kJ/kg
☐ j2: -40.90404 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
☑ m2: =m1 kg
☑ Vol2: 0.056 m^3
MM2: 39.95 kg/kmol
R2: 0.20811 kJ/kg.K
☐ c_p2: 0.5203 kJ/kg.K

5. For State 3: enter p3 = p1, T3 = T2, m3 = m2 and press Enter. We get:



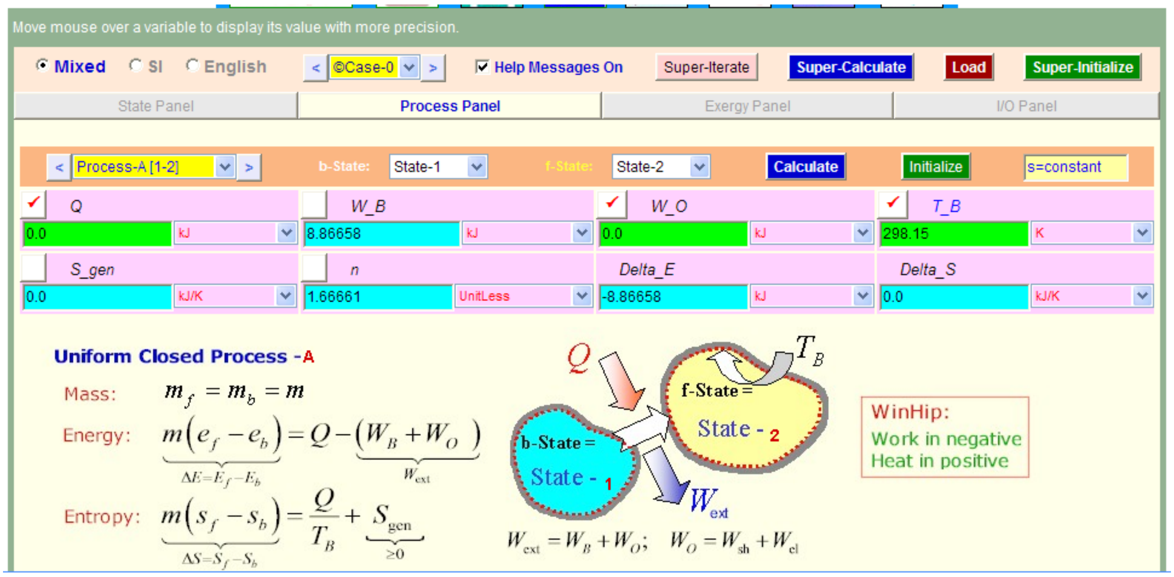
Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

State-3 | No-Plots | Formation Enthalpy: ○ No ● Yes | Ar

☑ p3: =p1 kPa
☑ T3: =T2 deg-C
☐ rho3: 15.32156 kg/m^3
☐ v3: 0.06527 m^3/kg
☐ u3: -86.59129 kJ/kg
☐ h3: -40.90404 kJ/kg
☐ s3: 3.31448 kJ/kg.K
☑ Vel3: 0.0 m/s
☑ z3: 0.0 m
☐ e3: -86.59129 kJ/kg
☐ j3: -40.90404 kJ/kg
phi3: kJ/kg
psi3: kJ/kg
☑ m3: =m2 kg
☐ Vol3: 0.00556 m^3
MM3: 39.95 kg/kmol
R3: 0.20811 kJ/kg.K
☐ c_p3: 0.5203 kJ/kg.K

6. Now, go to Process Panel. For Process A, enter State 1 and State 2 for b-State and f-State, W_O = 0 (i.e. work other than Boundary work) and Q = 0. Press Calculate (or, hit Enter). We get:



Move mouse over a variable to display its value with more precision.

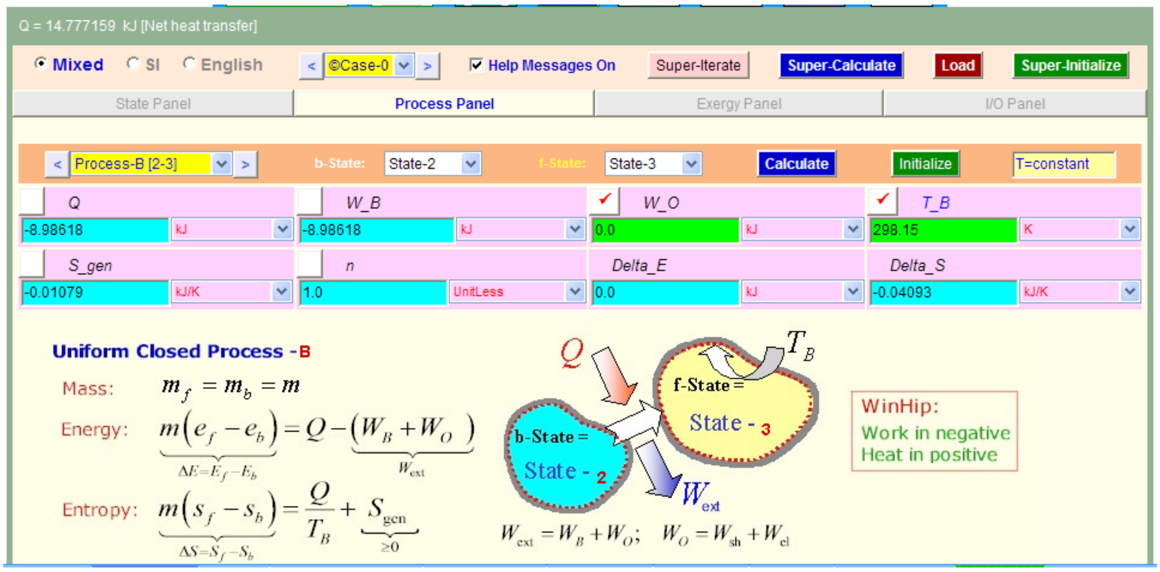
● Mixed ○ SI ○ English; ©Case-0; ☑ Help Messages On

Process Panel: Process-A [1-2]; b-State: State-1; f-State: State-2; s=constant

☑ Q: 0.0 kJ	☐ W_B: 8.86658 kJ	☑ W_O: 0.0 kJ	☑ T_B: 298.15 K
☐ S_gen: 0.0 kJ/K	☐ n: 1.66661 UnitLess	Delta_E: -8.86658 kJ	Delta_S: 0.0 kJ/K

See that: W_B for Process 1-2 is calculated as 8.867 kJ…..Ans.

7. Now, for Process B i.e. Process 2-3: Enter State 2 and State 3 for b-State and f-State respectively. And W_O = 0. Hit Enter. We get:



Q = 14.777159 kJ [Net heat transfer]

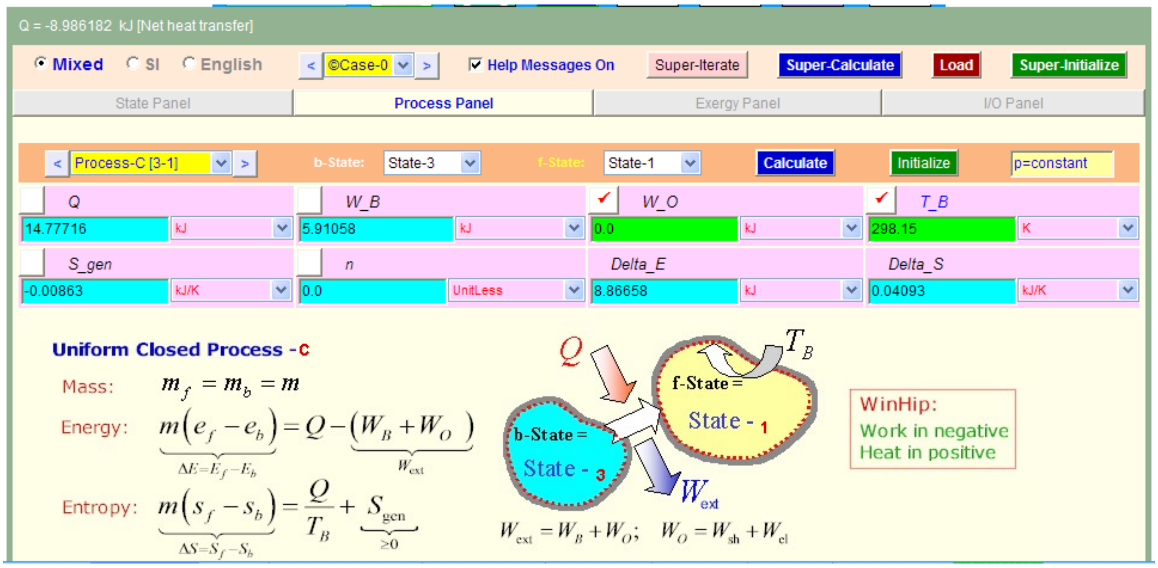
● Mixed ○ SI ○ English; ©Case-0; ☑ Help Messages On

Process Panel: Process-B [2-3]; b-State: State-2; f-State: State-3; T=constant

☐ Q: -8.98618 kJ	☐ W_B: -8.98618 kJ	☑ W_O: 0.0 kJ	☑ T_B: 298.15 K
☐ S_gen: -0.01079 kJ/K	☐ n: 1.0 UnitLess	Delta_E: 0.0 kJ	Delta_S: -0.04093 kJ/K

Note that for Process 2-3, W_B = -8.986 kJ, Q = -8.986 kJ … Ans.

8. Now, for Process 3-1, i.e. Process C: Enter State 3 and State13 for b-State and f-State respectively. And W_O = 0. Hit Enter. We get:



Q = -8.986182 kJ [Net heat transfer]

● Mixed ○ SI ○ English; ©Case-0; ☑ Help Messages On

Process-C [3-1]; b-State: State-3; f-State: State-1; p=constant

☐ Q: 14.77716 kJ
☐ W_B: 5.91058 kJ
☑ W_O: 0.0 kJ
☑ T_B: 298.15 K
☐ S_gen: -0.00863 kJ/K
☐ n: 0.0 UnitLess
Delta_E: 8.86658 kJ
Delta_S: 0.04093 kJ/K

Uniform Closed Process -C

Mass: $m_f = m_b = m$

Energy: $\underbrace{m(e_f - e_b)}_{\Delta E = E_f - E_b} = Q - \underbrace{(W_B + W_O)}_{W_{ext}}$

Entropy: $\underbrace{m(s_f - s_b)}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + \underbrace{S_{gen}}_{\geq 0}$

$W_{ext} = W_B + W_O; \quad W_O = W_{sh} + W_{el}$

WinHip:
Work in negative
Heat in positive

i.e. For Process 3-1: W_B = 5.9106 kJ, Q = 14.777 kJ … Ans.

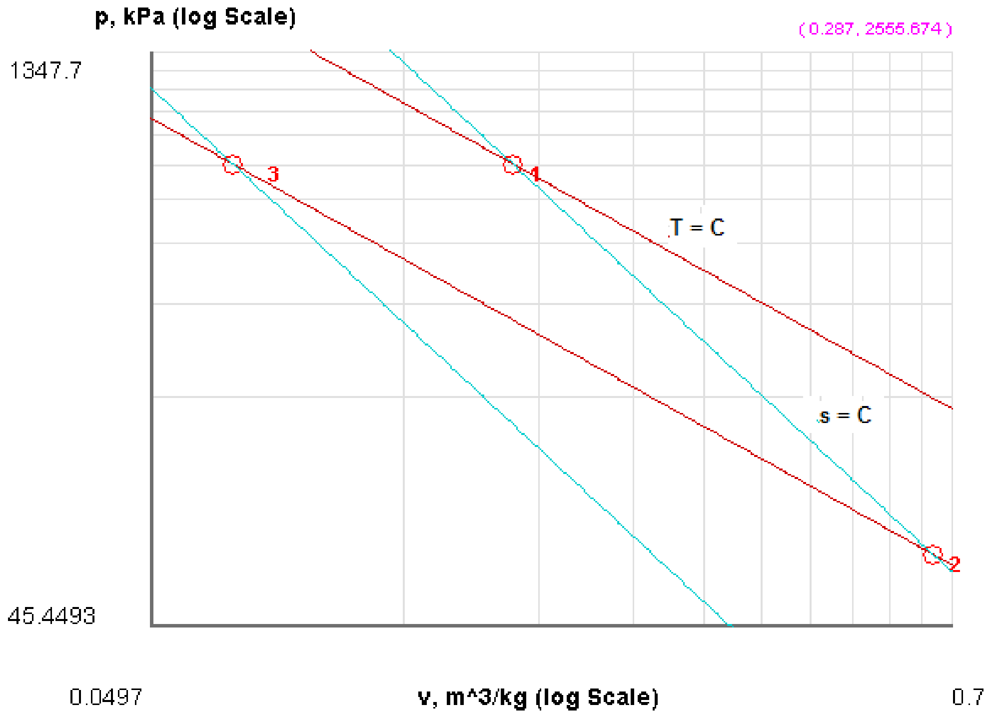
And, net work output of cycle = 8.867 + (-8.986) + 5.916 = 5.797 kJ … Ans.

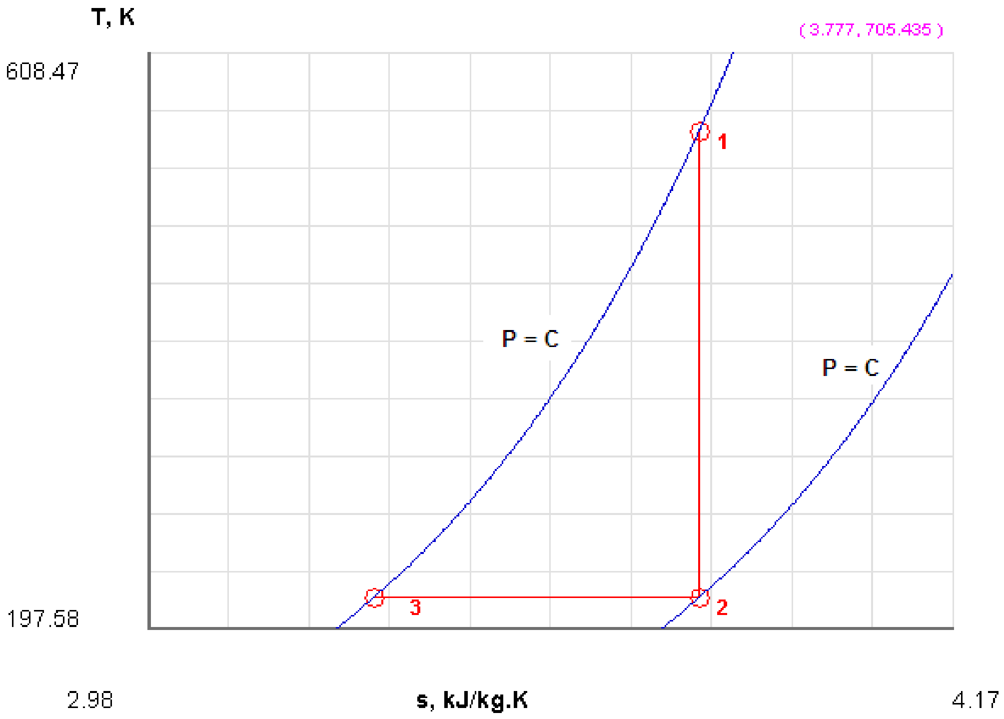
Change in enthalpy for Process 1-2: (h2 – h1) = -173.581 kJ/kg …. Ans.

Change in enthalpy for Process 2-3: (h3 – h2) = h3-h2 = 0 kJ/kg …. Ans.

Change in enthalpy for Process 3-1: (h3 – h1) = -173.581kJ/kg …. Ans.

9. Get the p-v and T-s plots by electing accordingly from the Plots widget:





10. Click on **SuperCalculate** and get the TEST code etc. from the I/O Panel:

```
#~~~~~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE

#

#Daemon Path: Systems>Closed>Process>Generic>Uniform>IG-Model; v-10.ca08

#

#--------------------Start of TEST-code---------------------------------------------------------------

States    {

          State-1: Ar;
          Given: { p1= 700.0 kPa; T1= 280.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; Vol1= 0.014 m^3; }

          State-2: Ar;
          Given: { s2= “s1” kJ/kg.K; Vel2= 0.0 m/s; z2= 0.0 m; m2= “m1” kg; Vol2= 0.056 m^3; }

          State-3: Ar;
          Given: { p3= “P1” kPa; T3= “T2” deg-C; Vel3= 0.0 m/s; z3= 0.0 m; m3= “m2” kg; }
          }

Analysis {

          Process-A: b-State = State-1; f-State = State-2;
          Given: { Q= 0.0 kJ; W_O= 0.0 kJ; T_B= 298.15 K; }

          Process-B: b-State = State-2; f-State = State-3;
          Given: { W_O= 0.0 kJ; T_B= 298.15 K; }

          Process-C: b-State = State-3; f-State = State-1;
          Given: { W_O= 0.0 kJ; T_B= 298.15 K; }
          }

#----------------------End of TEST-code-------------------------------------------------------------
```

```
#--------Property spreadsheet starts:
#
#    State   p(kPa)  T(K)    v(m^3/kg)   u(kJ/kg)    h(kJ/kg)    s(kJ/kg)
#    1       700.0   553.2   0.1645      17.56       132.68      3.795
#    2       69.45   219.5   0.6578      -86.59      -40.9       3.795
#    3       700.0   219.5   0.0653      -86.59      -40.9       3.314
#
#--------Property spreadsheet ends-----------------------------------------------------------------

# Mass, Energy, and Entropy Analysis Results:


#
#    Process-A: b-State = State-1; f-State = State-2;
#    Given: Q= 0.0 kJ; W_O= 0.0 kJ; T_B= 298.15 K;
#    Calculated: W_B= 8.86658 kJ; S_gen= -0.0 kJ/K; n= 1.6666132 UnitLess; Delta_E= -8.86658 kJ;
Delta_S= -0.0 kJ/K;
#
#    Process-B: b-State = State-2; f-State = State-3;
#    Given: W_O= 0.0 kJ; T_B= 298.15 K;
#    Calculated: Q= -8.986182 kJ; W_B= -8.986182 kJ; S_gen= -0.010793186 kJ/K; n= 1.0 UnitLess;
#    Delta_E= -0.0 kJ; Delta_S= -0.040932987 kJ/K;
#
#    Process-C: b-State = State-3; f-State = State-1;
#    Given: W_O= 0.0 kJ; T_B= 298.15 K;
#    Calculated: Q= 14.777159 kJ; W_B= 5.910579 kJ; S_gen= -0.008629847 kJ/K; n= 0.0 UnitLess;
Delta_E= 8.86658 kJ; Delta_S= 0.040932987 kJ/K;
#
```

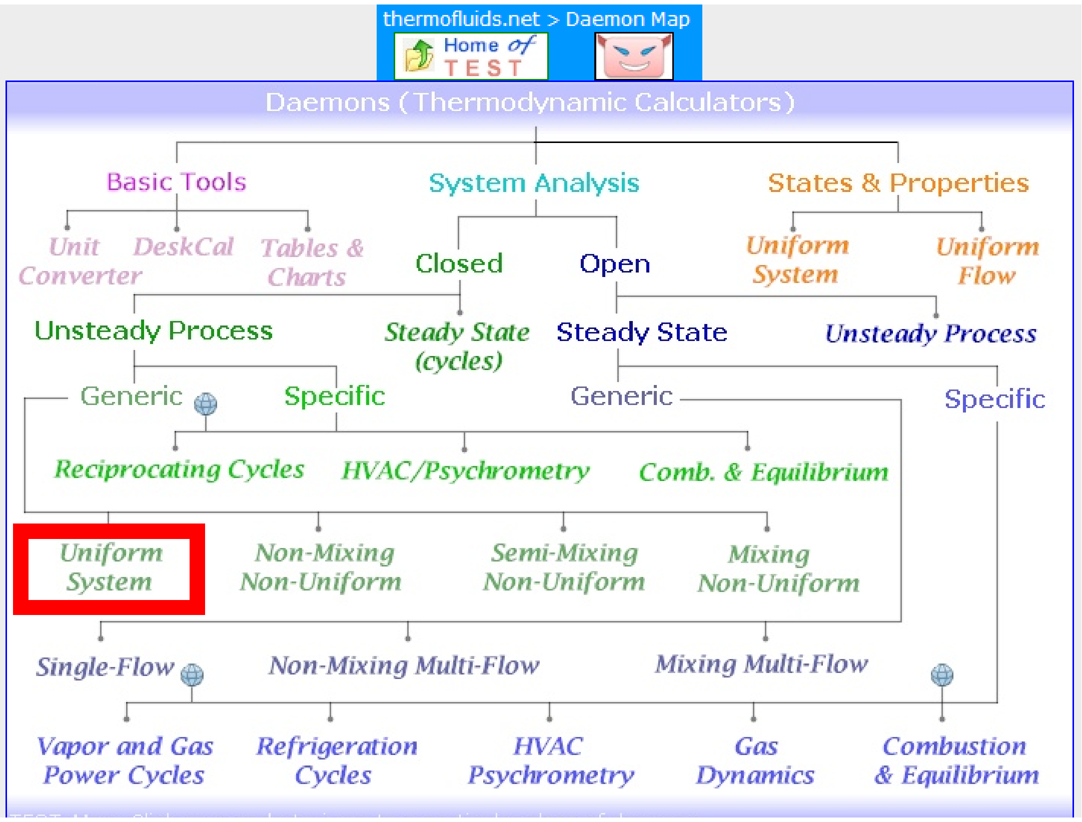
===

Prob.9.28. 1 kg of air at a pressure of 8 bar and temp 100 C undergoes a reversible, ploytropic process following the law p.v^1.2 = constant. If the final pressure is 1.8 bar, determine: (i) final sp. volume, temp and increase in entropy, and (ii) work done and heat transfer. [VTU – BTD – Dec. 06–Jan. 07]

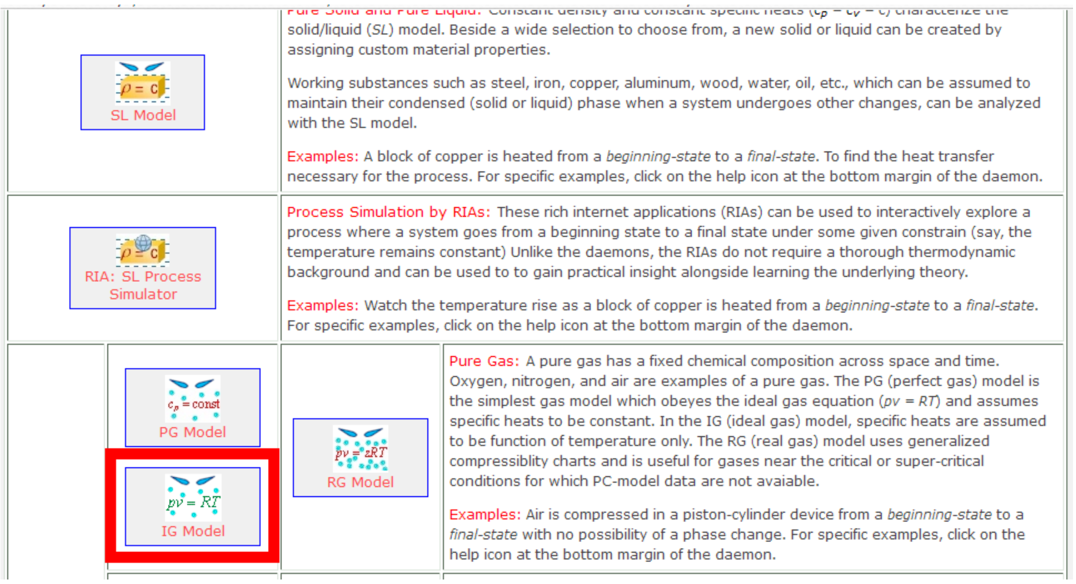
TEST Solution:

Following are the steps:

1. From the Daemons tree, select System Analysis – Closed – Uniform System:



2. For the Material model, select IG Model:



Pure Solid and Pure Liquid: Constant density and constant specific heats ($c_p = c_v = c$) characterize the solid/liquid (*SL*) model. Beside a wide selection to choose from, a new solid or liquid can be created by assigning custom material properties.

Working substances such as steel, iron, copper, aluminum, wood, water, oil, etc., which can be assumed to maintain their condensed (solid or liquid) phase when a system undergoes other changes, can be analyzed with the SL model.

Examples: A block of copper is heated from a *beginning-state* to a *final-state*. To find the heat transfer necessary for the process. For specific examples, click on the help icon at the bottom margin of the daemon.

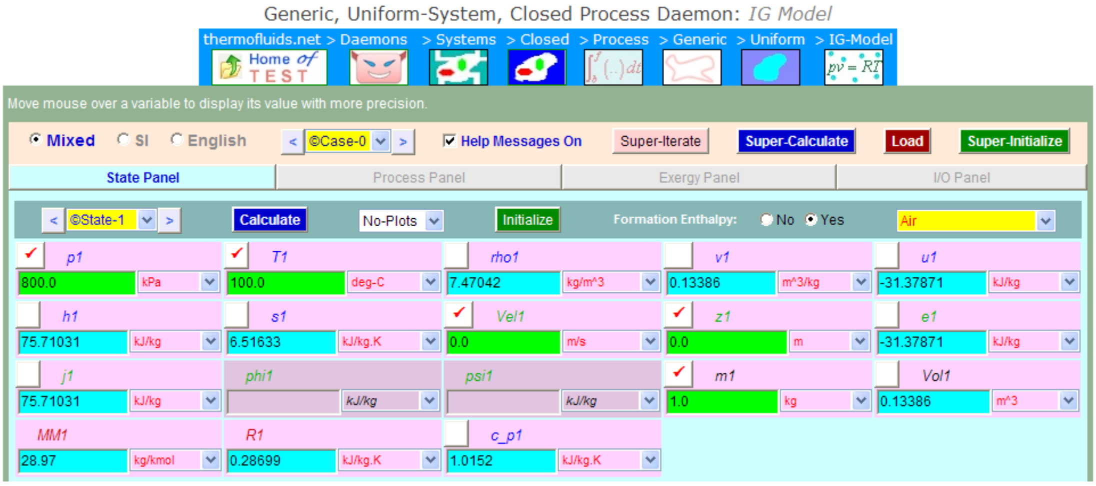
Process Simulation by RIAs: These rich internet applications (RIAs) can be used to interactively explore a process where a system goes from a beginning state to a final state under some given constrain (say, the temperature remains constant) Unlike the daemons, the RIAs do not require a thorough thermodynamic background and can be used to to gain practical insight alongside learning the underlying theory.

Examples: Watch the temperature rise as a block of copper is heated from a *beginning-state* to a *final-state*. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Gas: A pure gas has a fixed chemical composition across space and time. Oxygen, nitrogen, and air are examples of a pure gas. The PG (perfect gas) model is the simplest gas model which obeyes the ideal gas equation ($pv = RT$) and assumes specific heats to be constant. In the IG (ideal gas) model, specific heats are assumed to be function of temperature only. The RG (real gas) model uses generalized compressiblity charts and is useful for gases near the critical or super-critical conditions for which PC-model data are not avaiable.

Examples: Air is compressed in a piston-cylinder device from a *beginning-state* to a *final-state* with no possibility of a phase change. For specific examples, click on the help icon at the bottom margin of the daemon.

3. Select Air as the substance, enter for State 1 values of p1, T1 and m1, and hit Enter. We get:



Generic, Uniform-System, Closed Process Daemon: *IG Model*

thermofluids.net > Daemons > Systems > Closed > Process > Generic > Uniform > IG-Model

Move mouse over a variable to display its value with more precision.

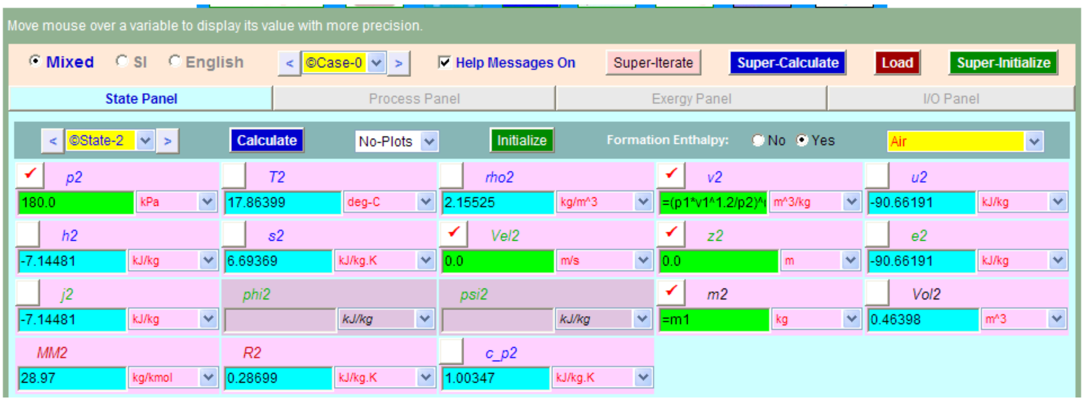
● Mixed ○ SI ○ English | ©Case-0 | ☑ Help Messages On | Super-Iterate | Super-Calculate | Load | Super-Initialize

State Panel | Process Panel | Exergy Panel | I/O Panel

©State-1 | Calculate | No-Plots | Initialize | Formation Enthalpy: ○ No ● Yes | Air

☑ p1: 800.0 kPa
☑ T1: 100.0 deg-C
☐ rho1: 7.47042 kg/m^3
☐ v1: 0.13386 m^3/kg
☐ u1: -31.37871 kJ/kg
☐ h1: 75.71031 kJ/kg
☐ s1: 6.51633 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: -31.37871 kJ/kg
☐ j1: 75.71031 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☑ m1: 1.0 kg
☐ Vol1: 0.13386 m^3
MM1: 28.97 kg/kmol
R1: 0.28699 kJ/kg.K
☐ c_p1: 1.0152 kJ/kg.K

4. For State 2: enter p2, m2 = m1 and v2 = (p1 * v1^1.2 / p2) and hit Enter. We get:



Move mouse over a variable to display its value with more precision.

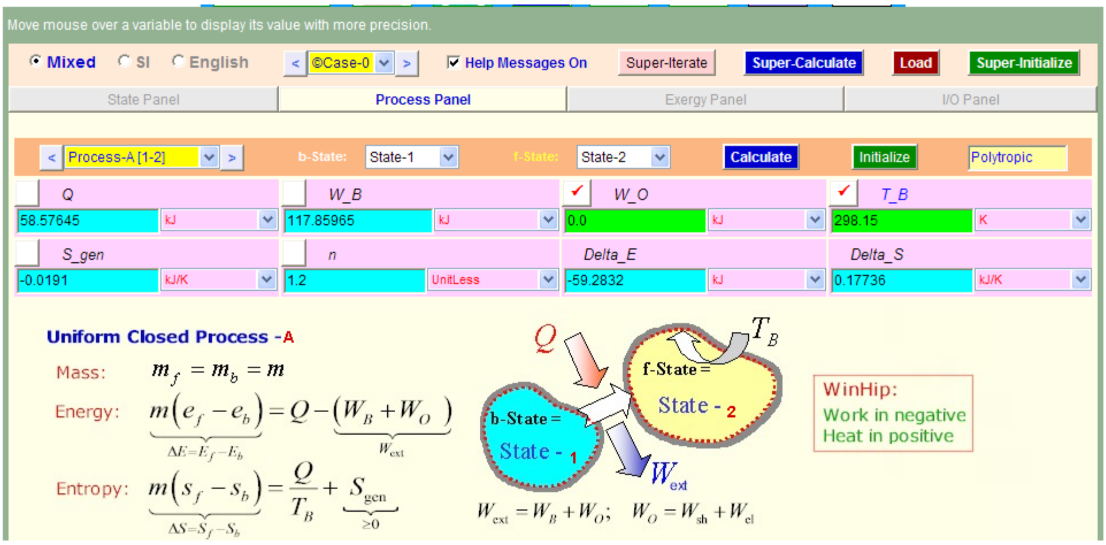
● Mixed ○ SI ○ English | ©Case-0 | ☑ Help Messages On | Super-Iterate | Super-Calculate | Load | Super-Initialize

State Panel | Process Panel | Exergy Panel | I/O Panel

©State-2 | Calculate | No-Plots | Initialize | Formation Enthalpy: ○ No ● Yes | Air

☑ p2: 180.0 kPa
☐ T2: 17.86399 deg-C
☐ rho2: 2.15525 kg/m^3
☑ v2: =(p1*v1^1.2/p2)^ m^3/kg
☐ u2: -90.66191 kJ/kg
☐ h2: -7.14481 kJ/kg
☐ s2: 6.69369 kJ/kg.K
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
☐ e2: -90.66191 kJ/kg
☐ j2: -7.14481 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
☑ m2: =m1 kg
☐ Vol2: 0.46398 m^3
MM2: 28.97 kg/kmol
R2: 0.28699 kJ/kg.K
☐ c_p2: 1.00347 kJ/kg.K

5. Go to Process Panel. For Process A, enter State 1 and State 2 for b-State and f-State, and W_O = 0 and hit Enter. We get:



Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English | ©Case-0 | ☑ Help Messages On | Super-Iterate | Super-Calculate | Load | Super-Initialize

State Panel | Process Panel | Exergy Panel | I/O Panel

Process-A [1-2] | b-State: State-1 | f-State: State-2 | Calculate | Initialize | Polytropic

☐ Q: 58.57645 kJ
☐ W_B: 117.85965 kJ
☑ W_O: 0.0 kJ
☑ T_B: 298.15 K
☐ S_gen: -0.0191 kJ/K
☐ n: 1.2 UnitLess
Delta_E: -59.2832 kJ
Delta_S: 0.17736 kJ/K

Uniform Closed Process -A

Mass: $m_f = m_b = m$

Energy: $\underbrace{m\left(e_f - e_b\right)}_{\Delta E = E_f - E_b} = Q - \underbrace{\left(W_B + W_O\right)}_{W_{ext}}$

Entropy: $\underbrace{m\left(s_f - s_b\right)}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + \underbrace{S_{gen}}_{\geq 0}$

$W_{ext} = W_B + W_O$; $W_O = W_{sh} + W_{el}$

WinHip:
Work in negative
Heat in positive

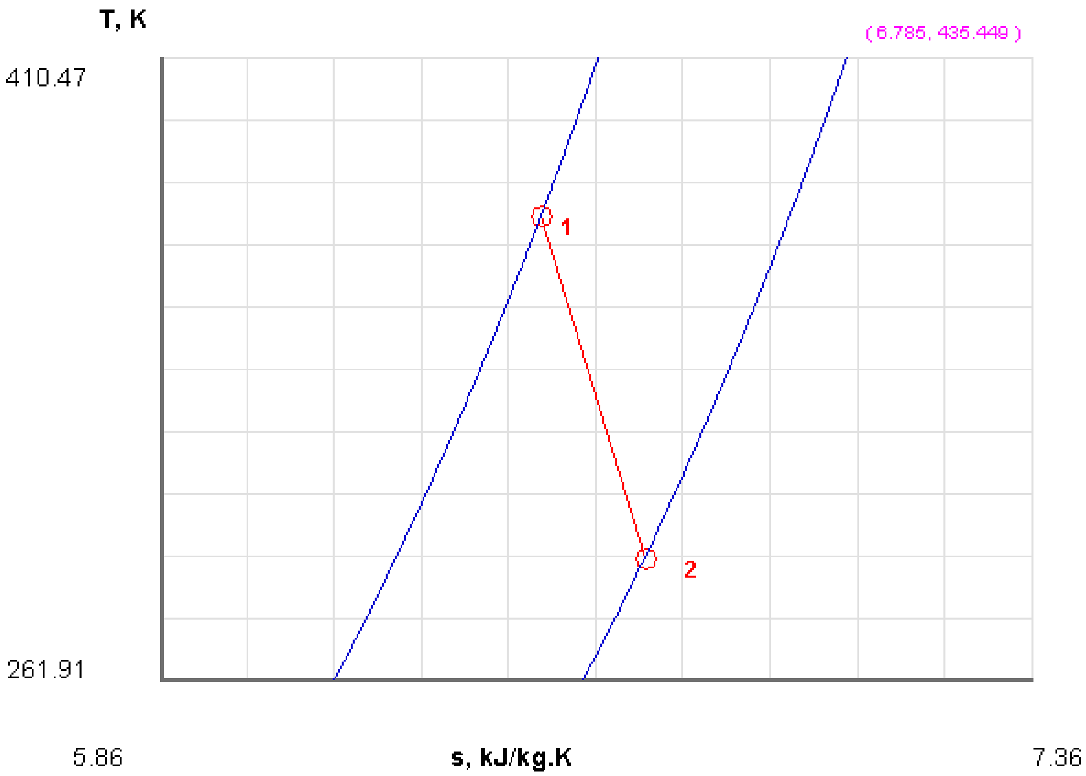
6. **Note that Heat transfer, Q = 58.576 kJ, Work done, W_B = 117.86 kJ. . Ans.**

   At State 2:

   sp. vol. v2 = 0.464 m^3, temp, T2 = 17.864 C, and

   change in entropy = (s2 – s1) = 0.177kJ/K …. Ans.

7. Draw the T-s diagram from the Plots widget:



8. Click on SuperCalculate, and get the TEST code etc from the I/O panel:

```
#~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE

#

#Daemon Path: Systems>Closed>Process>Generic>Uniform>IG-Model; v-10.ca08

#
```

```
#--------------------Start of TEST-code-----------------------------------------------------------

States   {

         State-1: Air;
         Given: { p1= 800.0 kPa; T1= 100.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 1.0 kg; }

         State-2: Air;
         Given: { p2= 180.0 kPa; v2= “(p1*v1^1.2/p2)^(1/1.2)” m^3/kg; Vel2= 0.0 m/s; z2= 0.0 m; m2=
“m1” kg; }

         }

Analysis {

         Process-A: b-State = State-1; f-State = State-2;

         Given: { W_O= 0.0 kJ; T_B= 298.15 K; }

         }

#----------------------End of TEST-code----------------------------------------------------------
```

```
#

#******DETAILED OUTPUT:

# Evaluated States:

#
#       State-1: Air > IG-Model;
#               Given: p1= 800.0 kPa; T1= 100.0 deg-C; Vel1= 0.0 m/s;
#                       z1= 0.0 m; m1= 1.0 kg;
#       Calculated: rho1= 7.4704 kg/m^3; v1= 0.1339 m^3/kg; u1= -31.3787 kJ/kg;
#                       h1= 75.7103 kJ/kg; s1= 6.5163 kJ/kg.K; e1= -31.3787 kJ/kg;
#                       j1= 75.7103 kJ/kg; Vol1= 0.1339 m^3; MM1= 28.97 kg/kmol;
#                       R1= 0.287 kJ/kg.K; c_p1= 1.0152 kJ/kg.K;
#
#       State-2: Air > IG-Model;
#               Given: p2= 180.0 kPa; v2= "(p1*v1^1.2/p2)^(1/1.2)" m^3/kg; Vel2= 0.0 m/s;
#                       z2= 0.0 m; m2= "m1" kg;
#       Calculated: T2= 17.864 deg-C; rho2= 2.1552 kg/m^3; u2= -90.6619 kJ/kg;
#                       h2= -7.1448 kJ/kg; s2= 6.6937 kJ/kg.K; e2= -90.6619 kJ/kg;
#                       j2= -7.1448 kJ/kg; Vol2= 0.464 m^3; MM2= 28.97 kg/kmol;
#                       R2= 0.287 kJ/kg.K; c_p2= 1.0035 kJ/kg.K;
#
#--------Property spreadsheet starts: #

#       State   p(kPa)      T(K)   v(m^3/kg)   u(kJ/kg)    h(kJ/kg)    s(kJ/kg)
#       1       800.0       373.2  0.1339      -31.38      75.71       6.516
#       2       180.0       291.0  0.464       -90.66      -7.14       6.694

#

#--------Property spreadsheet ends------------------------------------------------------------------

#
```

 # Mass, Energy, and Entropy Analysis Results:

#

Process-A: b-State = State-1; f-State = State-2;

Given: W_O= 0.0 kJ; T_B= 298.15 K;

Calculated: Q= 58.57645 kJ; W_B= 117.85965 kJ; S_gen= -0.019103007 kJ/K; n= 1.2 UnitLess;

Delta_E= -59.2832 kJ; **Delta_S= 0.17736337 kJ/K;**

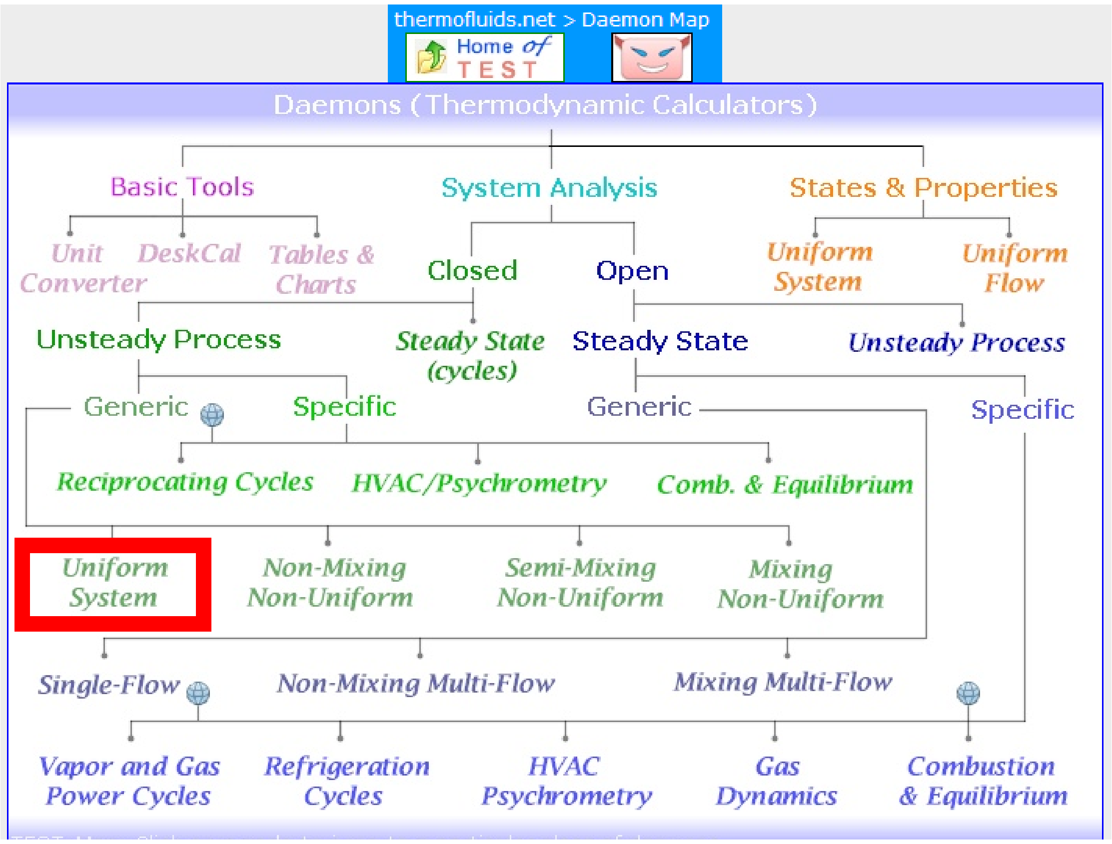
#

==

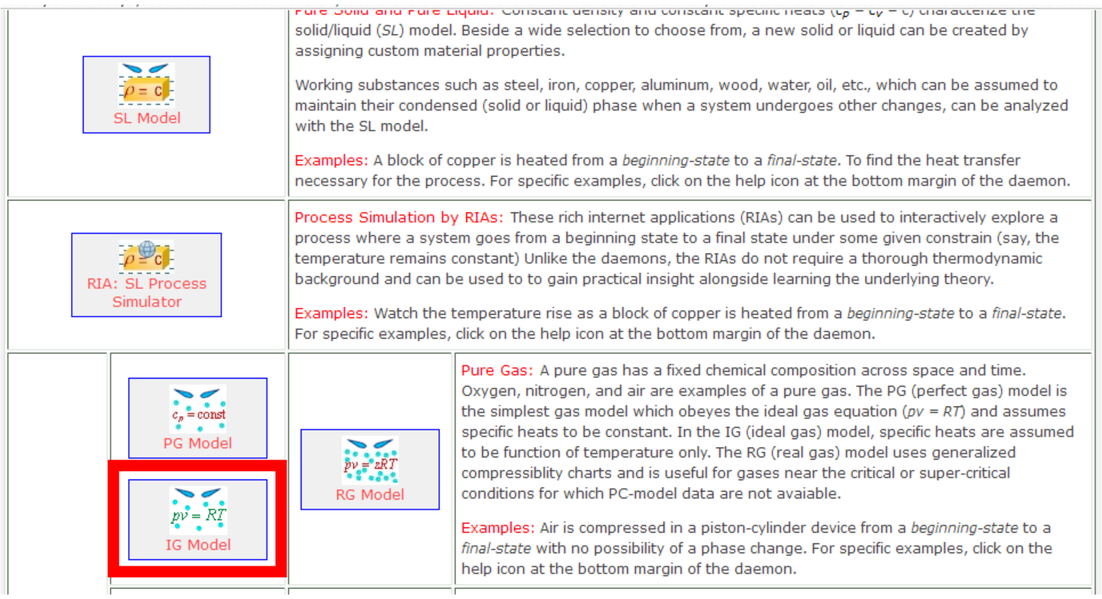
Prob.9.29. 0.5 kg of air is compressed reversibly and adiabatically from 80 kPa, 60 C to 0.4 MPa and is then expanded at const. pressure to the original volume. Sketch these processes on the p-v and T-s planes. Compute the heat transfer and work transfer for the whole path. [VTU – BTD – June–July 08:]

TEST Solution:

1. From the Daemon tree, select System Analysis – Closed – Uniform System:



2. For the Material model, choose IG model:



Pure Solid and Pure Liquid: Constant density and constant specific heats ($c_p = c_v = c$) characterize the solid/liquid (*SL*) model. Beside a wide selection to choose from, a new solid or liquid can be created by assigning custom material properties.

Working substances such as steel, iron, copper, aluminum, wood, water, oil, etc., which can be assumed to maintain their condensed (solid or liquid) phase when a system undergoes other changes, can be analyzed with the SL model.

Examples: A block of copper is heated from a *beginning-state* to a *final-state*. To find the heat transfer necessary for the process. For specific examples, click on the help icon at the bottom margin of the daemon.

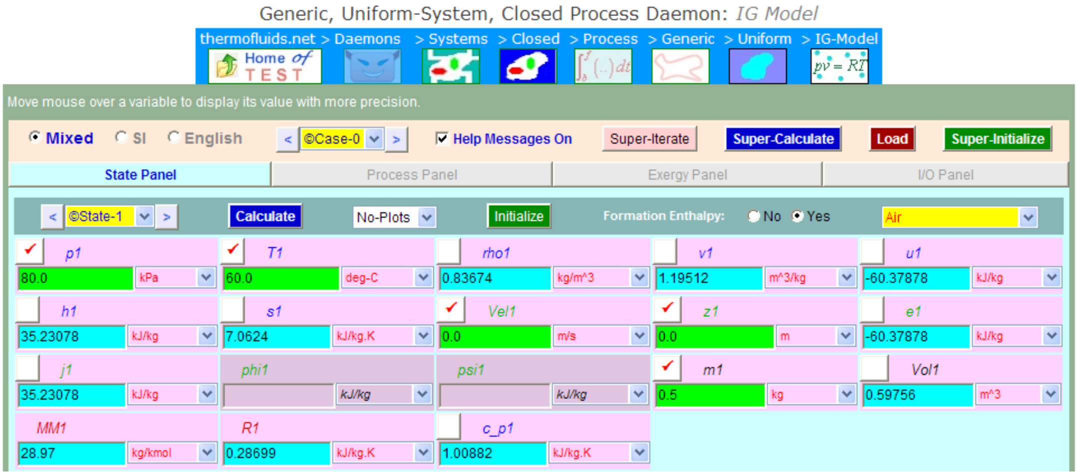
Process Simulation by RIAs: These rich internet applications (RIAs) can be used to interactively explore a process where a system goes from a beginning state to a final state under some given constrain (say, the temperature remains constant) Unlike the daemons, the RIAs do not require a thorough thermodynamic background and can be used to to gain practical insight alongside learning the underlying theory.

Examples: Watch the temperature rise as a block of copper is heated from a *beginning-state* to a *final-state*. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Gas: A pure gas has a fixed chemical composition across space and time. Oxygen, nitrogen, and air are examples of a pure gas. The PG (perfect gas) model is the simplest gas model which obeys the ideal gas equation ($pv = RT$) and assumes specific heats to be constant. In the IG (ideal gas) model, specific heats are assumed to be function of temperature only. The RG (real gas) model uses generalized compressiblity charts and is useful for gases near the critical or super-critical conditions for which PC-model data are not avaiable.

Examples: Air is compressed in a piston-cylinder device from a *beginning-state* to a *final-state* with no possibility of a phase change. For specific examples, click on the help icon at the bottom margin of the daemon.

3. Select Air as the working substance, and for State 1, enter values of p1, T1 and m1, and hit Enter. We get:



● Mixed ○ SI ○ English; Case-0; ☑ Help Messages On

State-1; No-Plots; Formation Enthalpy: ○ No ● Yes; Air

☑ p1 = 80.0 kPa; ☑ T1 = 60.0 deg-C; ☐ rho1 = 0.83674 kg/m^3; ☐ v1 = 1.19512 m^3/kg; ☐ u1 = -60.37878 kJ/kg

☐ h1 = 35.23078 kJ/kg; ☐ s1 = 7.0624 kJ/kg.K; ☑ Vel1 = 0.0 m/s; ☑ z1 = 0.0 m; ☐ e1 = -60.37878 kJ/kg

☐ j1 = 35.23078 kJ/kg; phi1 = kJ/kg; psi1 = kJ/kg; ☑ m1 = 0.5 kg; ☐ Vol1 = 0.59756 m^3

MM1 = 28.97 kg/kmol; R1 = 0.28699 kJ/kg.K; ☐ c_p1 = 1.00882 kJ/kg.K

4. For State 2: enter p2, m2 = m1, and s2 = s1 (since isentropic), hit Enter. We get:

● Mixed ○ SI ○ English; Case-0; ☑ Help Messages On

State-2; No-Plots; Formation Enthalpy: ○ No ● Yes; Air

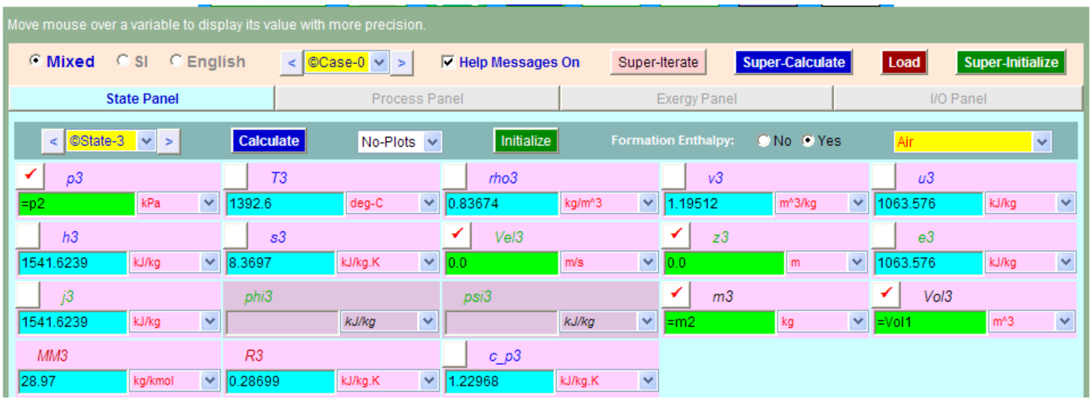
☑ p2 = 400.0 kPa; ☐ T2 = 250.01303 deg-C; ☐ rho2 = 2.66417 kg/m^3; ☐ v2 = 0.37535 m^3/kg; ☐ u2 = 79.79284 kJ/kg

☐ h2 = 229.93358 kJ/kg; ☑ s2 = =s1 kJ/kg.K; ☑ Vel2 = 0.0 m/s; ☑ z2 = 0.0 m; ☐ e2 = 79.79284 kJ/kg

☐ j2 = 229.93358 kJ/kg; phi2 = kJ/kg; psi2 = kJ/kg; ☑ m2 = =m1 kg; ☐ Vol2 = 0.18768 m^3

MM2 = 28.97 kg/kmol; R2 = 0.28699 kJ/kg.K; ☐ c_p2 = 1.04149 kJ/kg.K

5. For State 3: enter p3 = p2, m3 = m2 and Vol3 = Vol1. Hit Enter. We get:



● Mixed ○ SI ○ English; Case-0; ☑ Help Messages On

State-3; No-Plots; Formation Enthalpy: ○ No ● Yes; Air

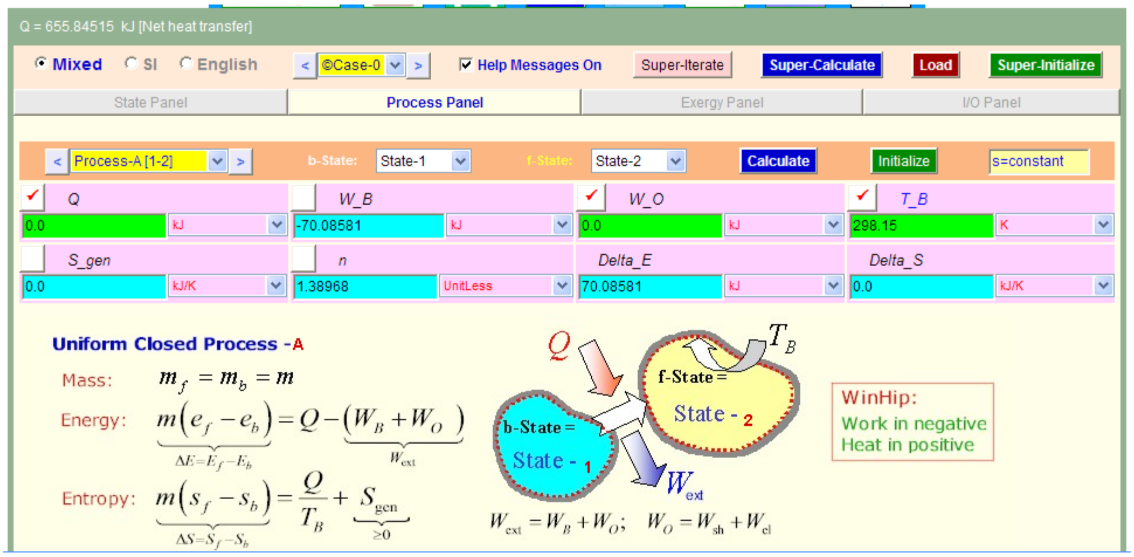
☑ p3 = =p2 kPa; ☐ T3 = 1392.6 deg-C; ☐ rho3 = 0.83674 kg/m^3; ☐ v3 = 1.19512 m^3/kg; ☐ u3 = 1063.576 kJ/kg

☐ h3 = 1541.6239 kJ/kg; ☐ s3 = 8.3697 kJ/kg.K; ☑ Vel3 = 0.0 m/s; ☑ z3 = 0.0 m; ☐ e3 = 1063.576 kJ/kg

☐ j3 = 1541.6239 kJ/kg; phi3 = kJ/kg; psi3 = kJ/kg; ☑ m3 = =m2 kg; ☑ Vol3 = =Vol1 m^3

MM3 = 28.97 kg/kmol; R3 = 0.28699 kJ/kg.K; ☐ c_p3 = 1.22968 kJ/kg.K

6. Now, go to Process Panel. For Process A: enter State 1 and State 2 for b-State and f-State, W_O = 0 (i.e. Work other than Boundary work), and hit Enter. We get:



Q = 655.84515 kJ [Net heat transfer]

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

Process-A [1-2]　b-State: State-1　f-State: State-2　s=constant

☑ Q	W_B	☑ W_O	☑ T_B
0.0 kJ	-70.08581 kJ	0.0 kJ	298.15 K
S_gen	n	Delta_E	Delta_S
0.0 kJ/K	1.38968 UnitLess	70.08581 kJ	0.0 kJ/K

Uniform Closed Process -A

Mass: $m_f = m_b = m$

Energy: $\underbrace{m\left(e_f - e_b\right)}_{\Delta E = E_f - E_b} = Q - \underbrace{\left(W_B + W_O\right)}_{W_{\text{ext}}}$

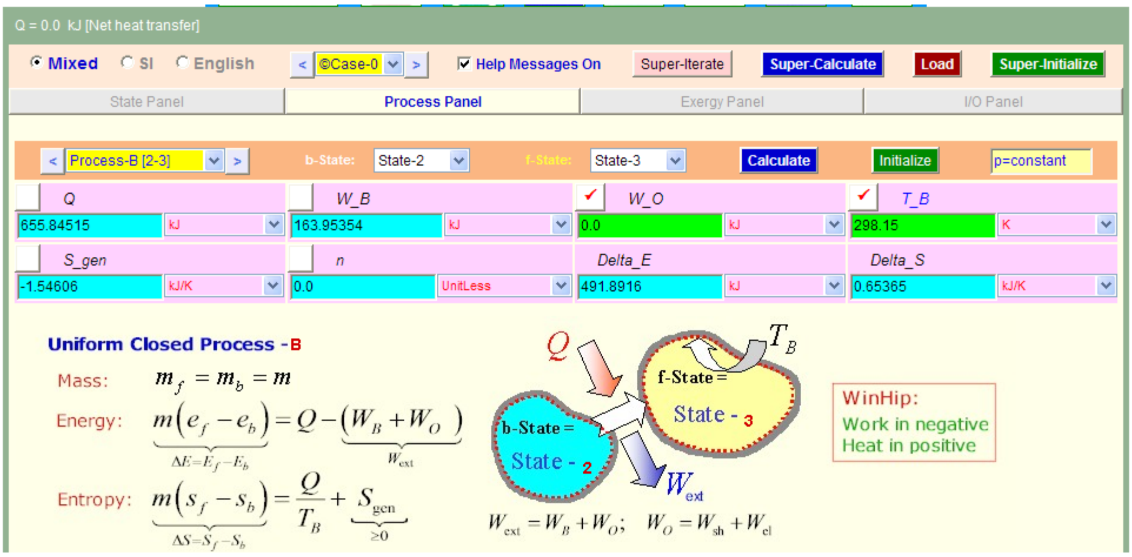
Entropy: $\underbrace{m\left(s_f - s_b\right)}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + \underbrace{S_{\text{gen}}}_{\geq 0}$

$W_{\text{ext}} = W_B + W_O;\quad W_O = W_{\text{sh}} + W_{\text{el}}$

WinHip:
Work in negative
Heat in positive

We see that: Work done in Process 1-2 = W_B = -70.09 kJ …(-ve sign means work is done on the gas)… Ans.

7. For Process B: enter State 2 and State 3 for b-State and f-State, W_O = 0 (i.e. Work other than Boundary work), and hit Enter. We get:



Q = 0.0 kJ [Net heat transfer]

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

Process-B [2-3]　b-State: State-2　f-State: State-3　p=constant

Q	W_B	☑ W_O	☑ T_B
655.84515 kJ	163.95354 kJ	0.0 kJ	298.15 K
S_gen	n	Delta_E	Delta_S
-1.54606 kJ/K	0.0 UnitLess	491.8916 kJ	0.65365 kJ/K

Uniform Closed Process -B

Mass: $m_f = m_b = m$

Energy: $\underbrace{m\left(e_f - e_b\right)}_{\Delta E = E_f - E_b} = Q - \underbrace{\left(W_B + W_O\right)}_{W_{\text{ext}}}$

Entropy: $\underbrace{m\left(s_f - s_b\right)}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + \underbrace{S_{\text{gen}}}_{\geq 0}$

$W_{\text{ext}} = W_B + W_O;\quad W_O = W_{\text{sh}} + W_{\text{el}}$

WinHip:
Work in negative
Heat in positive

We see that: Work done in Process 2-3 = W_B = 163.95 kJ …(+ve sign means work is done by the gas)… Ans.

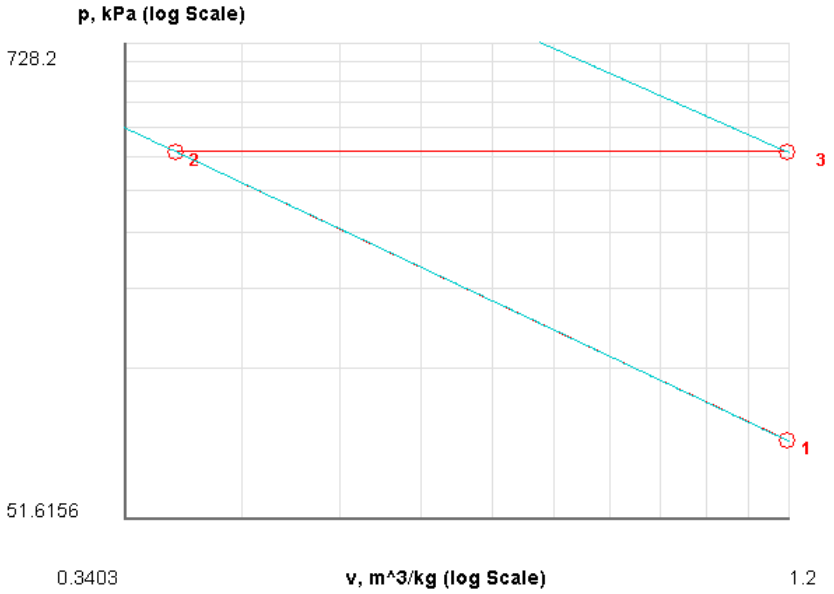
Heat transfer, Q = 655.85 kJ … Ans.

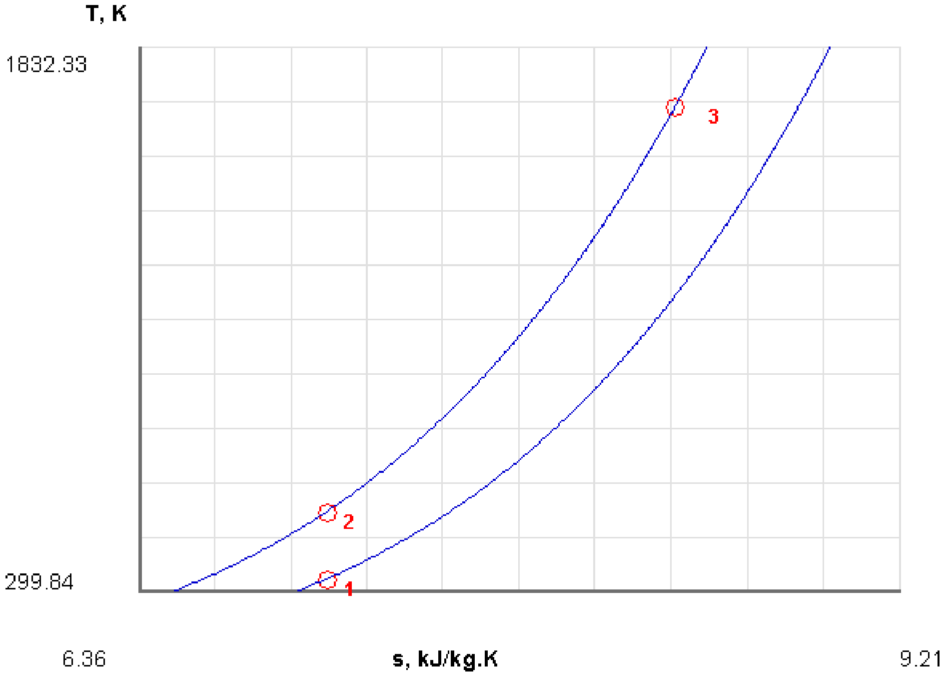
Therefore, for the whole cycle:

W_net = -70.08 + 163.95 = 93.86 kJ .. Ans.

Q_net = 0 + 655.85 = 655.85 kJ … Ans.

8. Draw the p-v and T-s diagrams from the Plots widget:





9. Click on SuperCalculate and get the TEST code etc from the I/O panel:

```
#~~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE (

#

#Daemon Path: Systems>Closed>Process>Generic>Uniform>IG-Model; v-10.ca08

#

#--------------------Start of TEST-code---------------------------------------------------------------

States	{

	State-1: Air;
	Given: { p1= 80.0 kPa; T1= 60.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 0.5 kg; }

	State-2: Air;
	Given: { p2= 400.0 kPa; s2= "s1" kJ/kg.K; Vel2= 0.0 m/s; z2= 0.0 m; m2= "m1" kg; }

	State-3: Air;
	Given: { p3= "P2" kPa; Vel3= 0.0 m/s; z3= 0.0 m; m3= "m2" kg; Vol3= "Vol1" m^3; }

	}

Analysis {

	Process-A: b-State = State-1; f-State = State-2;
	Given: { Q= 0.0 kJ; W_O= 0.0 kJ; T_B= 298.15 K; }

	Process-B: b-State = State-2; f-State = State-3;
	Given: { W_O= 0.0 kJ; T_B= 298.15 K; }
	}

#----------------------End of TEST-code-------------------------------------------------------------
```

```
#--------Property spreadsheet starts: #

#        State   p(kPa)      T(K)    v(m^3/kg)   u(kJ/kg)   h(kJ/kg)   s(kJ/kg)
#        1       80.0        333.2   1.1951      -60.38     35.23      7.062
#        2       400.0       523.2   0.3754      79.79      229.93     7.062
#        3       400.0       1665.8  1.1951      1063.58    1541.62    8.37
#
#--------Property spreadsheet ends-----------------------------------------------------------------

#
```

 # Mass, Energy, and Entropy Analysis Results:

```
#
#        Process-A: b-State = State-1; f-State = State-2;
#                 Given: Q= 0.0 kJ; W_O= 0.0 kJ; T_B= 298.15 K;
#        Calculated: W_B= -70.08581 kJ; S_gen= -0.0 kJ/K; n= 1.3896776 UnitLess; Delta_E= 70.08581
kJ; Delta_S= -0.0 kJ/K;
#
```

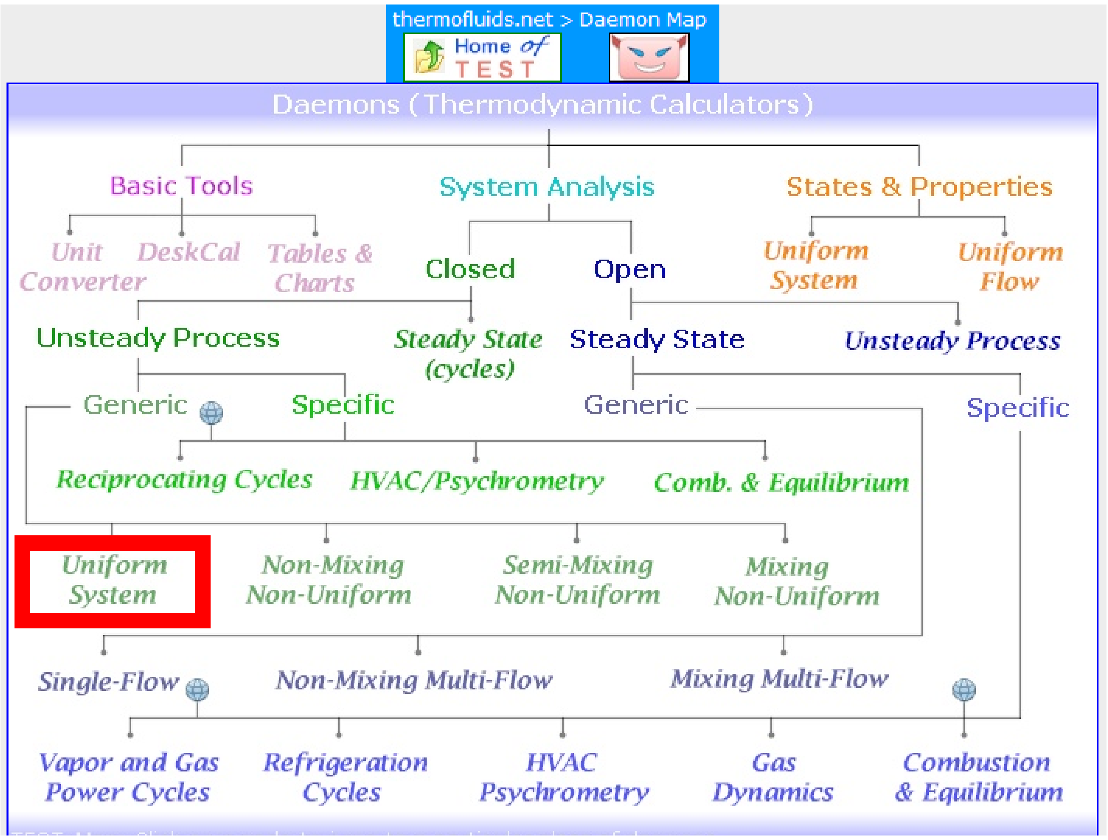
```
#         Process-B: b-State = State-2; f-State = State-3;
#                   Given: W_O= 0.0 kJ; T_B= 298.15 K;
#                   Calculated: Q= 655.84515 kJ; W_B= 163.95354 kJ; S_gen= -1.5460639 kJ/K; n= 0.0 UnitLess;
#                   Delta_E= 491.8916 kJ; Delta_S= 0.6536515 kJ/K;

=====================================================================
```

Prob.9.30. A quantity of air at a pressure of 100 kPa, 27 C, occupying a volume of 0.5 m^3 is compressed to a pressure of 500 kPa and volume of 0.12 m^3 according to the law p.v^n = const. Find: (i) value of index n (ii) mass of air (iii) work transfer (iv) heat transferred during the process, and (iv) change in entropy. [VTU – BTD – July 2007.]

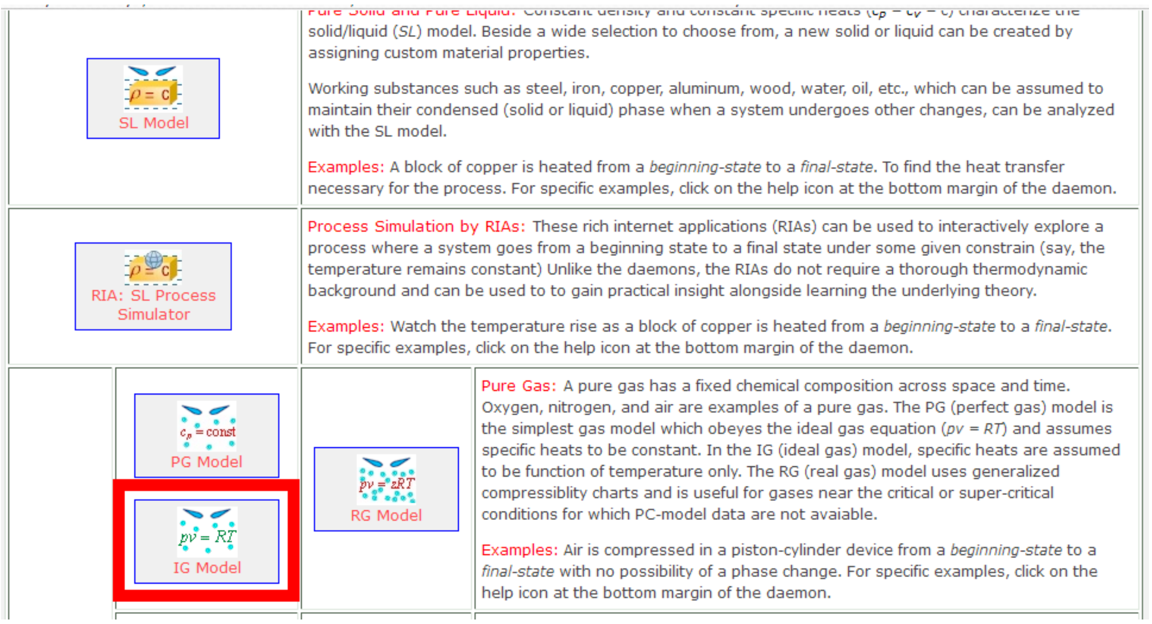
TEST Solution:

Following are the steps:

1. Select the System Analysis-Closed-Uniform System daemon:



2. For Material model, choose IG model:



Pure Solid and Pure Liquid: Constant density and constant specific heats ($c_p = c_v = c$) characterize the solid/liquid (*SL*) model. Beside a wide selection to choose from, a new solid or liquid can be created by assigning custom material properties.

Working substances such as steel, iron, copper, aluminum, wood, water, oil, etc., which can be assumed to maintain their condensed (solid or liquid) phase when a system undergoes other changes, can be analyzed with the SL model.

Examples: A block of copper is heated from a *beginning-state* to a *final-state*. To find the heat transfer necessary for the process. For specific examples, click on the help icon at the bottom margin of the daemon.

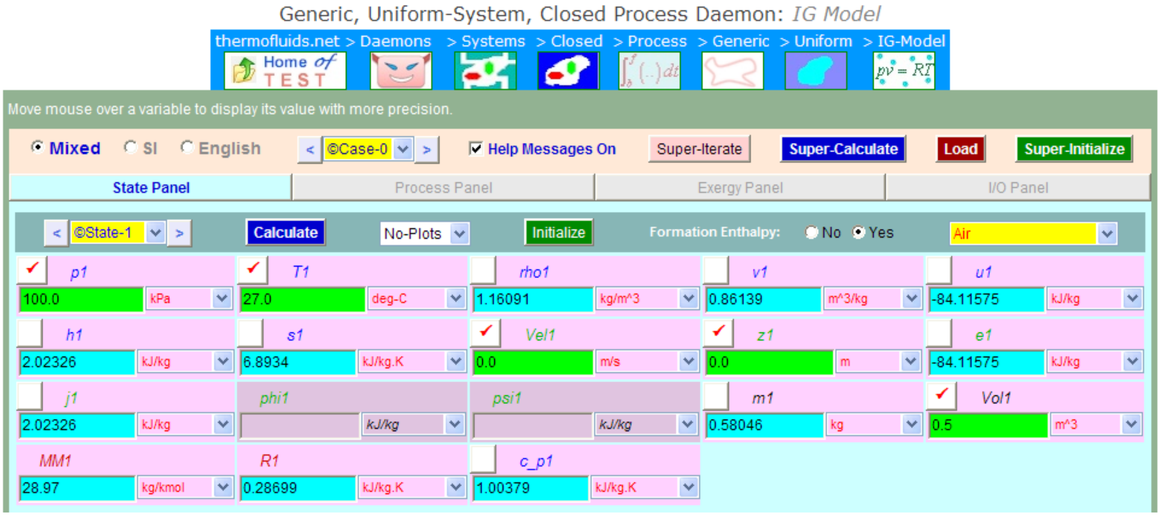
Process Simulation by RIAs: These rich internet applications (RIAs) can be used to interactively explore a process where a system goes from a beginning state to a final state under some given constrain (say, the temperature remains constant) Unlike the daemons, the RIAs do not require a thorough thermodynamic background and can be used to to gain practical insight alongside learning the underlying theory.

Examples: Watch the temperature rise as a block of copper is heated from a *beginning-state* to a *final-state*. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Gas: A pure gas has a fixed chemical composition across space and time. Oxygen, nitrogen, and air are examples of a pure gas. The PG (perfect gas) model is the simplest gas model which obeys the ideal gas equation (*pv = RT*) and assumes specific heats to be constant. In the IG (ideal gas) model, specific heats are assumed to be function of temperature only. The RG (real gas) model uses generalized compressiblity charts and is useful for gases near the critical or super-critical conditions for which PC-model data are not avaiable.

Examples: Air is compressed in a piston-cylinder device from a *beginning-state* to a *final-state* with no possibility of a phase change. For specific examples, click on the help icon at the bottom margin of the daemon.

3. Select Air as working substance, and for State 1, enter values of p1, T1 and Vol1. Hit Enter. Immediately, other properties are calculated:



Generic, Uniform-System, Closed Process Daemon: *IG Model*

Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English

☑ Help Messages On

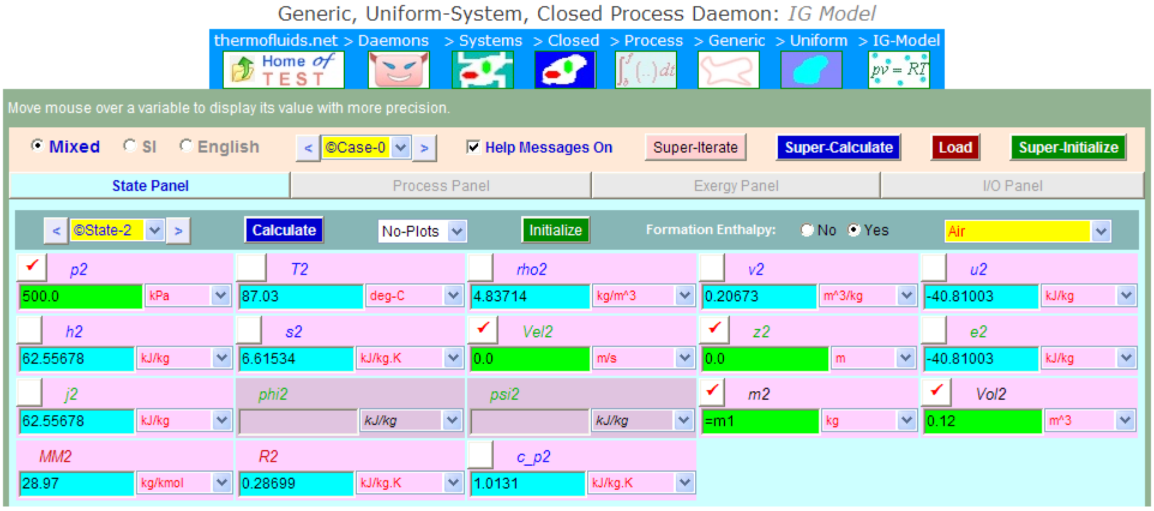
Formation Enthalpy: ○ No ● Yes

Air

☑ p1: 100.0 kPa
☑ T1: 27.0 deg-C
☐ rho1: 1.16091 kg/m^3
☐ v1: 0.86139 m^3/kg
☐ u1: -84.11575 kJ/kg
☐ h1: 2.02326 kJ/kg
☐ s1: 6.8934 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: -84.11575 kJ/kg
☐ j1: 2.02326 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: 0.58046 kg
☑ Vol1: 0.5 m^3
MM1: 28.97 kg/kmol
R1: 0.28699 kJ/kg.K
☐ c_p1: 1.00379 kJ/kg.K

Observe that: mass of air m1 = 0.58046 kg … Ans.

4. For State 2: enter p2, m2 = m1, and Vol2. Hit Enter. We get:



Generic, Uniform-System, Closed Process Daemon: *IG Model*

Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English

©Case-0

☑ Help Messages On

©State-2

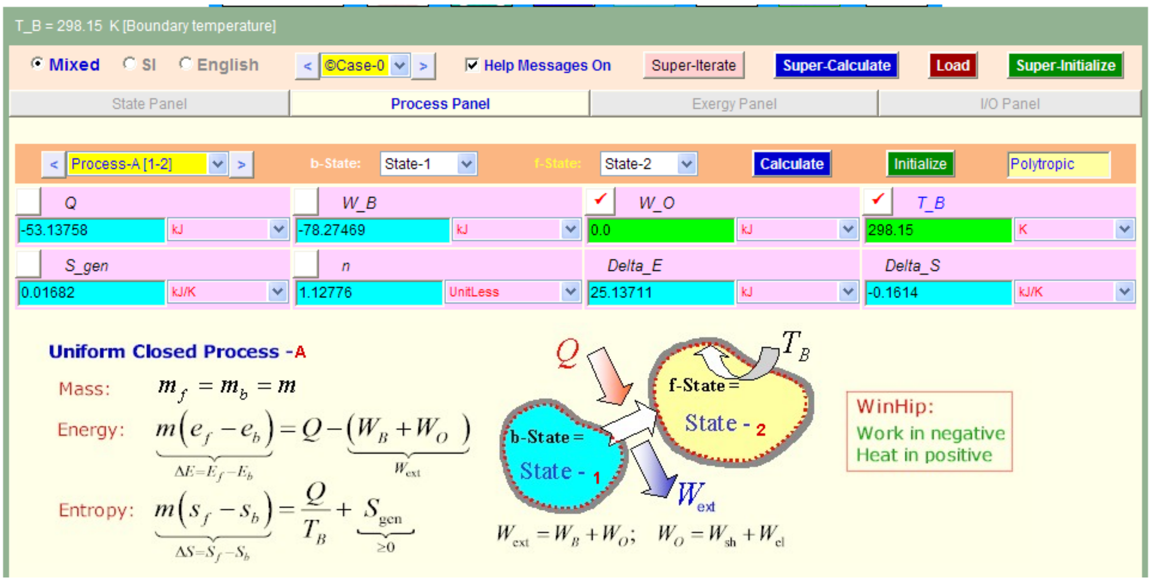
No-Plots

Formation Enthalpy: ○ No ● Yes

Air

✓ p2	☐ T2	☐ rho2	☐ v2	☐ u2
500.0 kPa	87.03 deg-C	4.83714 kg/m^3	0.20673 m^3/kg	-40.81003 kJ/kg
☐ h2	☐ s2	✓ Vel2	✓ z2	☐ e2
62.55678 kJ/kg	6.61534 kJ/kg.K	0.0 m/s	0.0 m	-40.81003 kJ/kg
☐ j2	phi2	psi2	✓ m2	✓ Vol2
62.55678 kJ/kg	kJ/kg	kJ/kg	=m1 kg	0.12 m^3
MM2	R2	☐ c_p2		
28.97 kg/kmol	0.28699 kJ/kg.K	1.0131 kJ/kg.K		

5. Now, go to Process Panel: For Process A, enter State 1 and State 2 for b-State and f-State. Also, W_O = 0. Hit Enter. We get:



T_B = 298.15 K [Boundary temperature]

Process-A [1-2]   b-State: State-1   f-State: State-2

Q: -53.13758 kJ
W_B: -78.27469 kJ
✓ W_O: 0.0 kJ
✓ T_B: 298.15 K
S_gen: 0.01682 kJ/K
n: 1.12776 UnitLess
Delta_E: 25.13711 kJ
Delta_S: -0.1614 kJ/K

Uniform Closed Process -A

Mass: $m_f = m_b = m$

Energy: $\underbrace{m\left(e_f - e_b\right)}_{\Delta E = E_f - E_b} = Q - \underbrace{\left(W_B + W_O\right)}_{W_{ext}}$

Entropy: $\underbrace{m\left(s_f - s_b\right)}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + \underbrace{S_{gen}}_{\geq 0}$

$W_{ext} = W_B + W_O; \quad W_O = W_{sh} + W_{el}$

Thus:

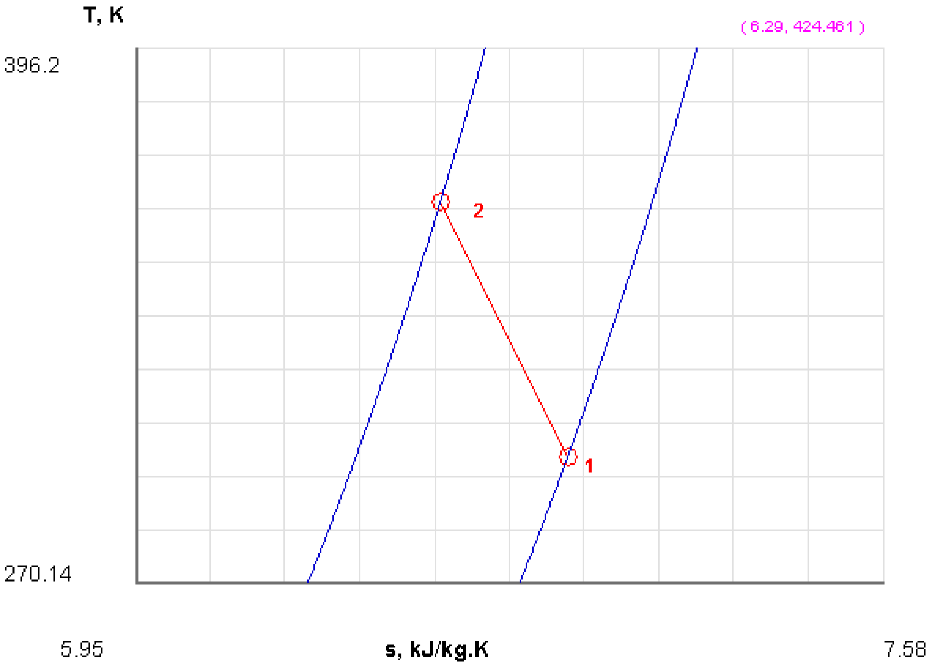
n = 1.12776, Mass of air = 0.58046 kg …. Ans.

Q = -53.14 kJ…heat rejected by the system… Ans.

W = -78.27 kJ ….work done on the system ….Ans.

Change in entropy of gas = Delta_S = -0.1614 kJ/K …Ans.

6. Get the T-s diagram from the Plots widget:



7. Click on SuperCalculate. Get the TEST code etc from the I/O panel:

```
#~~~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE

#

#Daemon Path: Systems>Closed>Process>Generic>Uniform>IG-Model; v-10.ca08

#

#--------------------Start of TEST-code--------------------------------------------------------------

States    {

          State-1: Air;
          Given: { p1= 100.0 kPa; T1= 27.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; Vol1= 0.5 m^3; }

          State-2: Air;
          Given: { p2= 500.0 kPa; Vel2= 0.0 m/s; z2= 0.0 m; m2= "m1" kg; Vol2= 0.12 m^3; }
          }
```

```
Analysis {

        Process-A: b-State = State-1; f-State = State-2;

        Given: { W_O= 0.0 kJ; T_B= 298.15 K; }

        }

#----------------------End of TEST-code------------------------------------------------------------

#
#--------Property spreadsheet starts: #
#       State   p(kPa)          T(K)    v(m^3/kg)       u(kJ/kg)        h(kJ/kg)        s(kJ/kg)
#       1       100.0           300.2   0.8614          -84.12          2.02            6.893
#       2       500.0           360.2   0.2067          -40.81          62.56   6.615
#
#--------Property spreadsheet ends------------------------------------------------------------------
#
```

```
# Mass, Energy, and Entropy Analysis Results:

#

#          Process-A: b-State = State-1; f-State = State-2;

#          Given: W_O= 0.0 kJ; T_B= 298.15 K;

#          Calculated: Q= -53.13758 kJ; W_B= -78.27469 kJ; S_gen= 0.01682128 kJ/K;

#          n= 1.1277552 UnitLess;

#          Delta_E= 25.137112 kJ; Delta_S= -0.16140303 kJ/K;

#

===============================================================================
```

Prob.9.31. Pressure and temperature of a mixture of 1 kg of O2 and 2 kg of N2 are 150 kPa and 20 C respectively. If the mixture is heated at constant pressure to a temp. of 100 C, determine the following: (i) change in enthalpy (ii) change in entropy (iii) change in int. energy.

Given: Cv of N2 = 0.743 kJ/kg.K and Cv of O2 = 0.65 kJ/kg.K. [VTU – BTD-Jan. 2005]

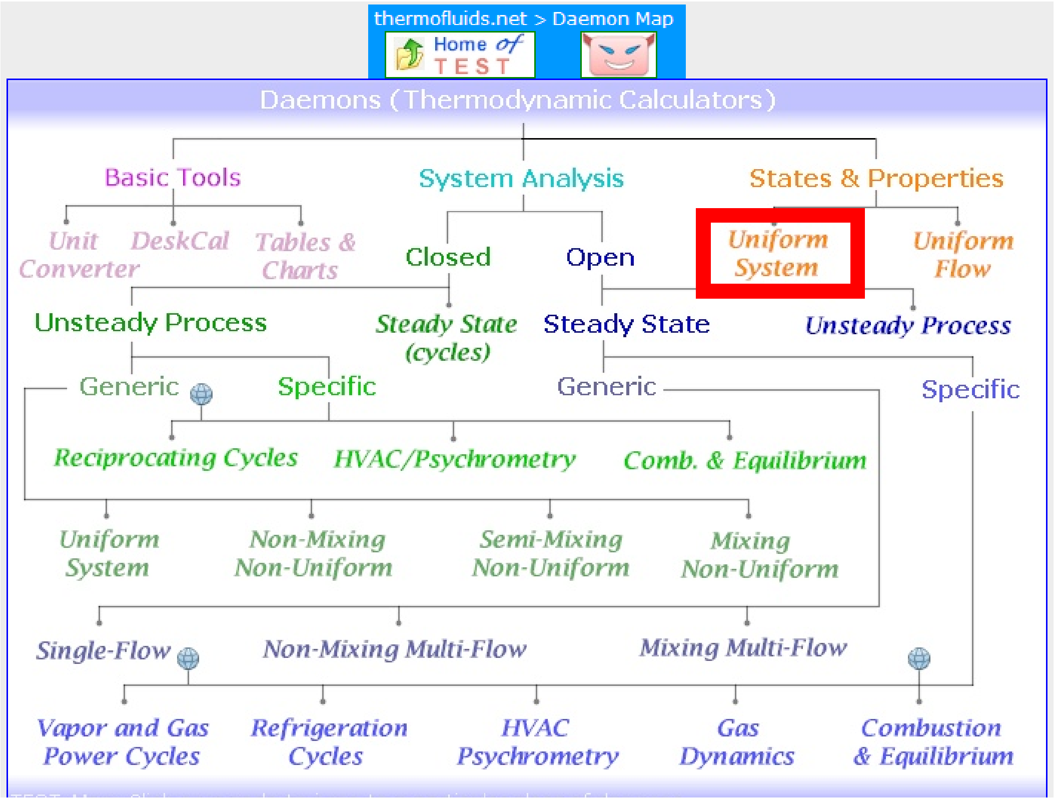
Note: This prob. Is the same as Prob.9.9 solved with Mathcad.

However, now we shall solve it with TEST. *Appreciate how easy it is to solve ideal gas mixture problems in TEST.*

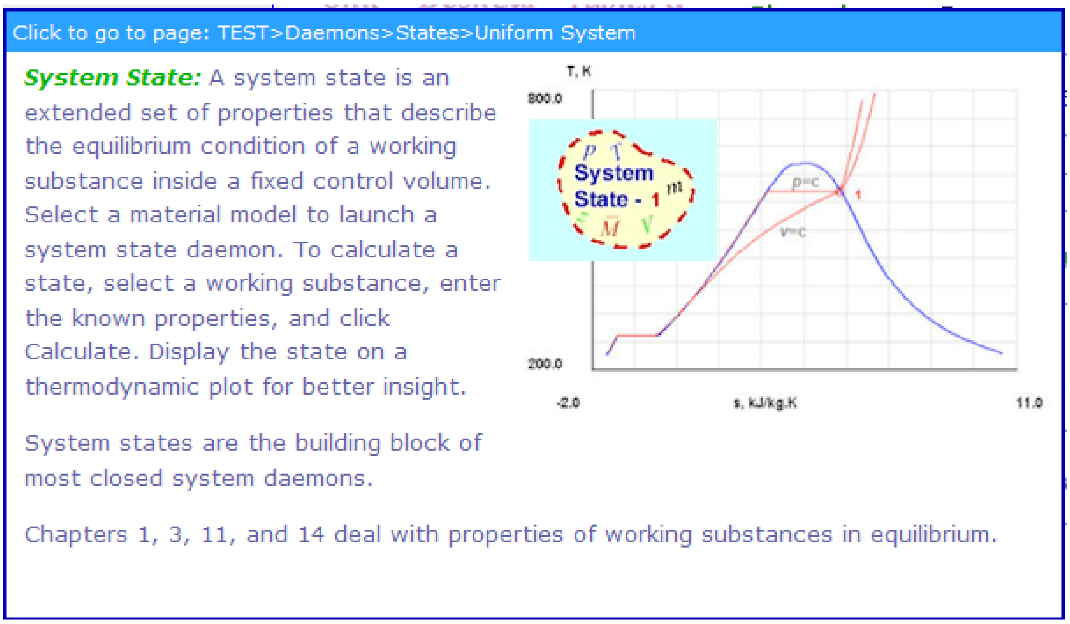
TEST Solution:

Following are the steps:

1. Go to Daemons tree, select States & Properties – Uniform System:



Hovering the mouse pointer on 'Uniform System' brings the following explanatory pop-up:



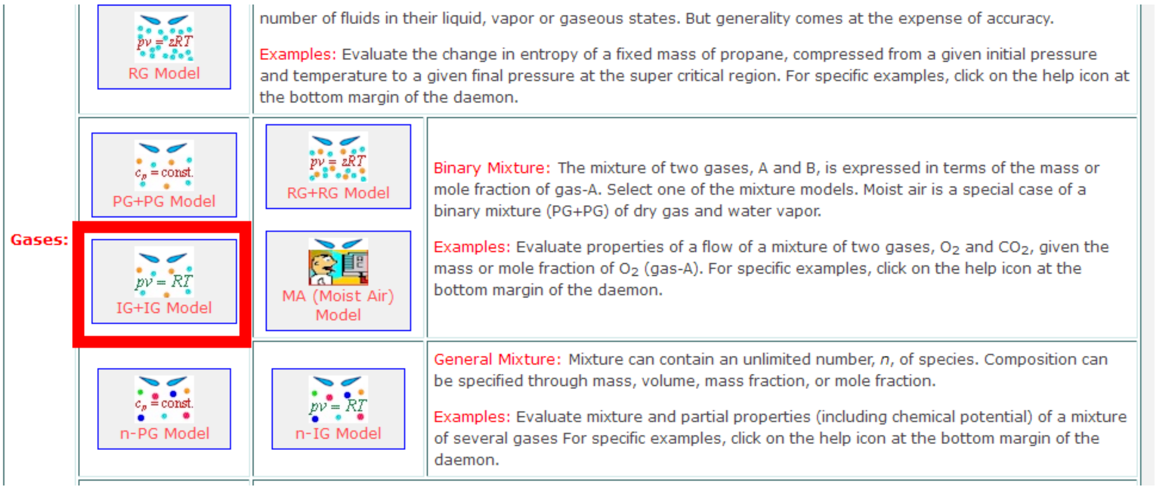
Click to go to page: TEST>Daemons>States>Uniform System

System State: A system state is an extended set of properties that describe the equilibrium condition of a working substance inside a fixed control volume. Select a material model to launch a system state daemon. To calculate a state, select a working substance, enter the known properties, and click Calculate. Display the state on a thermodynamic plot for better insight.

System states are the building block of most closed system daemons.

Chapters 1, 3, 11, and 14 deal with properties of working substances in equilibrium.

2. For Material model, select Binary mixtures – IG + IG model as shown below:



number of fluids in their liquid, vapor or gaseous states. But generality comes at the expense of accuracy.

Examples: Evaluate the change in entropy of a fixed mass of propane, compressed from a given initial pressure and temperature to a given final pressure at the super critical region. For specific examples, click on the help icon at the bottom margin of the daemon.

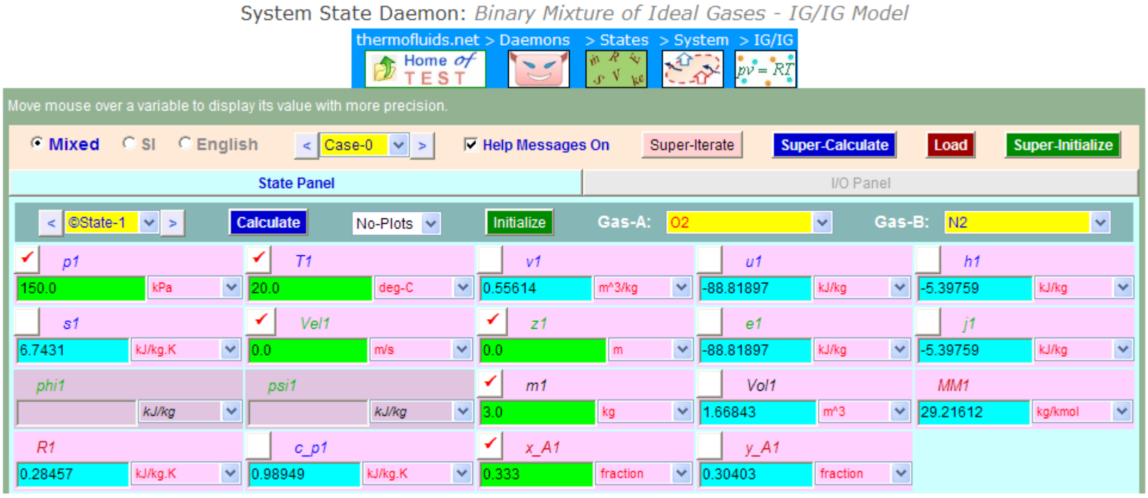
Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

General Mixture: Mixture can contain an unlimited number, *n*, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.

Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.

3. Select O2 for Gas-A and N2 for Gas-B. For State1, enter p1, T1, m1 (=3 kg for mixture), and x_A1 = mass fraction of Gas-A = 1/3 = 0.333. Remember that we have to enter either mass fraction x_A1 or mole fraction y_A1 for Gas-A only. Hit Enter. Immediately, all mixture properties are calculated.

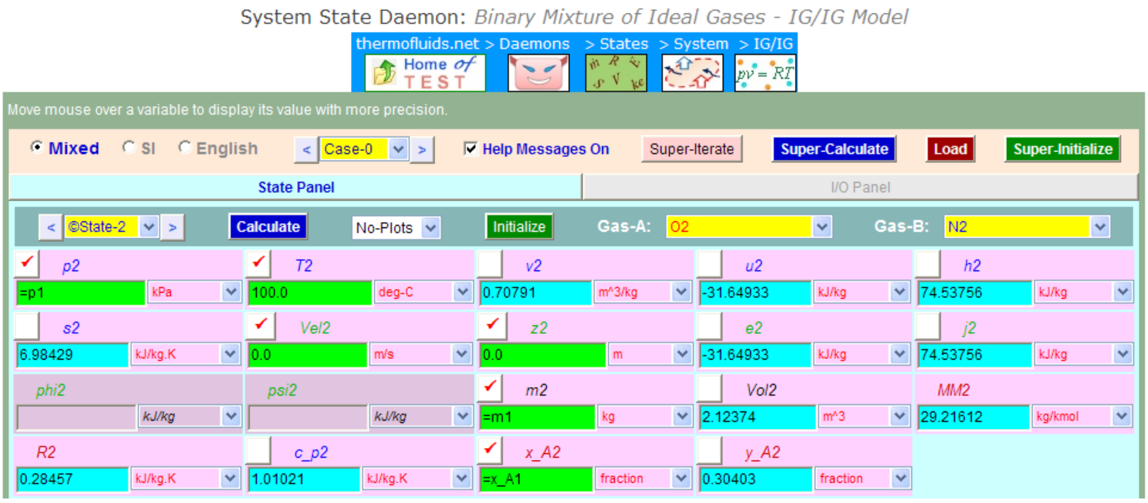


Gas-A: O2
Gas-B: N2

✓ p1	✓ T1	☐ v1	☐ u1	☐ h1
150.0 kPa	20.0 deg-C	0.55614 m^3/kg	-88.81897 kJ/kg	-5.39759 kJ/kg
☐ s1	✓ Vel1	✓ z1	☐ e1	☐ j1
6.7431 kJ/kg.K	0.0 m/s	0.0 m	-88.81897 kJ/kg	-5.39759 kJ/kg
phi1	psi1	✓ m1	☐ Vol1	MM1
kJ/kg	kJ/kg	3.0 kg	1.66843 m^3	29.21612 kg/kmol
R1	☐ c_p1	✓ x_A1	☐ y_A1	
0.28457 kJ/kg.K	0.98949 kJ/kg.K	0.333 fraction	0.30403 fraction	

Note from the above screen shot that mixture properties such as Mean Mol. wt. MM1, sp. heat of mixture, c_p1, Total volume of mixture, Vol1, entropy of mixture, s1 etc are immediately presented.

4. Now, go to State 2. Enter p2 = p1, T2, m2 = m1, x_A2 = x_A1, and hit Enter. We get for State 2 of the mixture:


System State Daemon: *Binary Mixture of Ideal Gases - IG/IG Model*

● Mixed ○ SI ○ English; Case-0; ☑ Help Messages On

State-2; No-Plots; Gas-A: O2; Gas-B: N2

☑ p2: =p1 kPa
☑ T2: 100.0 deg-C
☐ v2: 0.70791 m^3/kg
☐ u2: -31.64933 kJ/kg
☐ h2: 74.53756 kJ/kg
☐ s2: 6.98429 kJ/kg.K
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
☐ e2: -31.64933 kJ/kg
☐ j2: 74.53756 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
☑ m2: =m1 kg
☐ Vol2: 2.12374 m^3
MM2: 29.21612 kg/kmol
R2: 0.28457 kJ/kg.K
☐ c_p2: 1.01021 kJ/kg.K
☑ x_A2: =x_A1 fraction
☐ y_A2: 0.30403 fraction

5. Click on **SuperCalculate** and get the TEST code etc from the I/O panel:

```
#~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE

#

#        Daemon Path: States>System>IG-BinMixModel; v-10.ca08

#

#--------------------Start of TEST-code---------------------------------------------------------------------

States    {

          State-1: O2, N2;

          Given: { p1= 150.0 kPa; T1= 20.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 3.0 kg; x_A1= 0.333
fraction; }

          State-2: O2, N2;

          Given: { p2= “P1” kPa; T2= 100.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; m2= “m1” kg; x_A2= “x_A1”
fraction; }

          }

#----------------------End of TEST-code--------------------------------------------------------------------

#

#******DETAILED OUTPUT:

#

# Evaluated States:

#
#        State-1: O2, N2 > IG-BinMixModel;
#                 Given: p1= 150.0 kPa; T1= 20.0 deg-C; Vel1= 0.0 m/s;
#                        z1= 0.0 m; m1= 3.0 kg; x_A1= 0.333 fraction;
#
```

```
#               Calculated: v1= 0.5561 m^3/kg; u1= -88.819 kJ/kg; h1= -5.3976 kJ/kg;
#                           s1= 6.7431 kJ/kg.K; e1= -88.819 kJ/kg; j1= -5.3976 kJ/kg;
#                           Vol1= 1.6684 m^3; MM1= 29.2161 kg/kmol; R1= 0.2846 kJ/kg.K;
#                           c_p1= 0.9895 kJ/kg.K; y_A1= 0.304 fraction;
#
#       State-2: O2, N2 > IG-BinMixModel;
#               Given: p2= “P1” kPa; T2= 100.0 deg-C; Vel2= 0.0 m/s;
#                           z2= 0.0 m; m2= “m1” kg; x_A2= “x_A1” fraction;
#
#               Calculated: v2= 0.7079 m^3/kg; u2= -31.6493 kJ/kg; h2= 74.5376 kJ/kg;
#                           s2= 6.9843 kJ/kg.K; e2= -31.6493 kJ/kg; j2= 74.5376 kJ/kg;
#                           Vol2= 2.1237 m^3; MM2= 29.2161 kg/kmol; R2= 0.2846 kJ/kg.K;
#                           c_p2= 1.0102 kJ/kg.K; y_A2= 0.304 fraction;
#
#--------Property spreadsheet starts: #

# State  x_A    y_A    p(kPa)  T(K)    v(m3/kg)        u(kJ/kg)       h(kJ/kg)       s(kJ/kg)
# 1      0.33   0.3    150.0   293.1   0.5561          -88.82         -5.4           6.743
# 2      0.33          0.3     150.0   373.1   0.7079  -31.65         74.54          6.984

#

#******CALCULATE VARIABLES: Type in an expression starting with an ‘=’ sign (‘= mdot1*(h2-h1)’,
‘= sqrt(4*A1/PI)’, etc.) and press the Enter key)*********

#
```

 # Calculate change in enthalpy etc. in the I/O panel, using it as a calculator:

Change in enthalpy = m1*(h2-h1) = 239.80544471740723 = 239.81 kJ … Ans.

Change in entropy = m1*(s2-s1) = 0.7235612869262695 = 0.724 kJ/K … Ans.

Change in int. energy = m1*(u2-u1) = 171.50891876220703 = 171.51 kJ … Ans.

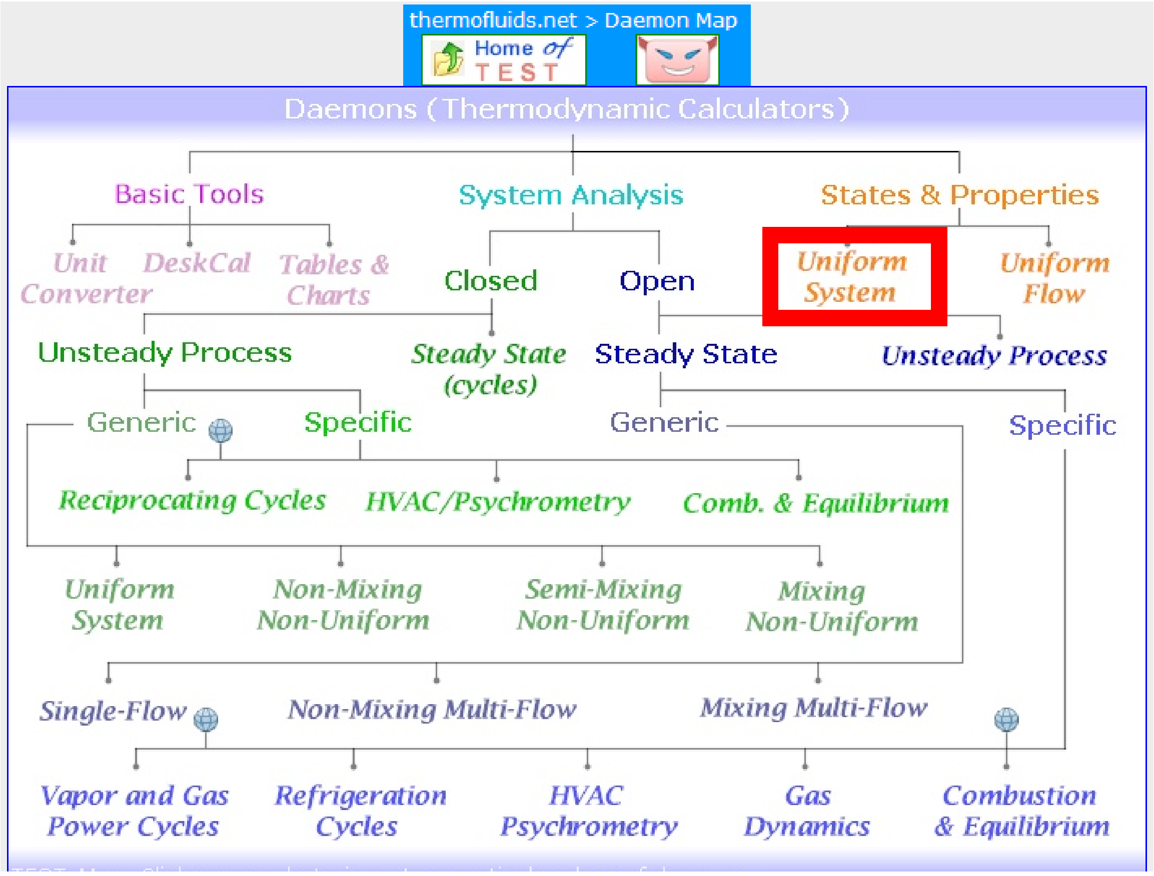
==

Prob.9.32. A gas mixture consists of 6 kmol of H2 and 4 kmol of N2. Determine the mass of each gas and the Gas const. of the mixture. [VTU – BTD – Jan. 2004]

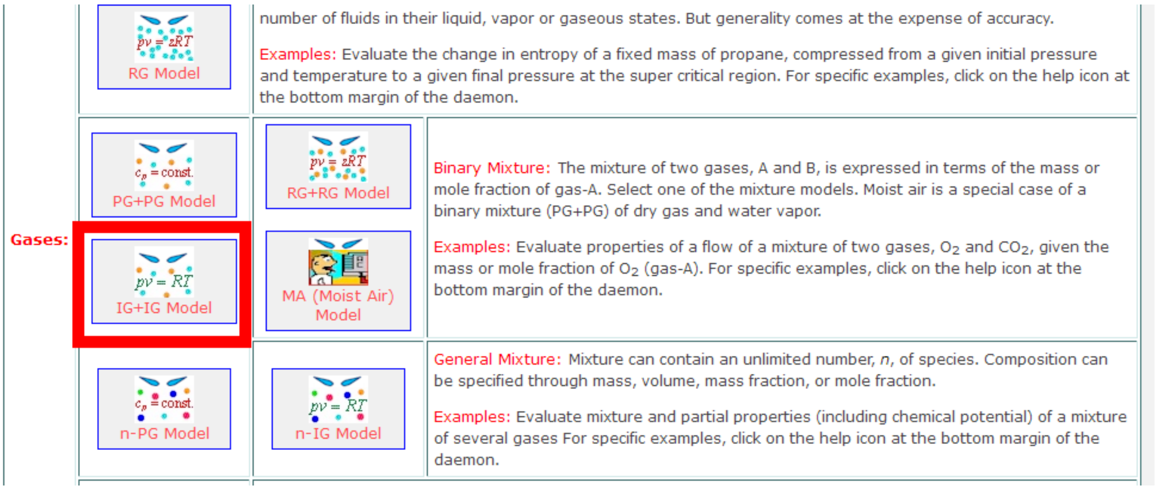
TEST Solution:

Following are the steps:

1. Go to Daemons tree, select States & Properties – Uniform System:



2. For Material model, select Binary mixtures – IG + IG model as shown below:



number of fluids in their liquid, vapor or gaseous states. But generality comes at the expense of accuracy.

Examples: Evaluate the change in entropy of a fixed mass of propane, compressed from a given initial pressure and temperature to a given final pressure at the super critical region. For specific examples, click on the help icon at the bottom margin of the daemon.

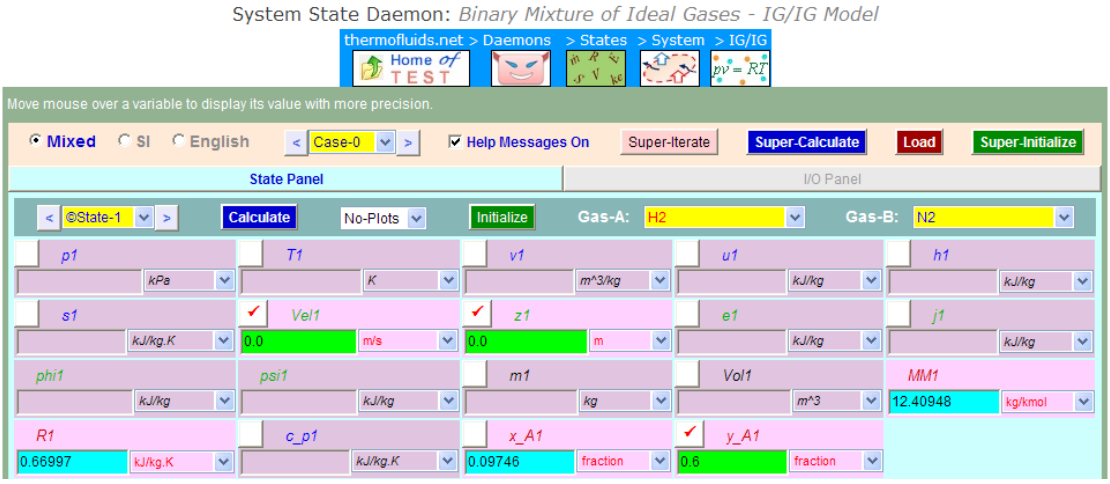
Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

General Mixture: Mixture can contain an unlimited number, *n*, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.

Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.

3. Select H2 for Gas-A and N2 for Gas-B. For State1, enter y_A1 = 0.6 (i.e. mole fraction for Gas-A), and hit Enter. Immediately, Gas const. for mixture (i.e. R1) and Mol. wt. for the mixture, MM1 are calculated.


System State Daemon: *Binary Mixture of Ideal Gases - IG/IG Model*

thermofluids.net > Daemons > States > System > IG/IG

Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

State Panel

State-1

No-Plots

Gas-A: H2

Gas-B: N2

Vel1: 0.0 m/s

z1: 0.0 m

MM1: 12.40948 kg/kmol

R1: 0.66997 kJ/kg.K

x_A1: 0.09746 fraction

y_A1: 0.6 fraction

Note from the above screen shot that for the mixture:

Mean Mol. wt. MM1 = 12.409 kg/mol … Ans.

Gas const. for mixture, R1 = 0.66997 kJ/kg.K…. Ans.

Mass of H2 and N2:

We see that mass fraction, x_A1 for H2 is 0.09746.

i.e. If the mixture mass is 1 kg,

Mass of H2 in the mixture = 0.09746 kg … Ans.

Mass of N2 in the mixture = 1 – 0.09746 = 0.9025 kg …. Ans.

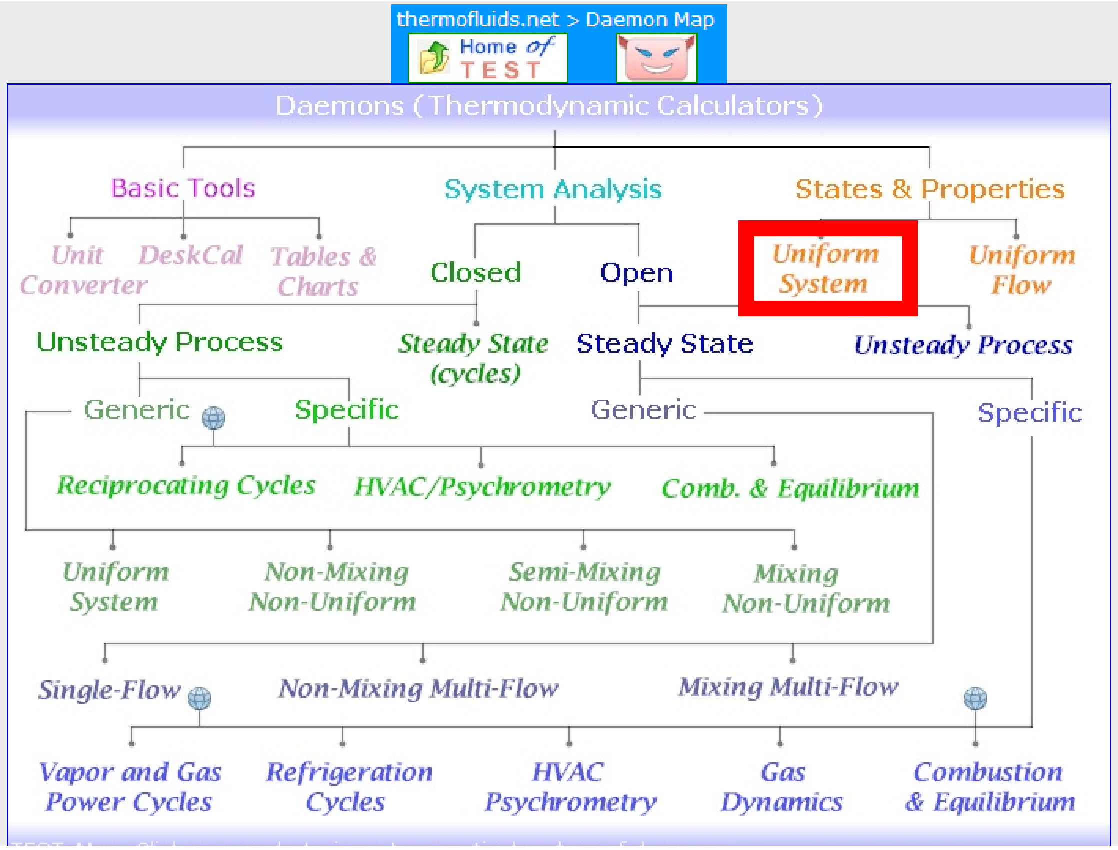
==

Prob.9.33. The gravimetric analysis of dry air is: O2 = 23%, and N2 = 77%. Calculate for air at 100 kPa and 15 C: (i) Mole fractions of components, (ii) The Gas const. (iii) Mol. wt. (iv) The respective partial pressures. [VTU – BTD – July 2003]

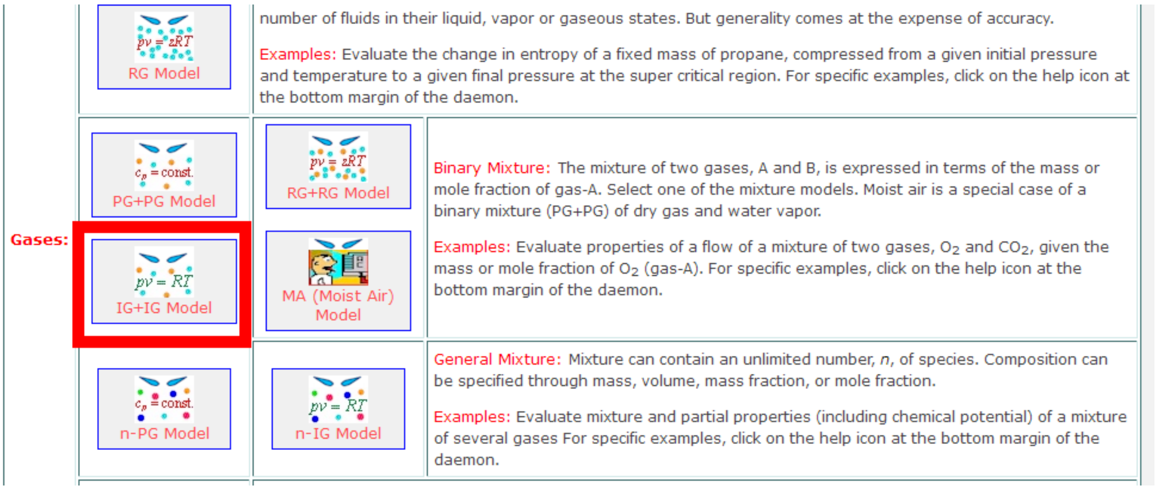
TEST Solution:

Following are the steps:

1. Go to Daemons tree, select States & Properties – Uniform System:



2. For Material model, select Binary mixtures – IG + IG model as shown below:



number of fluids in their liquid, vapor or gaseous states. But generality comes at the expense of accuracy.

Examples: Evaluate the change in entropy of a fixed mass of propane, compressed from a given initial pressure and temperature to a given final pressure at the super critical region. For specific examples, click on the help icon at the bottom margin of the daemon.

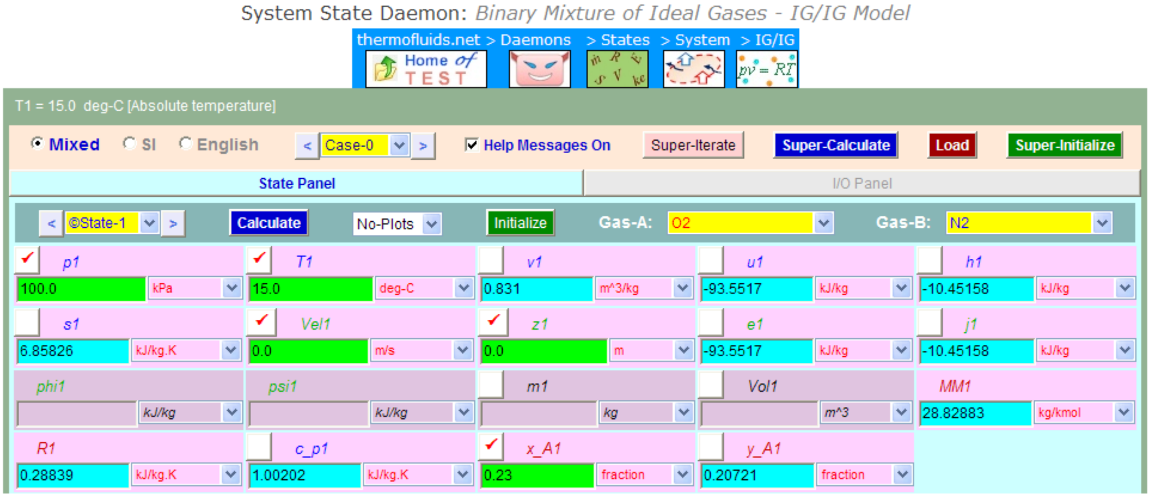
Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

General Mixture: Mixture can contain an unlimited number, *n*, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.

Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.

3. Select O2 for Gas-A and N2 for Gas-B. For State1, enter values of p1, T1, and mass fraction of O2 = x_A1 = 0.23 and hit Enter. Immediately, mole fraction y_A1 for O2, Gas const. for mixture (i.e. R1) and Mol. wt. for the mixture, MM1 are calculated.


System State Daemon: *Binary Mixture of Ideal Gases - IG/IG Model*

T1 = 15.0 deg-C [Absolute temperature]

● Mixed ○ SI ○ English Case-0 ☑ Help Messages On

State-1 No-Plots Gas-A: O2 Gas-B: N2

☑ p1 = 100.0 kPa
☑ T1 = 15.0 deg-C
☐ v1 = 0.831 m^3/kg
☐ u1 = -93.5517 kJ/kg
☐ h1 = -10.45158 kJ/kg
☐ s1 = 6.85826 kJ/kg.K
☑ Vel1 = 0.0 m/s
☑ z1 = 0.0 m
☐ e1 = -93.5517 kJ/kg
☐ j1 = -10.45158 kJ/kg
phi1 = kJ/kg
psi1 = kJ/kg
☐ m1 = kg
☐ Vol1 = m^3
MM1 = 28.82883 kg/kmol
R1 = 0.28839 kJ/kg.K
☐ c_p1 = 1.00202 kJ/kg.K
☑ x_A1 = 0.23 fraction
☐ y_A1 = 0.20721 fraction

We see from the above screen shot that:

Mole fraction of O2 = y_A1 = 0.20721 = 20.72% … Ans.

Therefore, mole fraction of N2 = 1 – 0.20721 = 0.79279 = 79.28%

Gas const. for the mixture = R1 = 0.28839 kJ/kg.K … Ans.

Partial pressures:

For O2: p_O2 = 0.20721 * 100 = 20.721 kPa … Ans.

For N2: p_N2 = 0.79279 * 100 = 79.279 kPa … Ans.

4. Click on **SuperCalculate** to get the TEST code etc:

```
#~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE

#

#         Daemon Path: States>System>IG-BinMixModel; v-10.ca08

#

#--------------------Start of TEST-code-----------------------------------------------------------------------

States    {

          State-1: O2, N2;

          Given: { p1= 100.0 kPa; T1= 15.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; x_A1= 0.23 fraction; }

          }

#---------------------End of TEST-code----------------------------------------------------------------------

#******DETAILED OUTPUT:

#

# Evaluated States:

#
#         State-1: O2, N2 > IG-BinMixModel;
#                   Given: p1= 100.0 kPa; T1= 15.0 deg-C; Vel1= 0.0 m/s;
#                             z1= 0.0 m; x_A1= 0.23 fraction;
#                   Calculated: v1= 0.831 m^3/kg; u1= -93.5517 kJ/kg; h1= -10.4516 kJ/kg;
#                             s1= 6.8583 kJ/kg.K; e1= -93.5517 kJ/kg; j1= -10.4516 kJ/kg;
#                             MM1= 28.8288 kg/kmol; R1= 0.2884 kJ/kg.K; c_p1= 1.002 kJ/kg.K;
#                             y_A1= 0.2072 fraction;
#

========================================================================
```

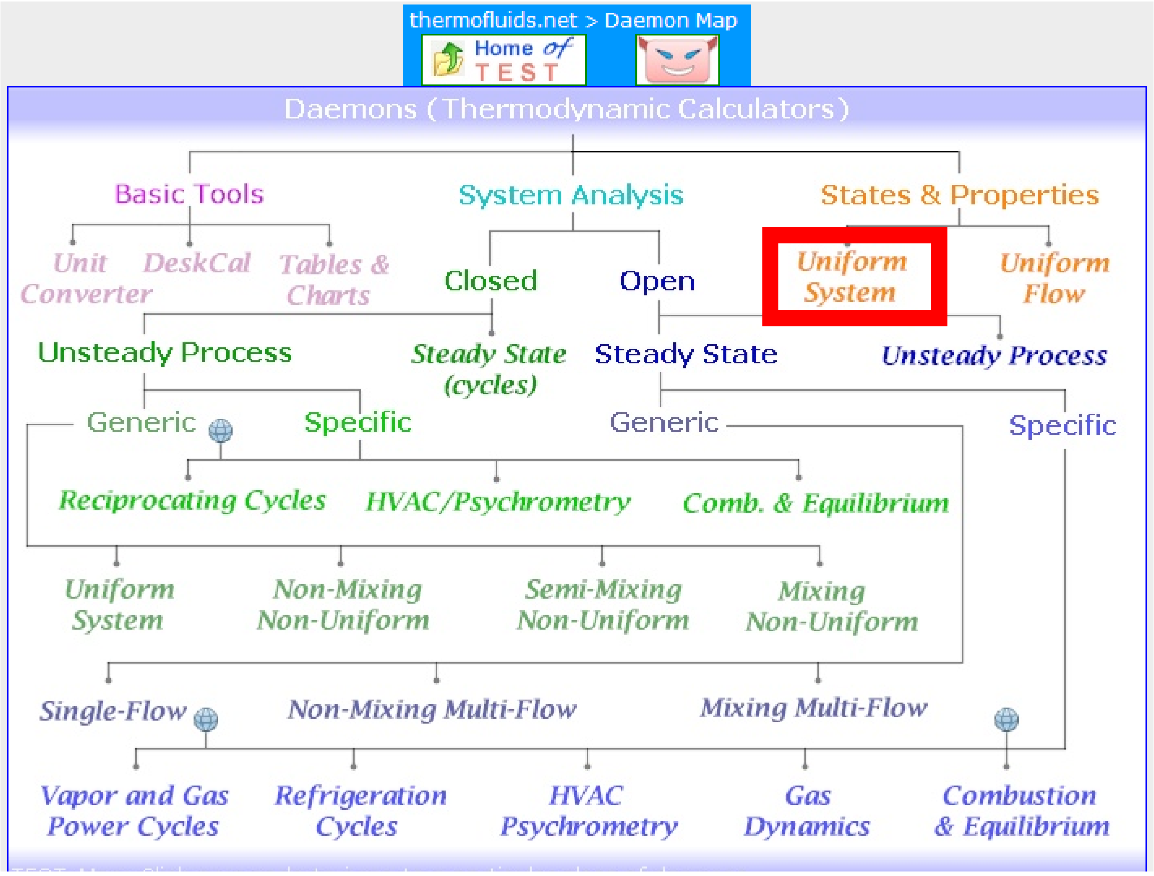
Prob.9.34. Determine the sp.vol.of H2 gas when its pressure is 60 bar and temp is 100 K, by using the compressibility chart. [VTU – BTD – Jan. 2003]

TEST Solution:

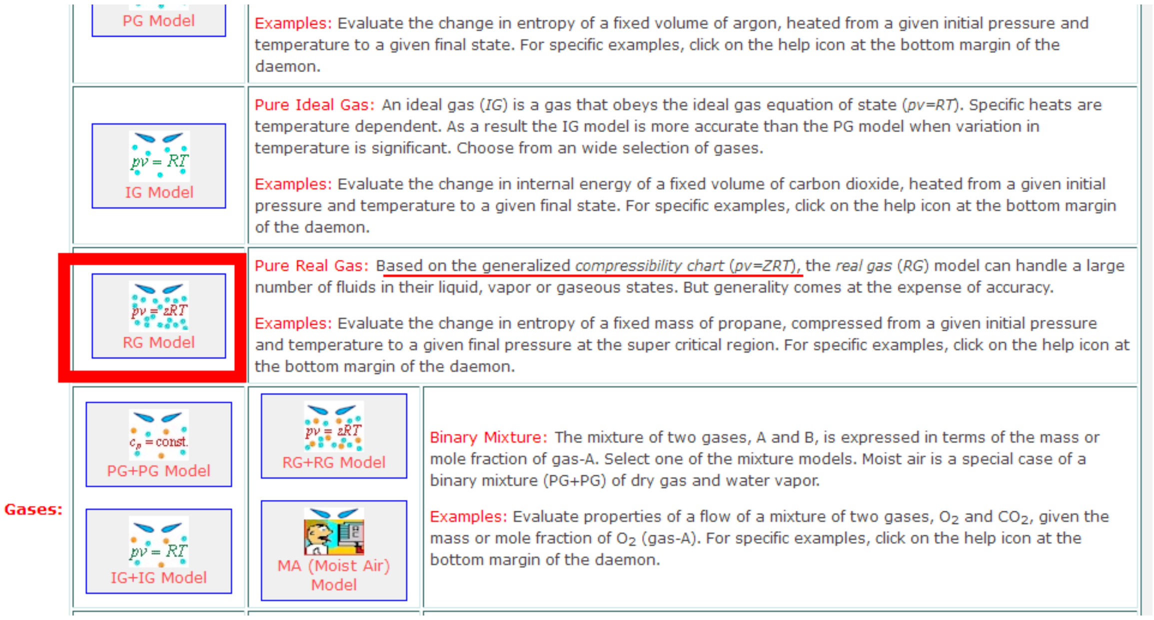
Result of using the compressibility chart is obtained very easily with TEST:

Following are the steps:

1. Go to Daemons tree, select States & Properties – Uniform System:



2. For Material model, select Gases – RG (Real Gas) model as shown below. ***Observe that it is based on generalized compressibility chart.***



Examples: Evaluate the change in entropy of a fixed volume of argon, heated from a given initial pressure and temperature to a given final state. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Ideal Gas: An ideal gas (*IG*) is a gas that obeys the ideal gas equation of state (*pv=RT*). Specific heats are temperature dependent. As a result the IG model is more accurate than the PG model when variation in temperature is significant. Choose from an wide selection of gases.

Examples: Evaluate the change in internal energy of a fixed volume of carbon dioxide, heated from a given initial pressure and temperature to a given final state. For specific examples, click on the help icon at the bottom margin of the daemon.

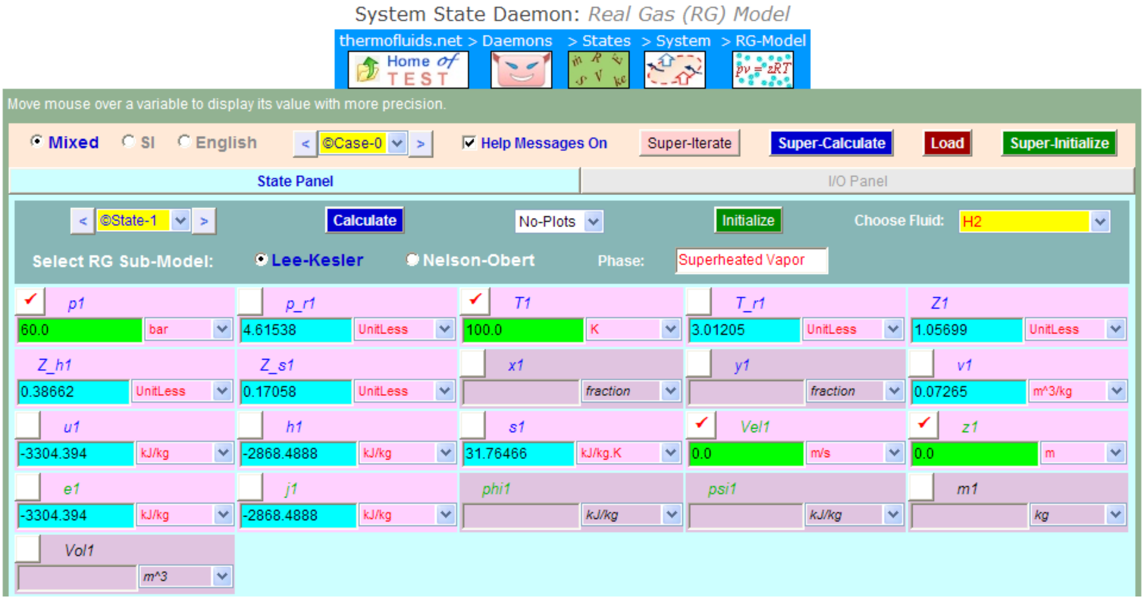
Pure Real Gas: Based on the generalized *compressibility chart* (*pv=ZRT*), the *real gas* (RG) model can handle a large number of fluids in their liquid, vapor or gaseous states. But generality comes at the expense of accuracy.

Examples: Evaluate the change in entropy of a fixed mass of propane, compressed from a given initial pressure and temperature to a given final pressure at the super critical region. For specific examples, click on the help icon at the bottom margin of the daemon.

Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

3. Select H2 for the substance. For State1, enter values of p1, T1 hit Enter. Immediately, many properties of H2 are calculated:



Choose Fluid: H2

Select RG Sub-Model: ● Lee-Kesler ○ Nelson-Obert

Phase: Superheated Vapor

✓ p1: 60.0 bar
☐ p_r1: 4.61538 UnitLess
✓ T1: 100.0 K
☐ T_r1: 3.01205 UnitLess
Z1: 1.05699 UnitLess
Z_h1: 0.38662 UnitLess
Z_s1: 0.17058 UnitLess
☐ x1: fraction
☐ y1: fraction
☐ v1: 0.07265 m^3/kg
☐ u1: -3304.394 kJ/kg
☐ h1: -2868.4888 kJ/kg
☐ s1: 31.76466 kJ/kg.K
✓ Vel1: 0.0 m/s
✓ z1: 0.0 m
☐ e1: -3304.394 kJ/kg
☐ j1: -2868.4888 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: kg
☐ Vol1: m^3

Observe that sp. volume = v1 = 0.07265 m^3/kg … Ans.

4. Click on **SuperCalculate**, and get the TEST code etc from the I/O panel:

```
#~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE

#        Daemon Path: States>System>RG-Model; v-10.ca08

#

#------------------Start of TEST-code-----------------------------------------------------------------------

States   {

        State-1: H2;

        Given: { p1= 60.0 bar; T1= 100.0 K; Vel1= 0.0 m/s; z1= 0.0 m; }

        }

#--------------------End of TEST-code------------------------------------------------------------------------
```

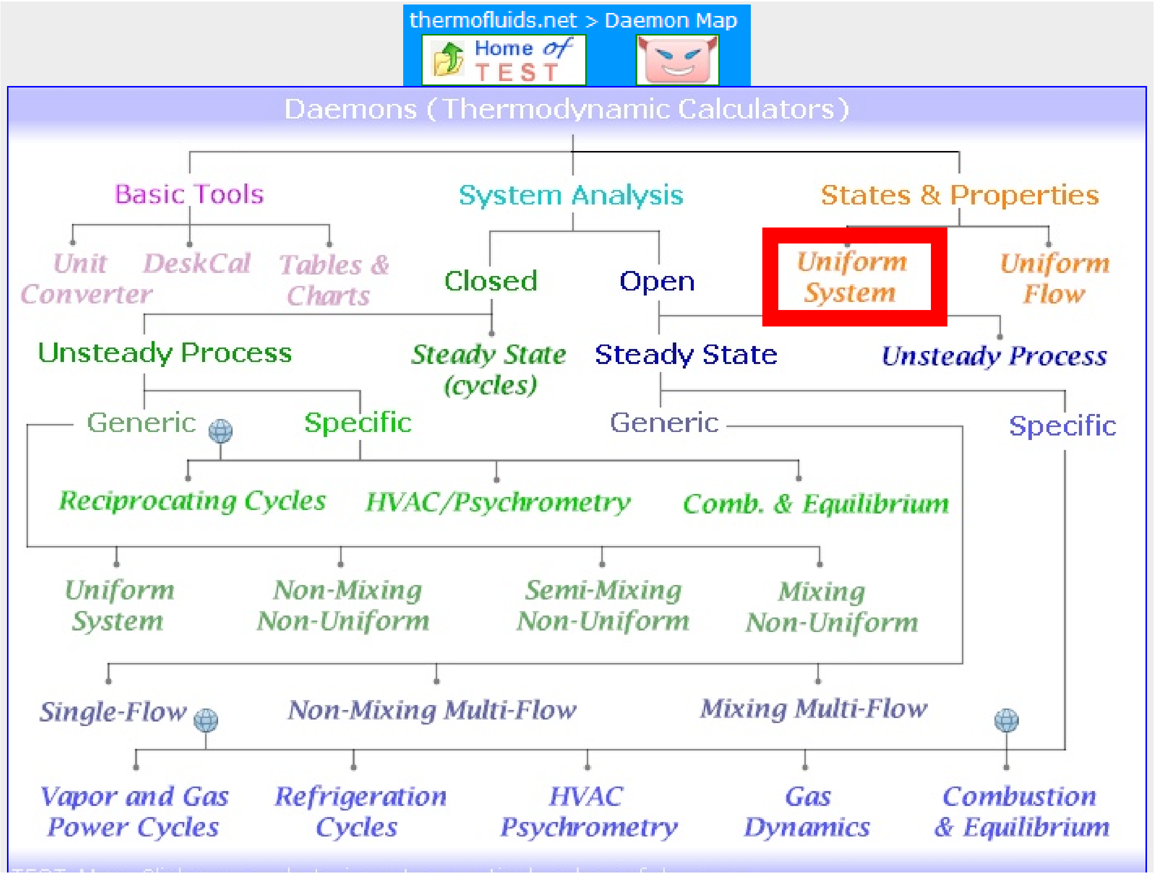
```
#

#******DETAILED OUTPUT:

#

# Evaluated States:

#
#        State-1: H2 > Superheated Vapor;
#                Given: p1= 60.0 bar; T1= 100.0 K; Vel1= 0.0 m/s;
#                        z1= 0.0 m;
#        Calculated: p_r1= 4.6154 UnitLess; T_r1= 3.012 UnitLess; Z1= 1.057 UnitLess;
#                        Z_h1= 0.3866 UnitLess; Z_s1= 0.1706 UnitLess; v1= 0.0727 m^3/kg;
#                        u1= -3304.394 kJ/kg; h1= -2868.4888 kJ/kg; s1= 31.7647 kJ/kg.K;
#                        e1= -3304.394 kJ/kg; j1= -2868.4888 kJ/kg;
#

===============================================================================
```

Prob.9.35. A mixture of H2 and O2 is in the ratio 2 to 1 by volume. Find the mass of H2 required and the volume of container per kg of O2 if the temp and pressure of the mixture are to be 300 K and 100 kPa respectively. [VTU – BTD – July 2002]

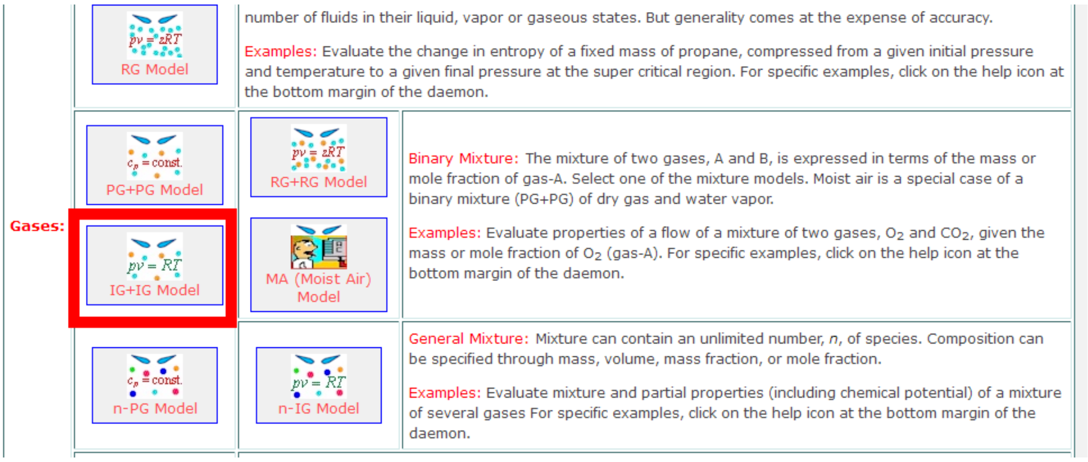
TEST Solution:

Following are the steps:

1. Go to Daemons tree, select States & Properties – Uniform System:



2. For Material model, select Binary mixtures – IG + IG model as shown below:



number of fluids in their liquid, vapor or gaseous states. But generality comes at the expense of accuracy.

Examples: Evaluate the change in entropy of a fixed mass of propane, compressed from a given initial pressure and temperature to a given final pressure at the super critical region. For specific examples, click on the help icon at the bottom margin of the daemon.

Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

General Mixture: Mixture can contain an unlimited number, *n*, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.

Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.

3. Select H2 for Gas-A and O2 for Gas-B. For State1, enter values of p1, T1, and mole fraction of H2 = y_A1 = 2/3 = 0.6667 and hit Enter. Immediately, mass fraction x_A1 for H2, Gas const. for mixture (i.e. R1) and Mol. wt. for the mixture, MM1 are calculated.

Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

©State-1

No-Plots

Gas-A: H2

Gas-B: O2

☑ p1 = 100.0 kPa
☑ T1 = 300.0 K
☐ v1 = 2.07685 m^3/kg
☐ u1 = -203.75261 kJ/kg
☐ h1 = 3.93237 kJ/kg
☐ s1 = 13.40953 kJ/kg.K
☑ Vel1 = 0.0 m/s
☑ z1 = 0.0 m
☐ e1 = -203.75262 kJ/kg
☐ j1 = 3.93237 kJ/kg
phi1 = kJ/kg
psi1 = kJ/kg
☐ m1 = kg
☐ Vol1 = m^3
MM1 = 12.00953 kg/kmol
R1 = 0.69228 kJ/kg.K
☐ c_p1 = 2.40818 kJ/kg.K
☐ x_A1 = 0.11191 fraction
☑ y_A1 = 0.6667 fraction

==

We observe that:

Mass fraction of H2 = x_A1 = 0.11191

Then, mass fraction of O2 = 1 – 0.11191 = 0.88809

Therefore, for 1 kg of O2:

Mass of mixture = 1/0.88809 = 1.126 kg.

And, Mass of H2 = 1.126 – 1 = 0.126 kg …. Ans.

Now, go to the above State panel, and enter mass of mixture, m1 = 1.126 kg, and hit Enter.

We get:

T1 = 300.0 K [Absolute temperature]

● Mixed ○ SI ○ English | ©Case-0 | ☑ Help Messages On

©State-1 | No-Plots | Gas-A: H2 | Gas-B: O2

☑ p1	☑ T1	☐ v1	☐ u1	☐ h1
100.0 kPa	300.0 K	2.07685 m^3/kg	-203.75261 kJ/kg	3.93237 kJ/kg
☐ s1	☑ Vel1	☑ z1	☐ e1	☐ j1
13.40953 kJ/kg.K	0.0 m/s	0.0 m	-203.75262 kJ/kg	3.93237 kJ/kg
phi1	psi1	☑ m1	☐ Vol1	MM1
kJ/kg	kJ/kg	1.126 kg	2.33853 m^3	12.00953 kg/kmol
R1	☐ c_p1	☐ x_A1	☑ y_A1	
0.69228 kJ/kg.K	2.40818 kJ/kg.K	0.11191 fraction	0.6667 fraction	

Thus:

Volume of mixture (i.e. volume of container required) = Vol1 = 2.33853 m^3 … Ans.

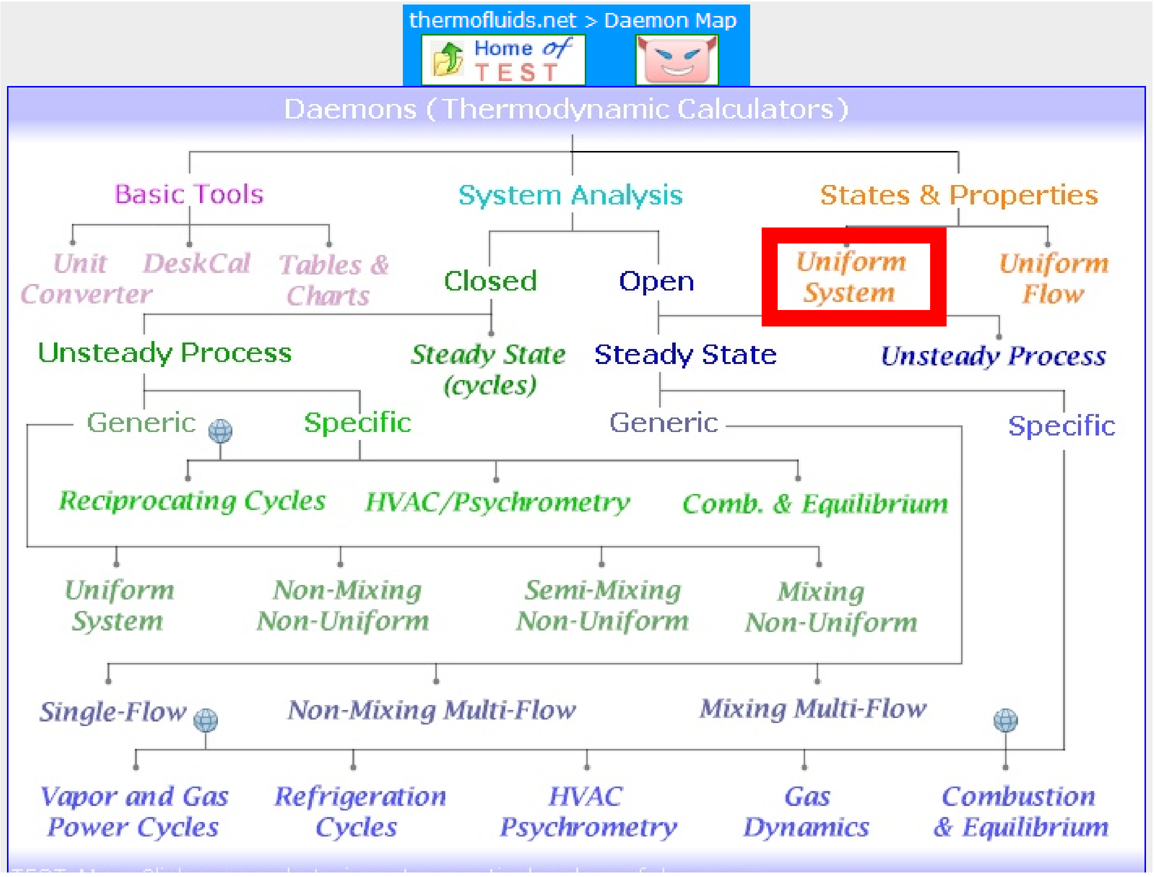
==

Prob.9.36. A mixture of 0.5 kg of CO2 and 0.3 kg of N2 is compressed from P1 = 1 bar, T1 = 20 C to P2 = 5 bar in a polytropic process for which n = 1.3. Find (i) the final temp (ii) work (iii) heat transfer (iv) change in entropy of the mixture. [VTU – BTD – Dec. 2012]

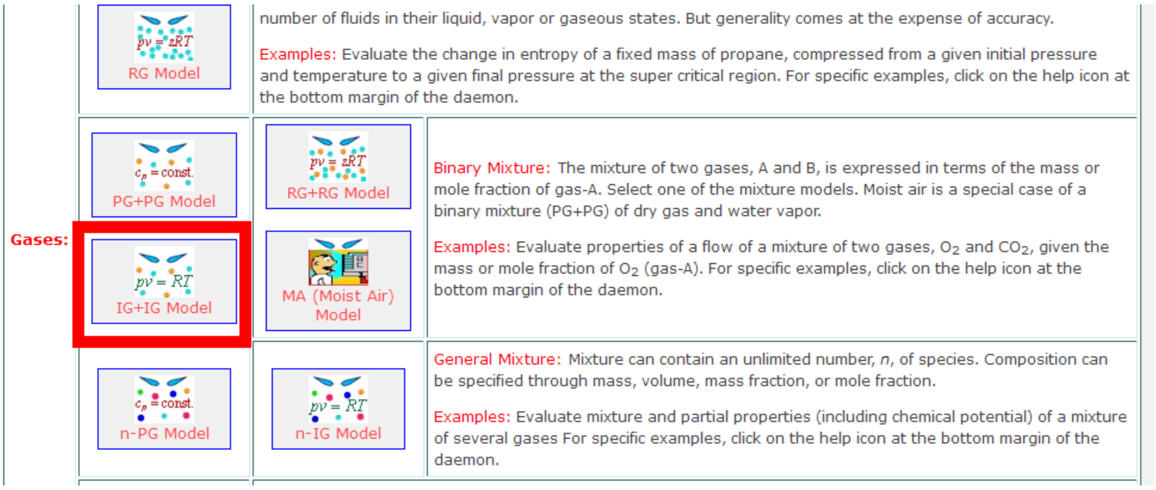
TEST Solution:

Following are the steps:

1. Go to Daemons tree, select States & Properties – Uniform System:



2. For Material model, select Binary mixtures – IG + IG model as shown below:



number of fluids in their liquid, vapor or gaseous states. But generality comes at the expense of accuracy.

Examples: Evaluate the change in entropy of a fixed mass of propane, compressed from a given initial pressure and temperature to a given final pressure at the super critical region. For specific examples, click on the help icon at the bottom margin of the daemon.

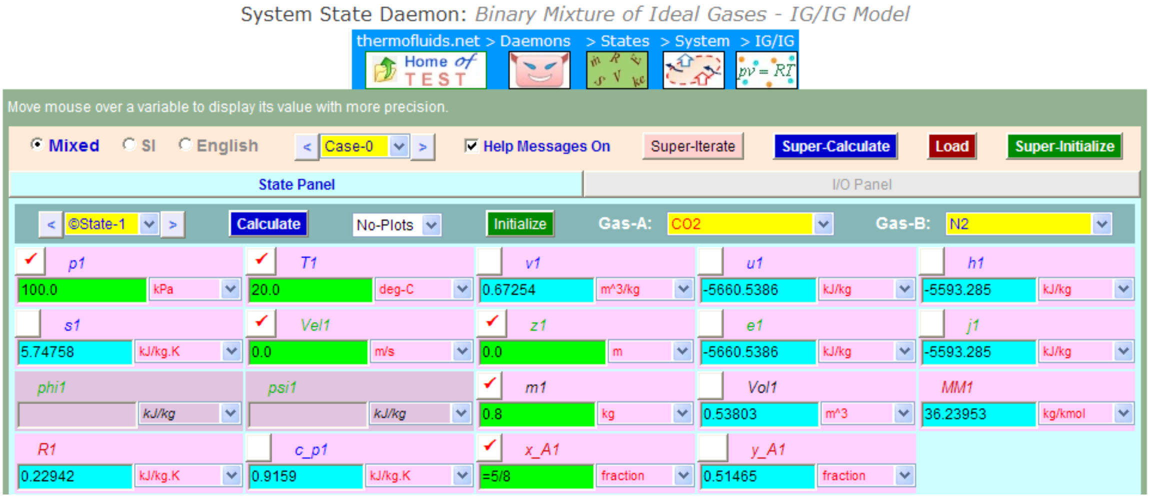
Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

General Mixture: Mixture can contain an unlimited number, *n*, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.

Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.

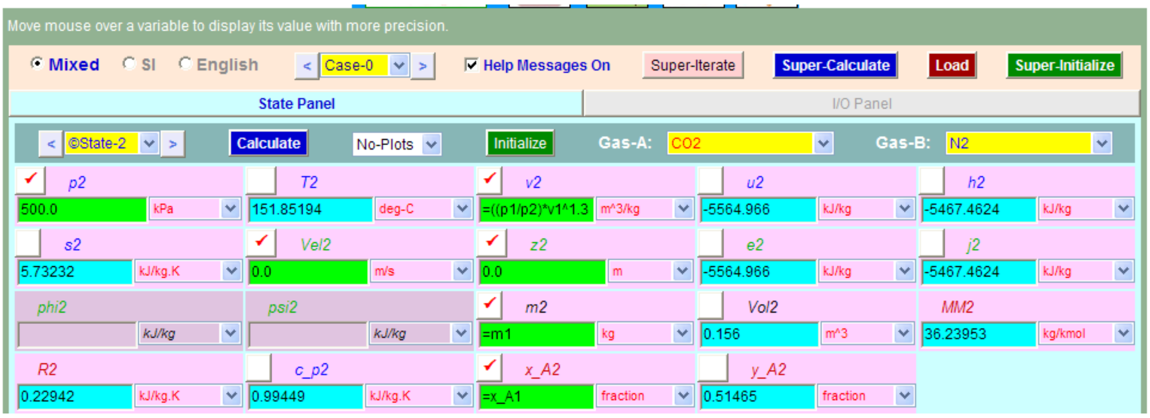
3. Select CO2 for Gas-A and N2 for Gas-B. For State1, enter values of p1, T1, and mass fraction of CO2 = x_A1 = 5/8 , and mass of mixture, m1 = 0.8 kg, and hit Enter. Immediately, mole fraction y_A1 for CO2, Gas const. for mixture (i.e. R1) and Mol. wt. for the mixture, MM1, mixture volume, Vol1 are calculated:



Gas-A: CO2
Gas-B: N2

✓ p1	✓ T1	☐ v1	☐ u1	☐ h1
100.0 kPa	20.0 deg-C	0.67254 m^3/kg	-5660.5386 kJ/kg	-5593.285 kJ/kg
☐ s1	✓ Vel1	✓ z1	☐ e1	☐ j1
5.74758 kJ/kg.K	0.0 m/s	0.0 m	-5660.5386 kJ/kg	-5593.285 kJ/kg
phi1	psi1	✓ m1	☐ Vol1	MM1
kJ/kg	kJ/kg	0.8 kg	0.53803 m^3	36.23953 kg/kmol
R1	☐ c_p1	✓ x_A1	☐ y_A1	
0.22942 kJ/kg.K	0.9159 kJ/kg.K	=5/8 fraction	0.51465 fraction	

4. For State 2, enter values of p2, v2 = [(p1/p2) * v1^1.3]^(1/1.3), m2 = m1, x_A2 = x_A1, and hit Enter. We get:



Move mouse over a variable to display its value with more precision.

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Case-0
☑ Help Messages On
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Gas-A: CO2
Gas-B: N2

☑ p2	500.0 kPa	☐ T2	151.85194 deg-C
☑ v2	=((p1/p2)*v1^1.3 m^3/kg	☐ u2	-5564.966 kJ/kg
☐ h2	-5467.4624 kJ/kg	☐ s2	5.73232 kJ/kg.K
☑ Vel2	0.0 m/s	☑ z2	0.0 m
☐ e2	-5564.966 kJ/kg	☐ j2	-5467.4624 kJ/kg
phi2	kJ/kg	psi2	kJ/kg
☑ m2	=m1 kg	☐ Vol2	0.156 m^3
MM2	36.23953 kg/kmol	R2	0.22942 kJ/kg.K
☐ c_p2	0.99449 kJ/kg.K	☑ x_A2	=x_A1 fraction
☐ y_A2	0.51465 fraction		

Thus:

Final temp = T2 = 151.85 C …. Ans.

Work done = (p1*Vol1 – p2*Vol2) / (1.3 – 1) = -80.664 kJ …work done on the system, since -ve… Ans.

Heat transfer:

By I Law: Q = dU + W

Now, dU = m1*(u2 – u1) = 76.458 kJ

Therefore, Q = 76.458+(-80. 664) = -4.206 kJ....heat rejected.... Ans.

Change in entropy: dS = m1 * (s2 – s1) = 0.0128 kJ/K … Ans.

5. Click on **SuperCalculate** and get the TEST code etc from the I/O panel:

```
#~~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE

#

#          Daemon Path: States>System>IG-BinMixModel; v-10.ca08

#

#--------------------Start of TEST-code-----------------------------------------------------------------------

States    {

          State-1: CO2, N2;

          Given: { p1= 100.0 kPa; T1= 20.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 0.8 kg; x_A1= “5/8” fraction; }

          State-2: CO2, N2;

          Given: { p2= 500.0 kPa; v2= “((p1/p2)*v1^1.3 )^(1/1.3)” m^3/kg; Vel2= 0.0 m/s; z2= 0.0 m; m2= “m1” kg; x_A2= “x_A1” fraction; }

          }

#----------------------End of TEST-code---------------------------------------------------------------------

#
```

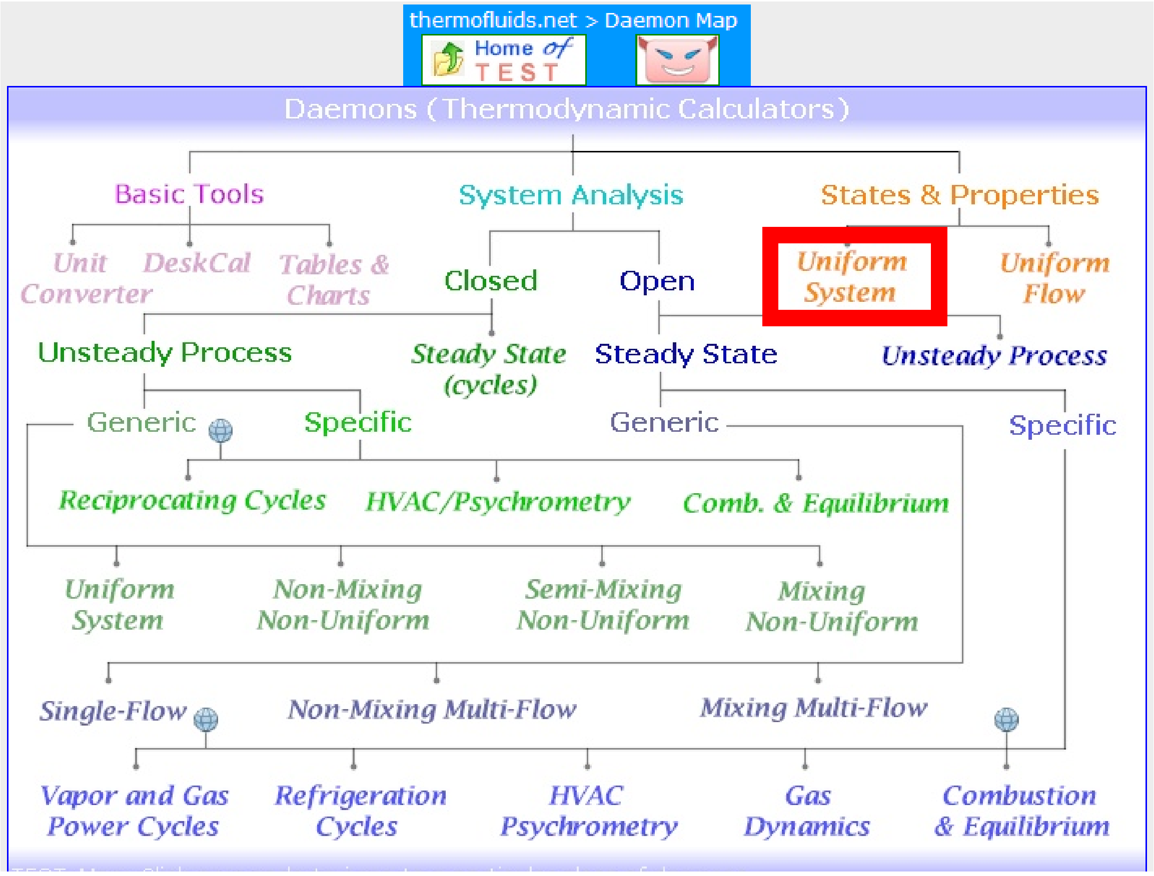
```
#******DETAILED OUTPUT:

#

# Evaluated States:

#
#       State-1: CO2, N2 > IG-BinMixModel;
#               Given: p1= 100.0 kPa; T1= 20.0 deg-C; Vel1= 0.0 m/s;
#                       z1= 0.0 m; m1= 0.8 kg; x_A1= “5/8” fraction;
#
#       Calculated: v1= 0.6725 m^3/kg; u1= -5660.5386 kJ/kg; h1= -5593.285 kJ/kg;
#                       s1= 5.7476 kJ/kg.K; e1= -5660.5386 kJ/kg; j1= -5593.285 kJ/kg;
#                       Vol1= 0.538 m^3; MM1= 36.2395 kg/kmol; R1= 0.2294 kJ/kg.K;
#                       c_p1= 0.9159 kJ/kg.K; y_A1= 0.5147 fraction;
#
#       State-2: CO2, N2 > IG-BinMixModel;
#       Given: p2= 500.0 kPa; v2= “((p1/p2)*v1^1.3 )^(1/1.3)” m^3/kg; Vel2= 0.0 m/s;
#                       z2= 0.0 m; m2= “m1” kg; x_A2= “x_A1” fraction;
#
#       Calculated: T2= 151.8519 deg-C; u2= -5564.966 kJ/kg; h2= -5467.4624 kJ/kg;
#                       s2= 5.7323 kJ/kg.K; e2= -5564.966 kJ/kg; j2= -5467.4624 kJ/kg;
#                       Vol2= 0.156 m^3; MM2= 36.2395 kg/kmol; R2= 0.2294 kJ/kg.K;
#                       c_p2= 0.9945 kJ/kg.K; y_A2= 0.5147 fraction;
#

#--------Property spreadsheet starts:

# State x_A     y_A     p(kPa)  T(K)    v(m3/kg)        u(kJ/kg)h(kJ/kg)s(kJ/kg)
# 1     0.62    0.51    100.0   293.1   0.6725          -5660.54        -5593.29        5.748
# 2     0.62    0.51    500.0   425.0   0.195           -5564.97        -5467.46        5.732

=====================================================================
```

Prob.9.37. A mixture of ideal gases consists of 3 kg of N2 and 5 kg of CO2 at a pressure of 300 kPa and temp of 20 C. Find: (i) mole fraction of each component (ii) equivalent mol. wt. of the mixture (iii) equivalent gas constant of the mixture, and (iv) the partial pressure and partial volume. [VTU – BTD – June–July 2008]

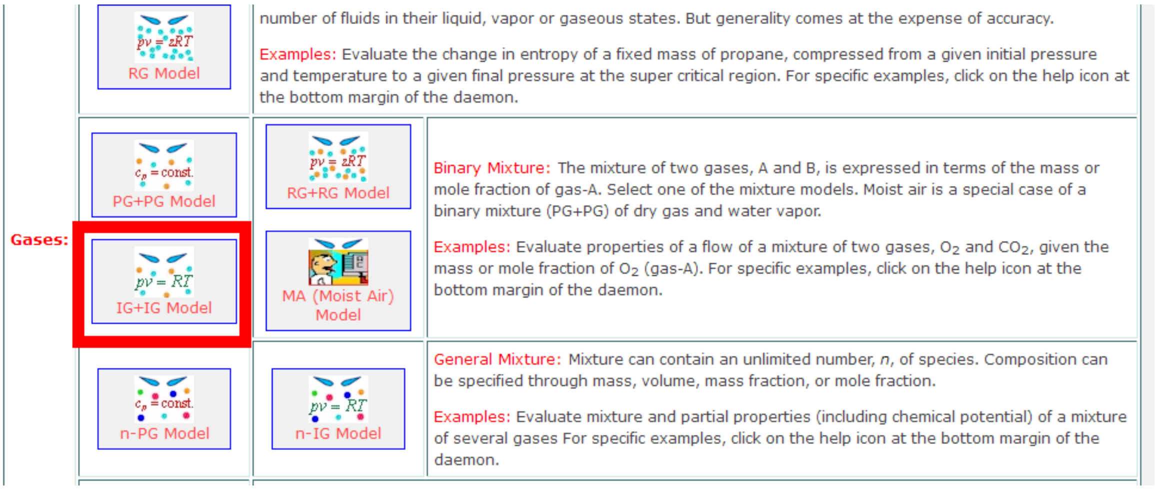
TEST Solution:

Following are the steps:

1. Go to Daemons tree, select States & Properties – Uniform System:



2. For Material model, select Binary mixtures – IG + IG model as shown below:



number of fluids in their liquid, vapor or gaseous states. But generality comes at the expense of accuracy.

Examples: Evaluate the change in entropy of a fixed mass of propane, compressed from a given initial pressure and temperature to a given final pressure at the super critical region. For specific examples, click on the help icon at the bottom margin of the daemon.

Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

General Mixture: Mixture can contain an unlimited number, *n*, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.

Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.

3. Select N2 for Gas-A and CO2 for Gas-B. For State1, enter values of p1, T1, and mass fraction of N2 = x_A1 = 3/8 , and mass of mixture, m1 = 8 kg, and hit Enter. Immediately, mole fraction y_A1 for N2, Gas const. for mixture (i.e. R1) and Mol. wt. for the mixture, MM1, mixture volume, Vol1 are calculated:

Gas-A: N2

Gas-B: CO2

☑ p1	☑ T1	☐ v1	☐ u1	☐ h1
300.0 kPa	19.999567 deg-C	0.22418 m^3/kg	-5660.5386 kJ/kg	-5593.285 kJ/kg
☐ s1	☑ Vel1	☑ z1	☐ e1	☐ j1
5.49554 kJ/kg.K	0.0 m/s	0.0 m	-5660.5386 kJ/kg	-5593.285 kJ/kg
phi1	psi1	☑ m1	☐ Vol1	MM1
kJ/kg	kJ/kg	8.0 kg	1.79344 m^3	36.23953 kg/kmol
R1	☐ c_p1	☑ x_A1	☐ y_A1	
0.22942 kJ/kg.K	0.9159 kJ/kg.K	=3/8 fraction	0.48535 fraction	

Thus:

Mole fraction of N2 = y_A1 = 0.48535 C …. Ans.

Therefore, Mole fraction of CO2 = 1 – 0.4853 = 0.5147…. Ans.

Equiv. mol. wt. of mixture = MM1 = 36.2395 kg/kmol… Ans.

Equiv. Gas const. of mixture = R1 = 0.22942 kJ/kg.K … Ans.

Partial pressure of N2 = y_A1 * p1 = 145.6 kPa …. Ans.

Partial pressure of CO2 = 300 – 145.6 = 154.4 kPa …. Ans.

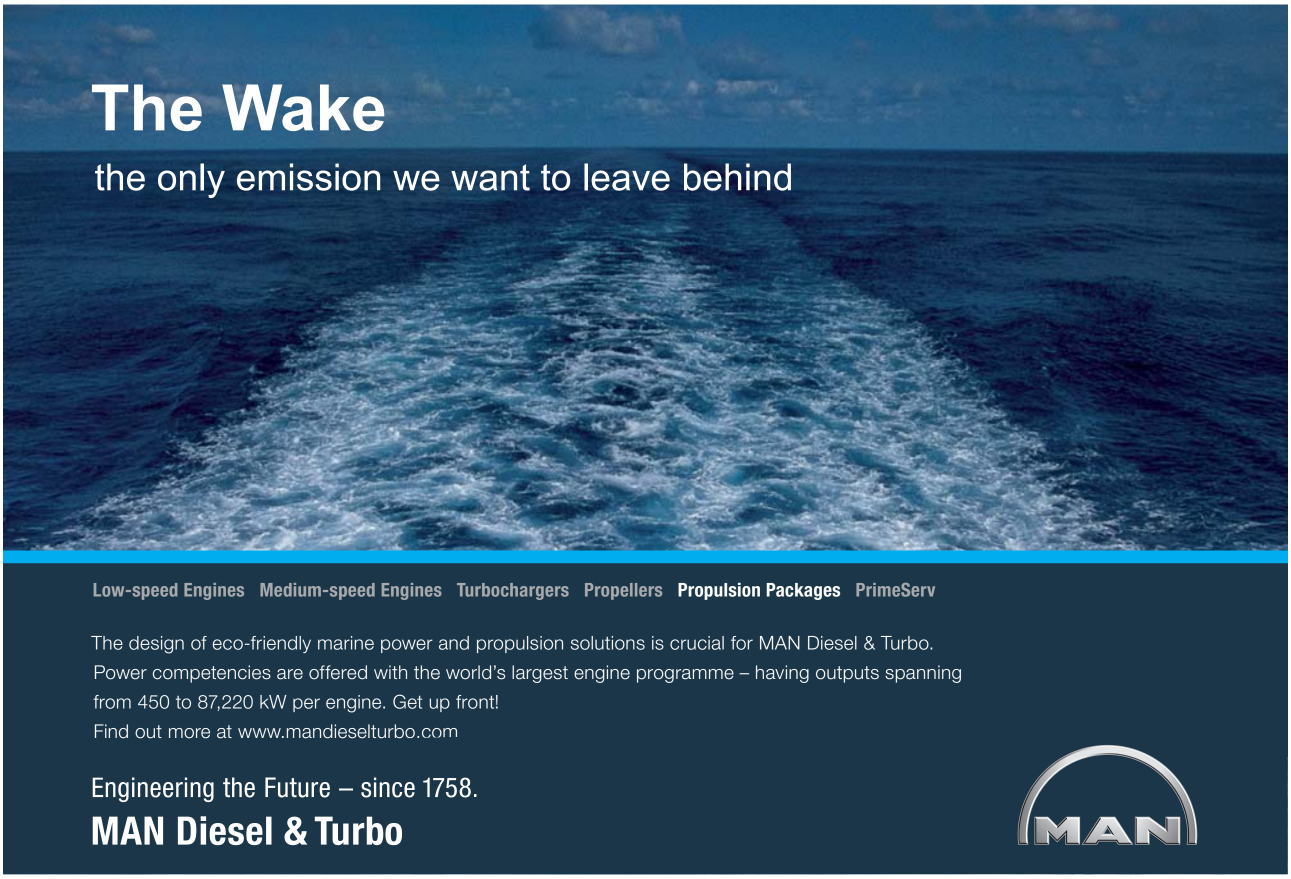
Partial volume of N2 = y_A1 * Vol1 = 0.87 m^3 …. Ans.

Partial volume of CO2 = Vol1 – 0.87 = 0.923 m^3…. Ans.

4. Click on **SuperCalculate** and get the TEST code etc from the I/O panel:

```
#~~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE

#

#          Daemon Path: States>System>IG-BinMixModel; v-10.ca08

#

#-------------------Start of TEST-code-----------------------------------------------------------------------

States   {

          State-1: N2, CO2;

          Given: { p1= 300.0 kPa; T1= 20.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 8.0 kg; x_A1= “3/8” fraction; }

          }

#---------------------End of TEST-code----------------------------------------------------------------------
```

```
#

#******DETAILED OUTPUT:

#

# Evaluated States:

#
#         State-1: N2, CO2 > IG-BinMixModel;
#                  Given: p1= 300.0 kPa; T1= 20.0 deg-C; Vel1= 0.0 m/s;
#                         z1= 0.0 m; m1= 8.0 kg; x_A1= "3/8" fraction;
#
#                  Calculated: v1= 0.2242 m^3/kg; u1= -5660.5386 kJ/kg; h1= -5593.285 kJ/kg;
#                         s1= 5.4955 kJ/kg.K; e1= -5660.5386 kJ/kg; j1= -5593.285 kJ/kg;

#                         Vol1= 1.7934 m^3; MM1= 36.2395 kg/kmol; R1= 0.2294 kJ/kg.K;

#                         c_p1= 0.9159 kJ/kg.K; y_A1= 0.4854 fraction;

#
```



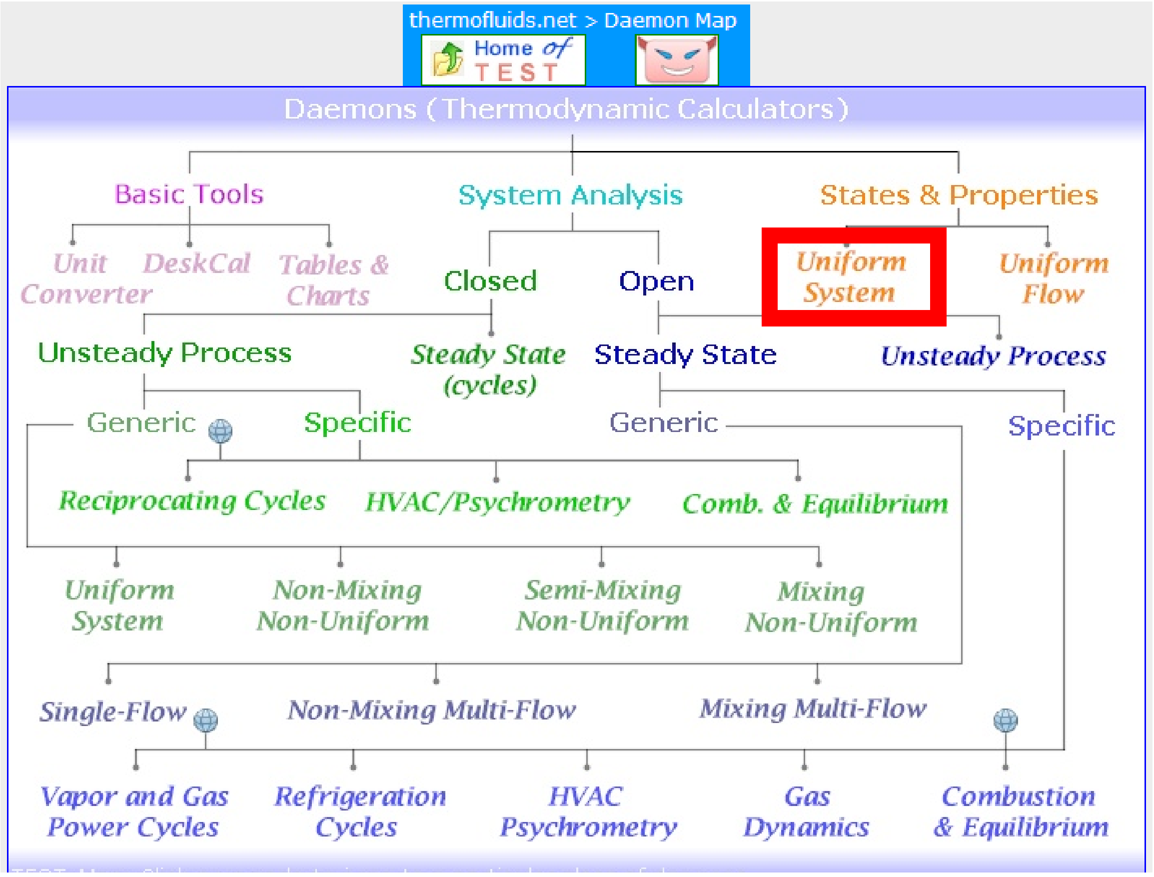
```
#--------Property spreadsheet starts:
#
# State  x_A     y_A     p(kPa)  T(K)    v(m3/kg)        u(kJ/kg)h(kJ/kg)s(kJ/kg)
# 1      0.38    0.49    300.0   293.1   0.2242          -5660.54 -5593.29        5.496

===========================================================================
```

Prob.9.38. A mixture of gases has the following volumetric composition: CO2 = 12%, O2 = 4%, N2 = 82% and CO = 2%. Calculate: (i) the gravimetric composition (ii) Mol. wt. of mixture (iii) Gas const. R for the mixture [VTU – BTD – March, 2001]

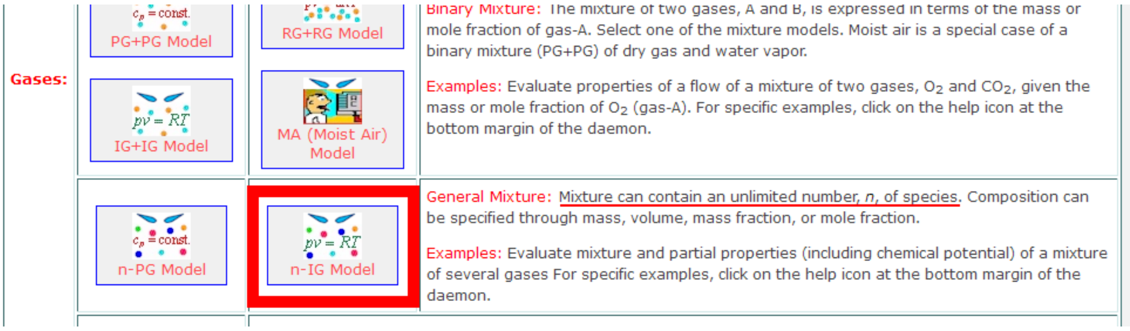
TEST Solution:

Following are the steps:

1. Go to Daemons tree, select States & Properties – Uniform System:



2. For Material model, select General mixture – n- IG model as shown below. It can contain an unlimited number, n, of species.



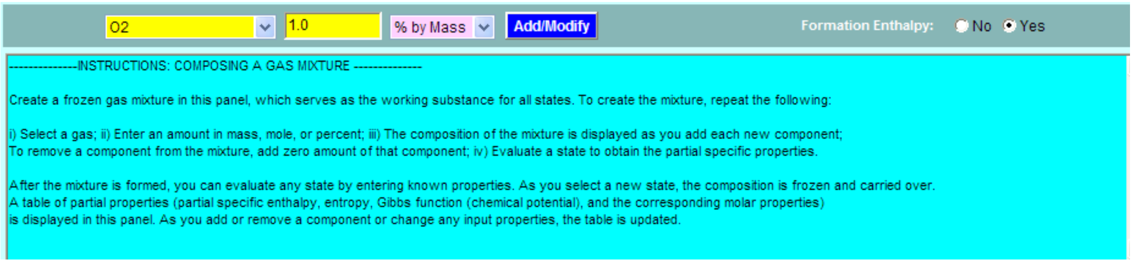
Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

General Mixture: Mixture can contain an unlimited number, *n*, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.

Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.

3. **Now, form the mixture:** To do this, Instructions are given in the blue window:



O2 | 1.0 | % by Mass

Formation Enthalpy: ○ No ● Yes

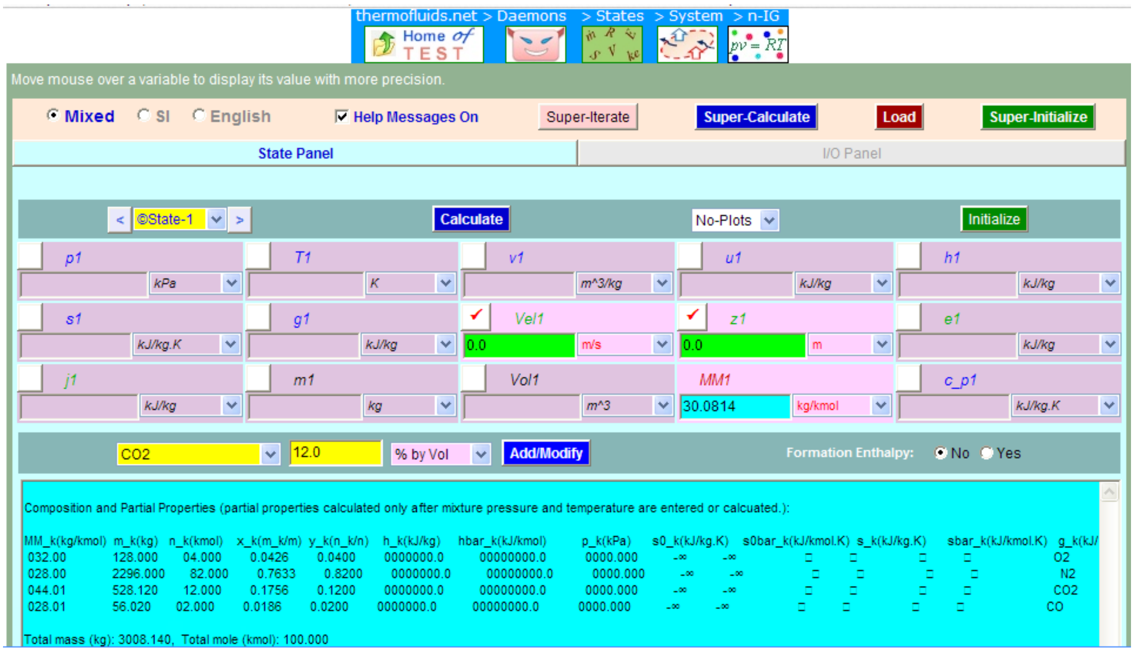
--------------INSTRUCTIONS: COMPOSING A GAS MIXTURE --------------

Create a frozen gas mixture in this panel, which serves as the working substance for all states. To create the mixture, repeat the following:

i) Select a gas; ii) Enter an amount in mass, mole, or percent; iii) The composition of the mixture is displayed as you add each new component;
To remove a component from the mixture, add zero amount of that component; iv) Evaluate a state to obtain the partial specific properties.

After the mixture is formed, you can evaluate any state by entering known properties. As you select a new state, the composition is frozen and carried over.
A table of partial properties (partial specific enthalpy, entropy, Gibbs function (chemical potential), and the corresponding molar properties)
is displayed in this panel. As you add or remove a component or change any input properties, the table is updated.

4. i.e. To form the mixture, go to the lower blue portion of the window, and select the gas from the widget, enter its % by volume or mass etc. as shown and click on Add/Modify. Then that gas gets entered in the blue window below. Do this for each component, and click on Calculate. We get:



Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English ☑ Help Messages On

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✓ Vel1: 0.0 m/s

✓ z1: 0.0 m

MM1: 30.0814 kg/kmol

CO2 | 12.0 | % by Vol

Formation Enthalpy: ● No ○ Yes

Composition and Partial Properties (partial properties calculated only after mixture pressure and temperature are entered or calcuated.):

```
MM_k(kg/kmol)  m_k(kg)   n_k(kmol)   x_k(m_k/m)  y_k(n_k/n)   h_k(kJ/kg)    hbar_k(kJ/kmol)     p_k(kPa)    s0_k(kJ/kg.K)   s0bar_k(kJ/kmol.K)  s_k(kJ/kg.K)    sbar_k(kJ/kmol.K)  g_k(kJ/
 032.00        128.000     04.000      0.0426      0.0400     0000000.0      00000000.0         0000.000       -∞      -∞             □      □              □      □               O2
 028.00        2296.000     82.000      0.7633      0.8200     0000000.0      00000000.0         0000.000       -∞      -∞             □      □              □      □               N2
 044.01        528.120     12.000      0.1756      0.1200     0000000.0      00000000.0         0000.000       -∞      -∞             □      □              □      □              CO2
 028.01        56.020     02.000      0.0186      0.0200     0000000.0      00000000.0         0000.000       -∞      -∞             □      □              □      □              CO

Total mass (kg): 3008.140,  Total mole (kmol): 100.000
```

Thus:

Gravimetric composition, i.e. x_A1 etc. See the x_k column in the blue window above:

We get: O2: 0.0426, N2: 0.7633, CO2:0.1756, and CO:0.0186 …. Ans.

Mol. wt. of mixture = MM1 = 30.0814 kg/kmol… Ans.

Gas const. for mixture = R1 = R_u /MM1 = 8.314 / 30.0814 = 0.27638 kJ/kg.K … Ans.

5. Click on **SuperCalculate** and get the TEST code etc from the I/O panel:

```
#~~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE

#

#          Daemon Path: States>System>IG-GenMixModel; v-10.ca08

#
```

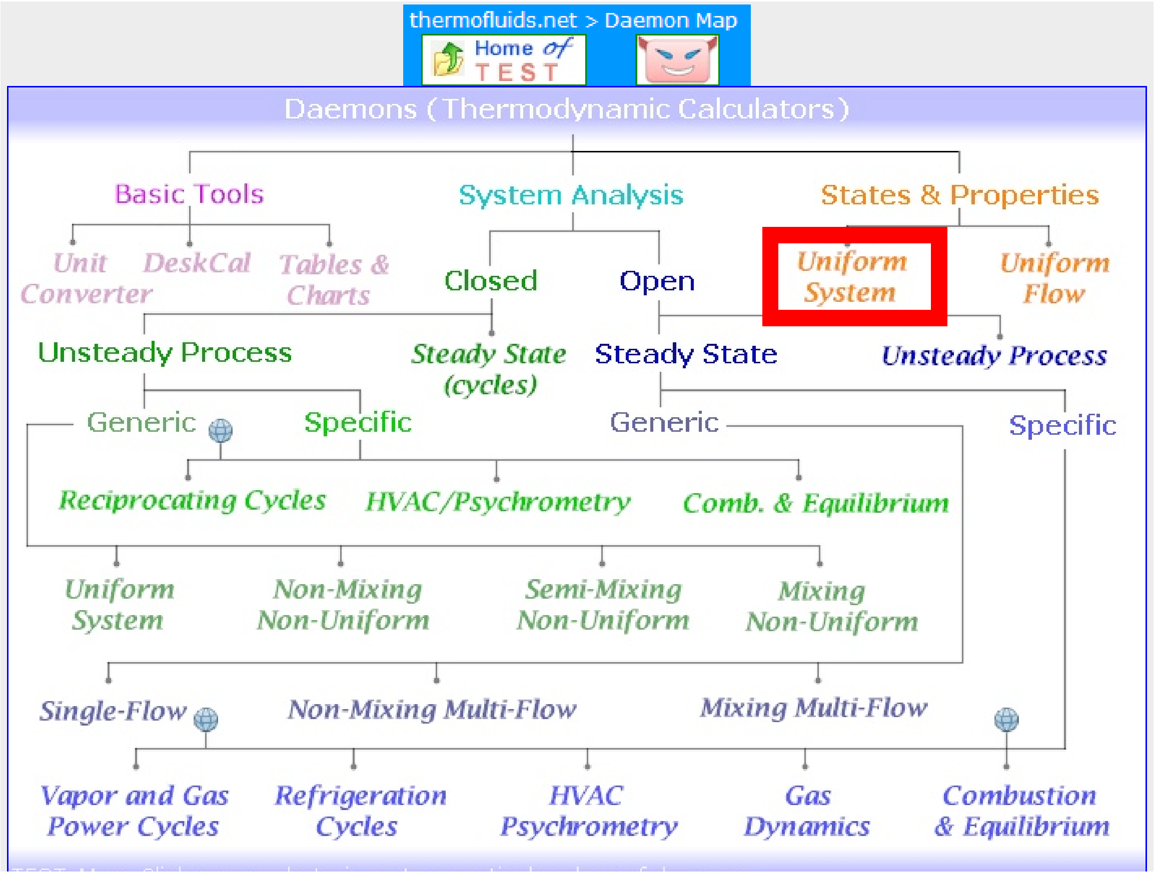
```
#--------------------Start of TEST-code-----------------------------------------------------------------------

States    {
          State-1: mixture, ;
          Given: { Vel1= 0.0 m/s; z1= 0.0 m; }

          }

#----------------------End of TEST-code-----------------------------------------------------------------------
#
#******DETAILED OUTPUT:
#
# Mixture composition:
#
# k       MM_k(kg/kmol)         m_k(kg)         n_k(kmol)        x_k(m_k/m)     y_k(n_k/n)
#
# O2      32.0      128.0       4.0             0.04255          0.04
# N2      28.0      2296.0      82.0            0.76326          0.82
# CO2     44.01     528.12      12.0            0.17556          0.12
# CO      28.01     56.02       2.0             0.01862          0.02
# Total   30.08     3008.14     100.0

#


# Evaluated States:


#


#         State-1: mixture, > ;
#                   Given: Vel1= 0.0 m/s; z1= 0.0 m;
#                   Calculated: MM1= 30.0814 kg/kmol;
#
============================================================================
```

Prob.9.39.A 2 kg mixture of 25% N2, 50% O2 and 25% CO2 by mass is at 150 kPa and 300 K. Find the mixture gas const. and the total volume. [Ref: 2]

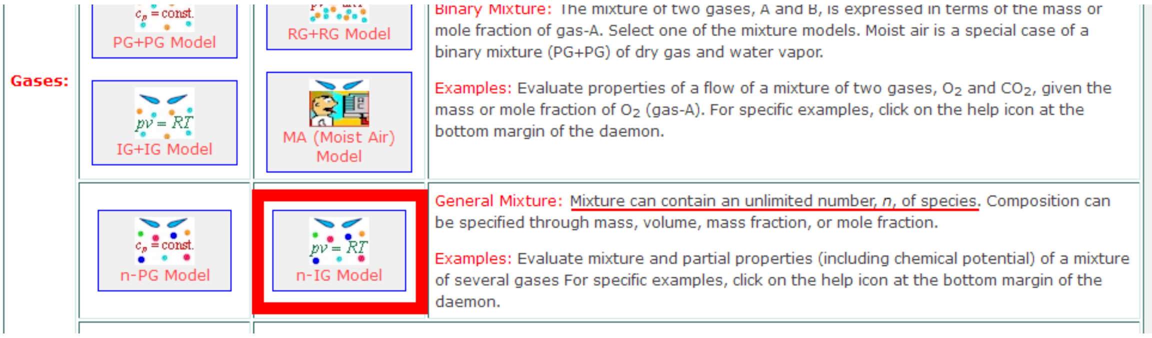
TEST Solution:

Following are the steps:

1. Go to Daemons tree, select States & Properties – Uniform System:



2. For Material model, select General mixture – n- IG model as shown below. It can contain an unlimited number, n, of species.



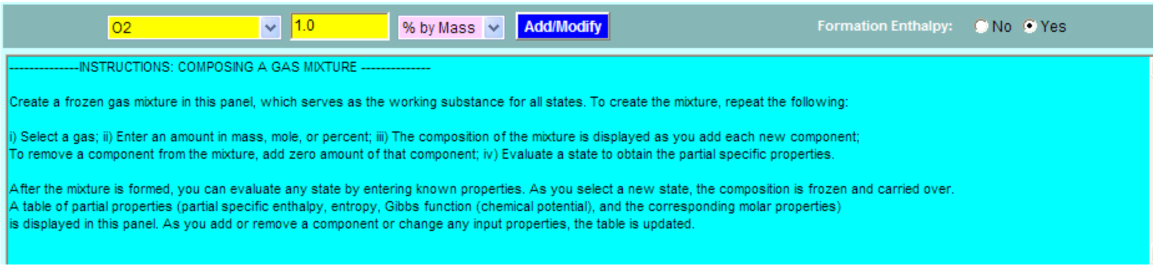
Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

General Mixture: Mixture can contain an unlimited number, *n*, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.

Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.

3. **Now, form the mixture:** To do this, Instructions are given in the blue window:



Formation Enthalpy: ○ No ● Yes

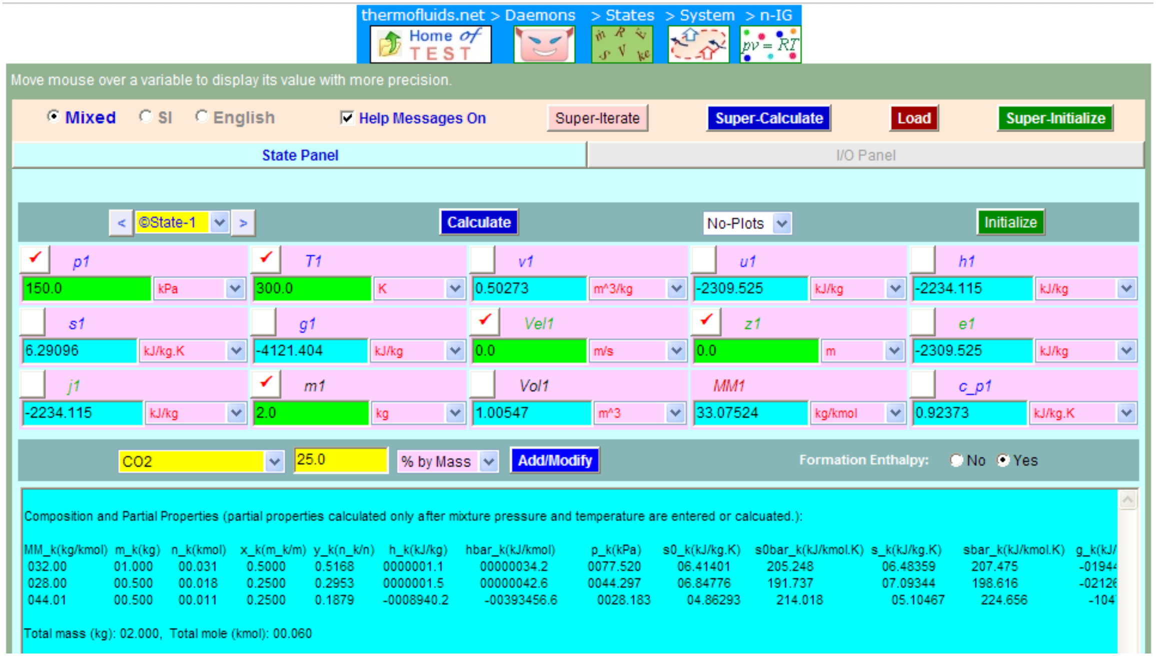
--------------INSTRUCTIONS: COMPOSING A GAS MIXTURE --------------

Create a frozen gas mixture in this panel, which serves as the working substance for all states. To create the mixture, repeat the following:

i) Select a gas; ii) Enter an amount in mass, mole, or percent; iii) The composition of the mixture is displayed as you add each new component;
To remove a component from the mixture, add zero amount of that component; iv) Evaluate a state to obtain the partial specific properties.

After the mixture is formed, you can evaluate any state by entering known properties. As you select a new state, the composition is frozen and carried over.
A table of partial properties (partial specific enthalpy, entropy, Gibbs function (chemical potential), and the corresponding molar properties)
is displayed in this panel. As you add or remove a component or change any input properties, the table is updated.

4. i.e. to form the mixture, go down to the lower blue window, and select the gas from the widget, enter its % by mass or volume etc. as shown and click on Add/Modify. Then that gas gets entered in the blue window below. Do this for each component, and also enter for State 1 (in the State panel) values for p1, T1 and m1. Then, click on Calculate. Many properties of the mixture are calculated immediately:



● Mixed ○ SI ○ English ☑ Help Messages On

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☑ p1: 150.0 kPa
☑ T1: 300.0 K
☐ v1: 0.50273 m^3/kg
☐ u1: -2309.525 kJ/kg
☐ h1: -2234.115 kJ/kg
☐ s1: 6.29096 kJ/kg.K
☐ g1: -4121.404 kJ/kg
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: -2309.525 kJ/kg
☐ j1: -2234.115 kJ/kg
☑ m1: 2.0 kg
☐ Vol1: 1.00547 m^3
MM1: 33.07524 kg/kmol
☐ c_p1: 0.92373 kJ/kg.K

CO2 | 25.0 | % by Mass

Formation Enthalpy: ○ No ● Yes

```
Composition and Partial Properties (partial properties calculated only after mixture pressure and temperature are entered or calcuated.):

MM_k(kg/kmol) m_k(kg) n_k(kmol) x_k(m_k/m) y_k(n_k/n) h_k(kJ/kg)  hbar_k(kJ/kmol)    p_k(kPa)  s0_k(kJ/kg.K) s0bar_k(kJ/kmol.K) s_k(kJ/kg.K)  sbar_k(kJ/kmol.K) g_k(kJ/
032.00        01.000  00.031    0.5000     0.5168     0000001.1   00000034.2         0077.520  06.41401      205.248            06.48359      207.475           -0194
028.00        00.500  00.018    0.2500     0.2953     0000001.5   00000042.6         0044.297  06.84776      191.737            07.09344      198.616           -0212
044.01        00.500  00.011    0.2500     0.1879     -0008940.2  -00393456.6        0028.183  04.86293      214.018            05.10467      224.656           -104

Total mass (kg): 02.000,  Total mole (kmol): 00.060
```

Thus:

Mixture Mol. wt. = MM1 = 33.07524 kg/kmol …. Ans.

Mixture Gas Const. = R_u / MM1 = 0.2514 kJ/kg.K … Ans.

Mixture volume = Vol1 = 1.00547 m^3 … Ans.

5. Click on **SuperCalculate** and get the TEST code etc from the I/O panel:

#~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE:

#

Daemon Path: States>System>IG-GenMixModel; v-10.ca08

#

```
#--------------------Start of TEST-code-----------------------------------------------------------------------

States    {
          State-1: mixture, ;
          Given: { p1= 150.0 kPa; T1= 300.0 K; Vel1= 0.0 m/s; z1= 0.0 m; m1= 2.0 kg; }

          }

#----------------------End of TEST-code----------------------------------------------------------------------

#******DETAILED OUTPUT:

#

# Mixture composition:

#

# k MM_k(kg/kmol)    m_k(kg)        n_k(kmol)      x_k(m_k/m)    y_k(n_k/n)
#
# O2 32.0      1.0    0.03125        0.5            0.5168
# N2 28.0      0.5    0.01786        0.25           0.29531
# CO2   44.01  0.5    0.01136        0.25           0.18788
# Total  33.08 2.0    0.06047

#

# Evaluated States:

#

#         State-1: mixture, > ;

#                  Given: p1= 150.0 kPa; T1= 300.0 K; Vel1= 0.0 m/s;

#                         z1= 0.0 m; m1= 2.0 kg;

#                  Calculated: v1= 0.5027 m^3/kg; u1= -2309.525 kJ/kg; h1= -2234.115 kJ/kg;

#                         s1= 6.291 kJ/kg.K; g1= -4121.404 kJ/kg; e1= -2309.525 kJ/kg;

#                         j1= -2234.115 kJ/kg; Vol1= 1.0055 m^3; MM1= 33.0752 kg/kmol;

#                         c_p1= 0.9237 kJ/kg.K;

#
```

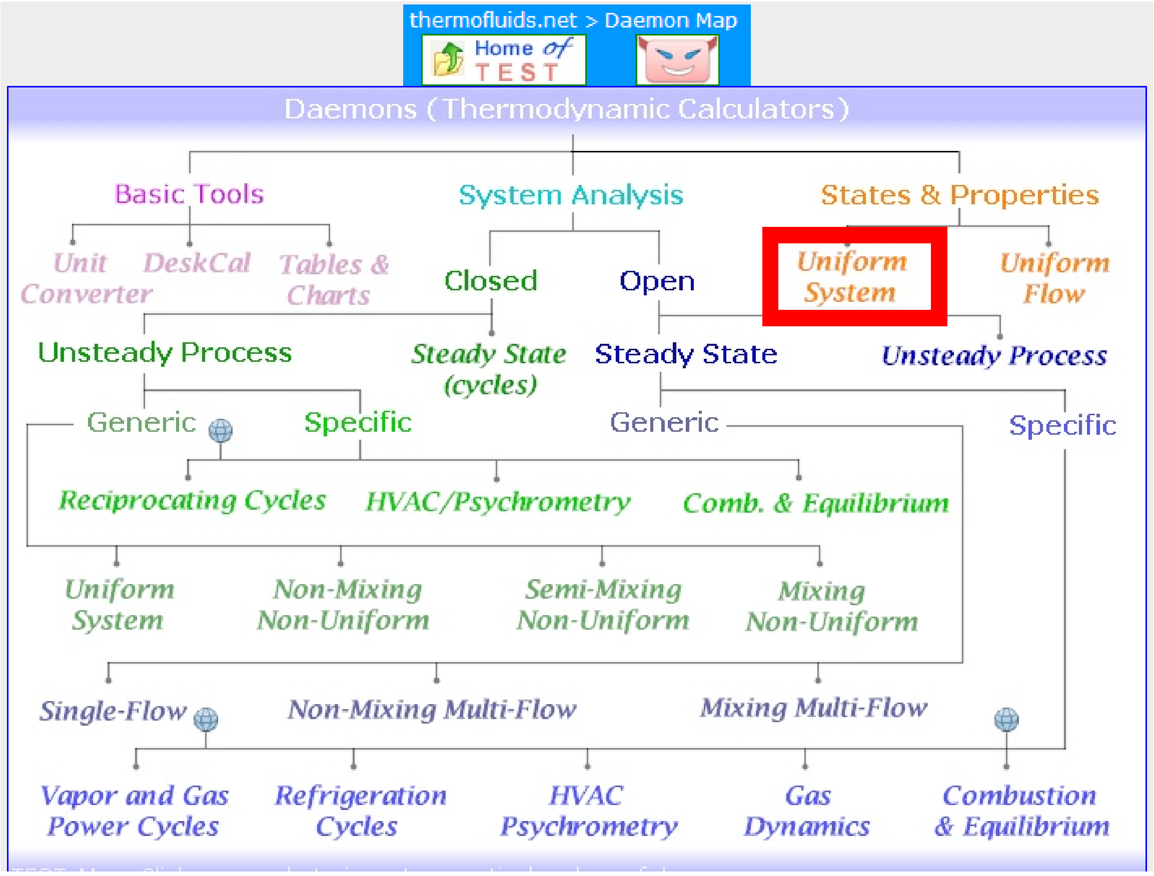
```
#--------Property spreadsheet starts:

#

# State  p(kPa)  (K)     v(m3/kg)      u(kJ/kg)      h(kJ/kg)      s(kJ/kg)
# 1      150.0   300.0   0.5027        -2309.52      -2234.11      6.291

==========================================================================
```

Prob.9.40. A mixture of ideal gases has the following composition by mass: N2 = 75%, O2 = 13%, CO2 = 12%. 2 kg of the mixture, initially at 3 bar and 127 C is compressed polytropically to 10 bar. The index of compression is 1.3. Calculate: (i) work done (ii) change in enthalpy, and (iii) change in internal energy. [M.U. – April 1996]

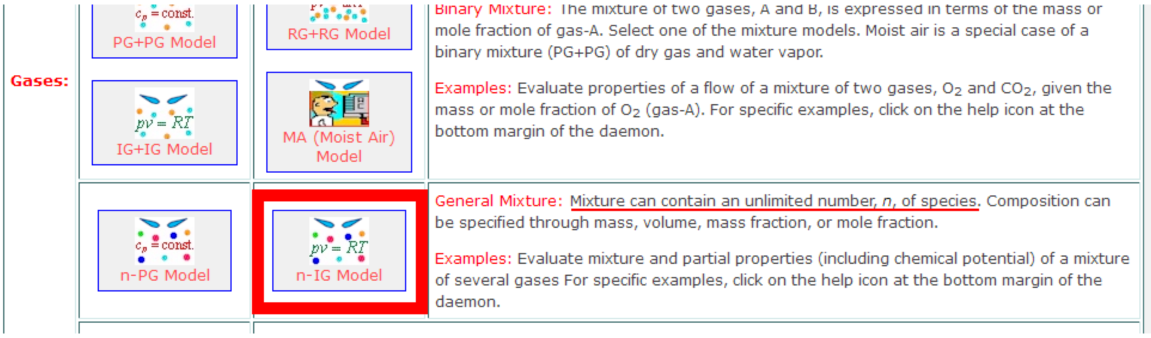
TEST Solution:

Following are the steps:

1. Go to Daemons tree, select States & Properties – Uniform System:



2. For Material model, select General mixture – n- IG model as shown below. It can contain an unlimited number, n, of species.



Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

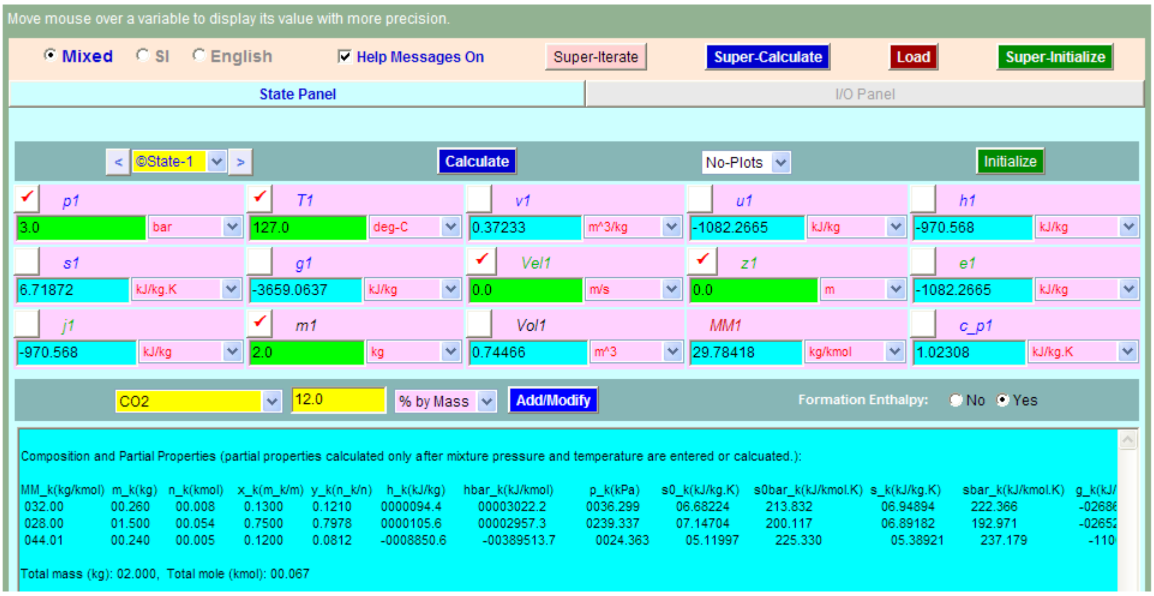
Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

General Mixture: Mixture can contain an unlimited number, *n*, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.

Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.

3. **Now, form the mixture:** To do this, follow Instructions given in the blue window:

i.e. to form the mixture, go down to the lower blue window, and select the gas from the widget, enter its % by mass or volume etc. as shown and click on Add/Modify. Then that gas gets entered in the blue window below. Do this for each component, and also enter **for State 1** (in the State panel) values for p1, T1 and m1. Then, click on Calculate. Many properties of the mixture are calculated immediately:



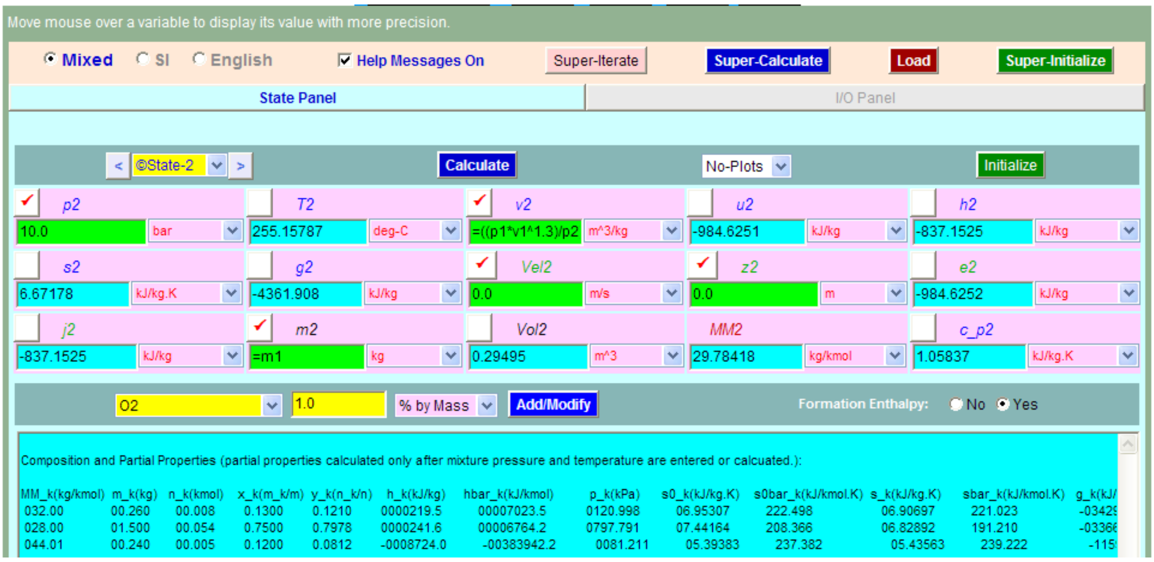
☑ p1: 3.0 bar
☑ T1: 127.0 deg-C
☐ v1: 0.37233 m^3/kg
☐ u1: -1082.2665 kJ/kg
☐ h1: -970.568 kJ/kg
☐ s1: 6.71872 kJ/kg.K
☐ g1: -3659.0637 kJ/kg
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: -1082.2665 kJ/kg
☐ j1: -970.568 kJ/kg
☑ m1: 2.0 kg
☐ Vol1: 0.74466 m^3
MM1: 29.78418 kg/kmol
☐ c_p1: 1.02308 kJ/kg.K

CO2 12.0 % by Mass
Formation Enthalpy: ○ No ● Yes

```
Composition and Partial Properties (partial properties calculated only after mixture pressure and temperature are entered or calcuated.):

MM_k(kg/kmol)  m_k(kg)  n_k(kmol)  x_k(m_k/m)  y_k(n_k/n)  h_k(kJ/kg)  hbar_k(kJ/kmol)  p_k(kPa)  s0_k(kJ/kg.K)  s0bar_k(kJ/kmol.K)  s_k(kJ/kg.K)  sbar_k(kJ/kmol.K)  g_k(kJ/
 032.00        00.260   00.008     0.1300      0.1210      0000094.4   00003022.2       0036.299  06.68224       213.832             06.94894      222.366            -0268
 028.00        01.500   00.054     0.7500      0.7978      0000105.6   00002957.3       0239.337  07.14704       200.117             06.89182      192.971            -0265
 044.01        00.240   00.005     0.1200      0.0812      -0008850.6  -00389513.7      0024.363  05.11997       225.330             05.38921      237.179            -110

Total mass (kg): 02.000,  Total mole (kmol): 00.067
```

Note from the above that Mixture vol. = 0.74466 m^3, Mixture Mol. wt. = 29.78418 kg/kmol, Mixture cp = 1.02308 kJ/kg.K.

4. Enter p2, m2 = m1 and v2 = [(p1 * v1^1.3) / p2]^(1/1.3) for State 2, and hit Enter:



☑ p2: 10.0 bar
☐ T2: 255.15787 deg-C
☑ v2: =((p1*v1^1.3)/p2 m^3/kg
☐ u2: -984.6251 kJ/kg
☐ h2: -837.1525 kJ/kg
☐ s2: 6.67178 kJ/kg.K
☐ g2: -4361.908 kJ/kg
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
☐ e2: -984.6252 kJ/kg
☐ j2: -837.1525 kJ/kg
☑ m2: =m1 kg
☐ Vol2: 0.29495 m^3
MM2: 29.78418 kg/kmol
☐ c_p2: 1.05837 kJ/kg.K

O2 1.0 % by Mass
Formation Enthalpy: ○ No ● Yes

```
Composition and Partial Properties (partial properties calculated only after mixture pressure and temperature are entered or calcuated.):

MM_k(kg/kmol)  m_k(kg)  n_k(kmol)  x_k(m_k/m)  y_k(n_k/n)  h_k(kJ/kg)  hbar_k(kJ/kmol)  p_k(kPa)  s0_k(kJ/kg.K)  s0bar_k(kJ/kmol.K)  s_k(kJ/kg.K)  sbar_k(kJ/kmol.K)  g_k(kJ/
 032.00        00.260   00.008     0.1300      0.1210      0000219.5   00007023.5       0120.998  06.95307       222.498             06.90697      221.023            -0342
 028.00        01.500   00.054     0.7500      0.7978      0000241.6   00006764.2       0797.791  07.44164       208.366             06.82892      191.210            -0336
 044.01        00.240   00.005     0.1200      0.0812      -0008724.0  -00383942.2      0081.211  05.39383       237.382             05.43563      239.222            -115
```

We see from the above that properties in State 2 are calculated.

5. Now, click on **SuperCalculate** and go to I/O panel. TEST code etc are available there. Also, we can use the I/O panel as a calculator to calculate the required quantities. Here, the advantage of using I/O panel is that you can transfer the quantities from the States panel just by entering the names of variables:

i.e. We get:

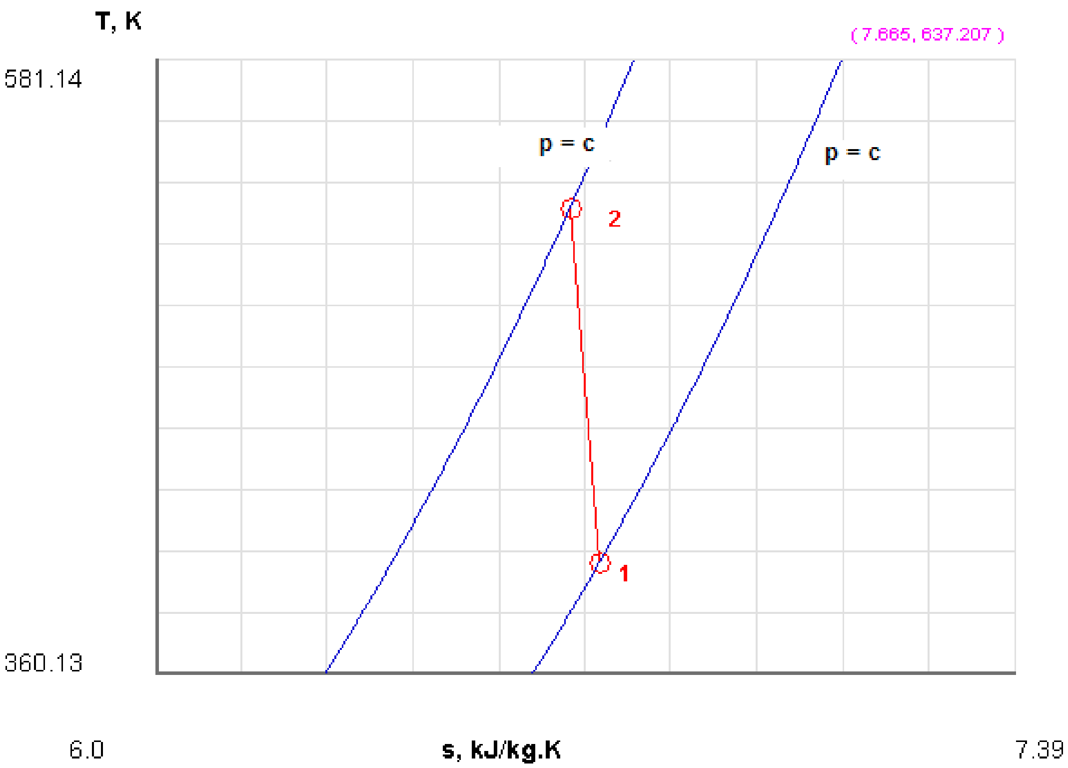
 # Work done: W = m1 * (p1 * v1 – p2 * v2)/(1.3 – 1) = -238.495 kJ ...work

done on the gas, so –ve…. Ans.

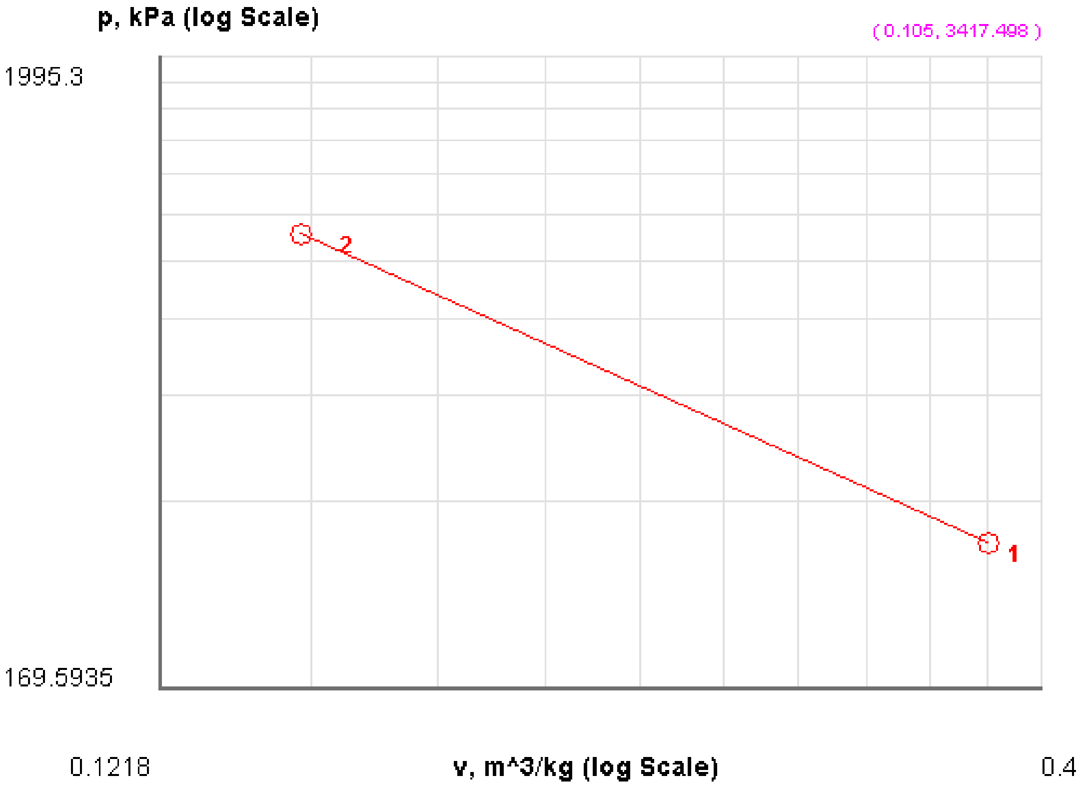
#Change in Enthalpy: dH = m1 * (h2 – h1) = 266.831 kJ…Ans.

#Change in Internal energy: dU = m1 * (u2 – u1) = 195.283 kJ …. Ans.

6. From the Plots widget, get **T-s diagram**, shown below:



And, the p-v diagram:



7. **Also, get the TEST code etc from the I/O panel:**

```
#~~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE

#

#          Daemon Path: States>System>IG-GenMixModel; v-10.ca08

#

#--------------------Start of TEST-code------------------------------------------------------------------------

States    {

          State-1: mixture, ;
          Given: { p1= 3.0 bar; T1= 127.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 2.0 kg; }

          State-2: mixture, ;
          Given: { p2= 10.0 bar; v2= “((p1*v1^1.3)/p2)^(1/1.3)” m^3/kg; Vel2= 0.0 m/s; z2= 0.0 m; m2=
“m1” kg; }

          }

#----------------------End of TEST-code-----------------------------------------------------------------------

#******DETAILED OUTPUT: #

#

# Mixture composition:

#

# k       MM_k(kg/kmol) m_k(kg)       n_k(kmol) x_k(m_k/m) y_k(n_k/n)
#
# O2            32.0     0.26          0.00812        0.13            0.12
# N2            28.0     1.5           0.05357        0.75            0.79779
# CO2           44.01    0.24          0.00545        0.12            0.08121
# Total         29.78    2.0           0.06715

#
```

```
# Evaluated States:
#
#       State-1: mixture, > ;
#               Given: p1= 3.0 bar; T1= 127.0 deg-C; Vel1= 0.0 m/s;
#                       z1= 0.0 m; m1= 2.0 kg;
#               Calculated: v1= 0.3723 m^3/kg; u1= -1082.2665 kJ/kg; h1= -970.568 kJ/kg;
#                       s1= 6.7187 kJ/kg.K; g1= -3659.0637 kJ/kg; e1= -1082.2665 kJ/kg;
#                       j1= -970.568 kJ/kg; Vol1= 0.7447 m^3; MM1= 29.7842 kg/kmol;
#                       c_p1= 1.0231 kJ/kg.K;
#
#       State-2: mixture, > ;
#               Given: p2= 10.0 bar; v2= "((p1*v1^1.3)/p2)^(1/1.3)" m^3/kg; Vel2= 0.0 m/s;
#                       z2= 0.0 m; m2= "m1" kg;
#               Calculated: T2= 255.1579 deg-C; u2= -984.6251 kJ/kg; h2= -837.1525 kJ/kg;
#                       s2= 6.6718 kJ/kg.K; g2= -4361.908 kJ/kg; e2= -984.6252 kJ/kg;
#                       j2= -837.1525 kJ/kg; Vol2= 0.295 m^3; MM2= 29.7842 kg/kmol;
#                       c_p2= 1.0584 kJ/kg.K;
#
#--------Property spreadsheet starts:


#
# State p(kPa)  T(K)   v(m3/kg)    u(kJ/kg)    h(kJ/kg)    s(kJ/kg)
# 1     300.0   400.1  0.3723      -1082.27    -970.57     6.719
# 2     1000.0  528.3  0.1475      -984.63     -837.15     6.672
#

#******CALCULATE VARIABLES: Type in an expression starting with an '=' sign ('= mdot1*(h2-h1)',
'= sqrt(4*A1/PI)', etc.) and press the Enter key)*********


#


# Work done: W


=m1 * (p1 * v1 – p2 * v2)/(1.3 – 1)


        m1 * (p1 * v1 – p2 * v2)/(1.3 – 1) = -238.4946396594271 kJ .... Ans.
```

#Change in Enthalpy: dH:

=m1 * (h2 – h1)

m1 * (h2 – h1) = 266.8309326171875 kJ …. Ans.

#Change in Internal energy: dU:

=m1 * (u2 – u1)

m1 * (u2 – u1) = 195.28271484375 kJ

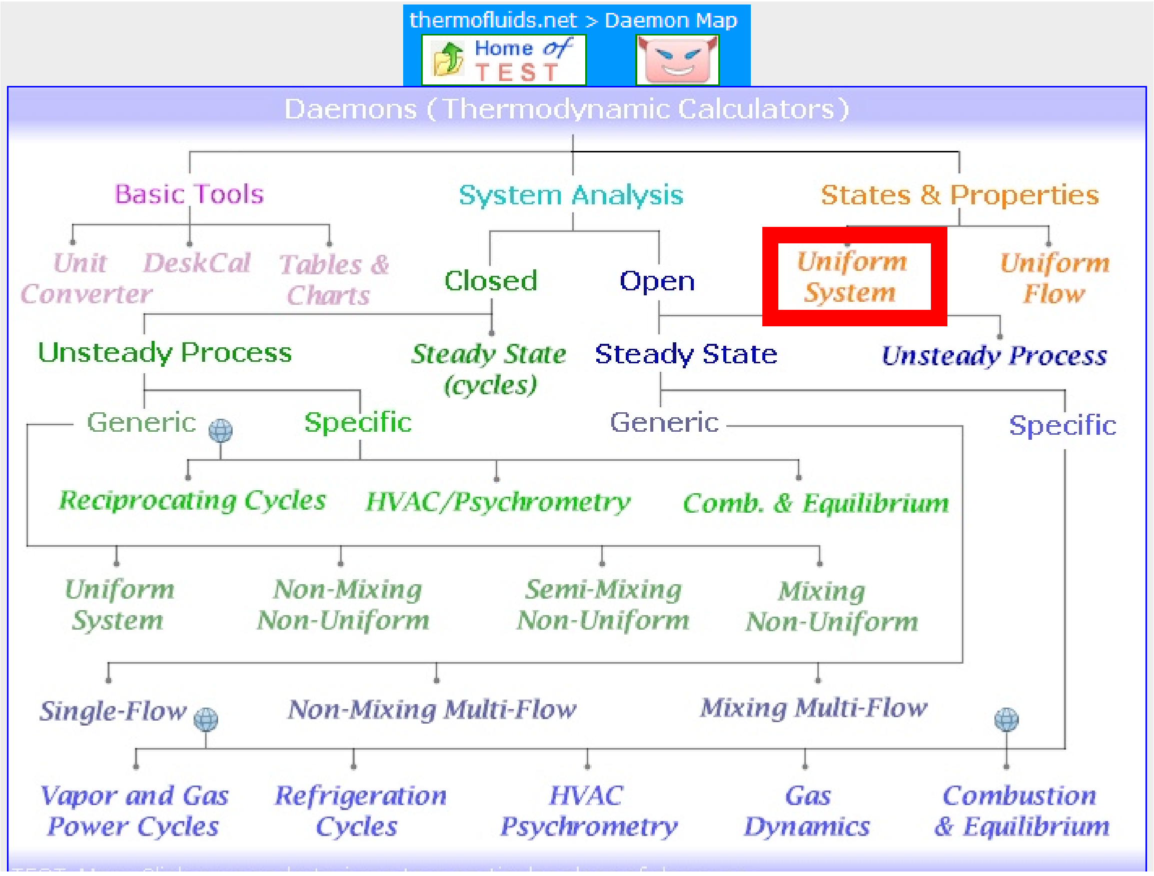
==

Prob.9.41. Natural gas as a mixture of 75% Methane and 25% Ethane by mass, is flowing to a compressor at 17 C and 100 kPa. The reversible adiabatic compressor brings the flow to 250 kPa. Find the exit temp and the needed work per kg flow. [Ref: 2]

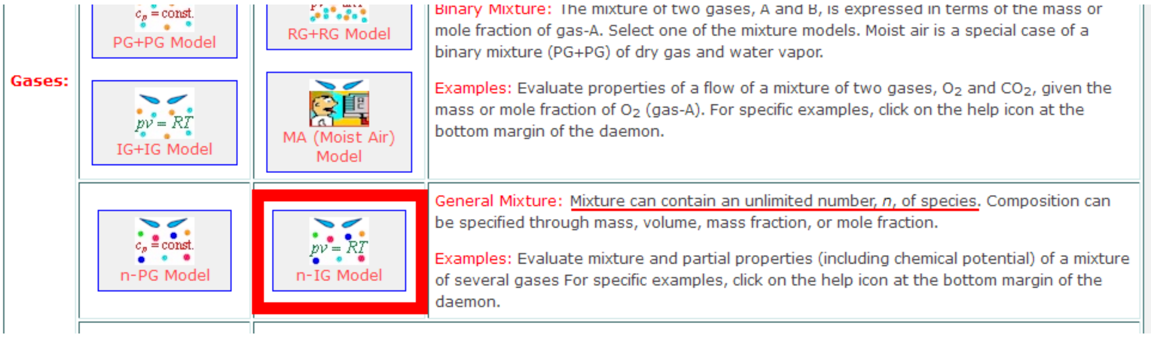
TEST Solution:

Following are the steps:

1. Go to Daemons tree, select States & Properties – Uniform System:



2. For Material model, select General mixture – n- IG model as shown below. It can contain an unlimited number, n, of species.



Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

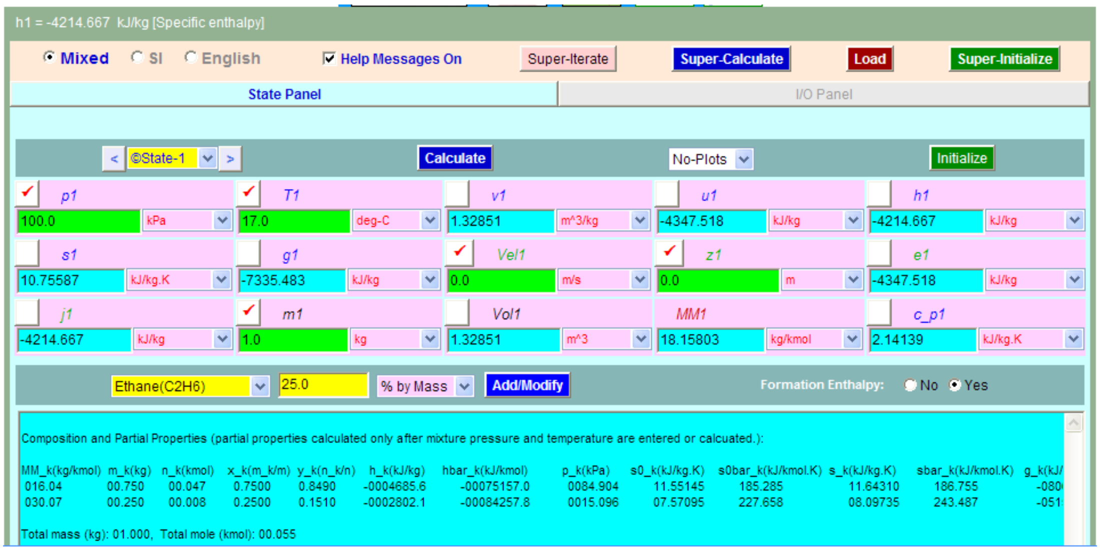
Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

General Mixture: Mixture can contain an unlimited number, *n*, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.

Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.

3. **Now, form the mixture:** To do this, follow Instructions given in the blue window:

i.e. to form the mixture, go down to the lower blue window, and select the gas from the widget, enter its % by mass or volume etc. as shown and click on Add/Modify. Then that gas gets entered in the blue window below. Do this for each component, and also enter **for State 1** (in the State panel) values for p1, T1 and m1. Then, click on Calculate. Many properties of the mixture are calculated immediately:



h1 = -4214.667 kJ/kg [Specific enthalpy]

State-1, No-Plots

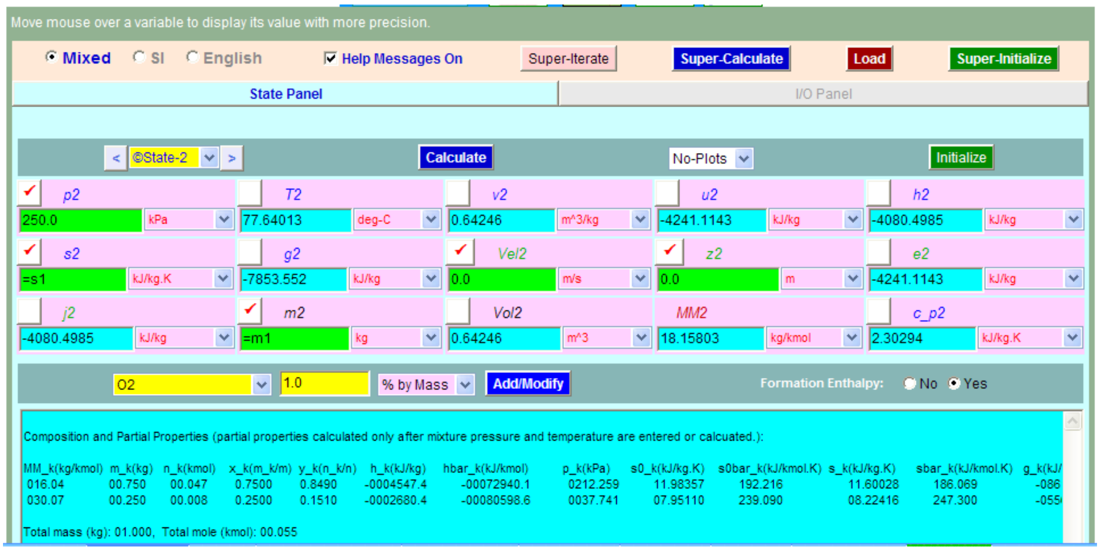
☑ p1: 100.0 kPa
☑ T1: 17.0 deg-C
☐ v1: 1.32851 m^3/kg
☐ u1: -4347.518 kJ/kg
☐ h1: -4214.667 kJ/kg
☐ s1: 10.75587 kJ/kg.K
☐ g1: -7335.483 kJ/kg
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: -4347.518 kJ/kg
☐ j1: -4214.667 kJ/kg
☑ m1: 1.0 kg
☐ Vol1: 1.32851 m^3
MM1: 18.15803 kg/kmol
☐ c_p1: 2.14139 kJ/kg.K

Ethane(C2H6) 25.0 % by Mass Add/Modify Formation Enthalpy: ○ No ● Yes

```
Composition and Partial Properties (partial properties calculated only after mixture pressure and temperature are entered or calcuated.):

MM_k(kg/kmol)  m_k(kg)  n_k(kmol)  x_k(m_k/m)  y_k(n_k/n)  h_k(kJ/kg)   hbar_k(kJ/kmol)   p_k(kPa)  s0_k(kJ/kg.K)  s0bar_k(kJ/kmol.K)  s_k(kJ/kg.K)  sbar_k(kJ/kmol.K)  g_k(kJ/
 016.04        00.750   00.047     0.7500      0.8490      -0004685.6   -00075157.0       0084.904  11.55145       185.285             11.64310      186.755            -080
 030.07        00.250   00.008     0.2500      0.1510      -0002802.1   -00084257.8       0015.096  07.57095       227.658             08.09735      243.487            -051

Total mass (kg): 01.000,  Total mole (kmol): 00.055
```

Note from the above that Mixture vol. = 1.32851 m^3, Mixture Mol. wt. = 18.15803 kg/kmol, Mixture cp = 2.14139 kJ/kg.K.

4. For State 2, enter p2, m2 = m1, and s2 = s1 (since rev. adiabatic process is an isentropic process), m2 = m1. Hit Enter:



Move mouse over a variable to display its value with more precision.

State-2, No-Plots

☑ p2: 250.0 kPa
☐ T2: 77.64013 deg-C
☐ v2: 0.64246 m^3/kg
☐ u2: -4241.1143 kJ/kg
☐ h2: -4080.4985 kJ/kg
☑ s2: =s1 kJ/kg.K
☐ g2: -7853.552 kJ/kg
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
☐ e2: -4241.1143 kJ/kg
☐ j2: -4080.4985 kJ/kg
☑ m2: =m1 kg
☐ Vol2: 0.64246 m^3
MM2: 18.15803 kg/kmol
☐ c_p2: 2.30294 kJ/kg.K

O2 1.0 % by Mass Add/Modify Formation Enthalpy: ○ No ● Yes

```
Composition and Partial Properties (partial properties calculated only after mixture pressure and temperature are entered or calcuated.):

MM_k(kg/kmol)  m_k(kg)  n_k(kmol)  x_k(m_k/m)  y_k(n_k/n)  h_k(kJ/kg)   hbar_k(kJ/kmol)   p_k(kPa)  s0_k(kJ/kg.K)  s0bar_k(kJ/kmol.K)  s_k(kJ/kg.K)  sbar_k(kJ/kmol.K)  g_k(kJ/
 016.04        00.750   00.047     0.7500      0.8490      -0004547.4   -00072940.1       0212.259  11.98357       192.216             11.60028      186.069            -086
 030.07        00.250   00.008     0.2500      0.1510      -0002680.4   -00080598.6       0037.741  07.95110       239.090             08.22416      247.300            -055

Total mass (kg): 01.000,  Total mole (kmol): 00.055
```

We see from the above that properties in State 2 are calculated.

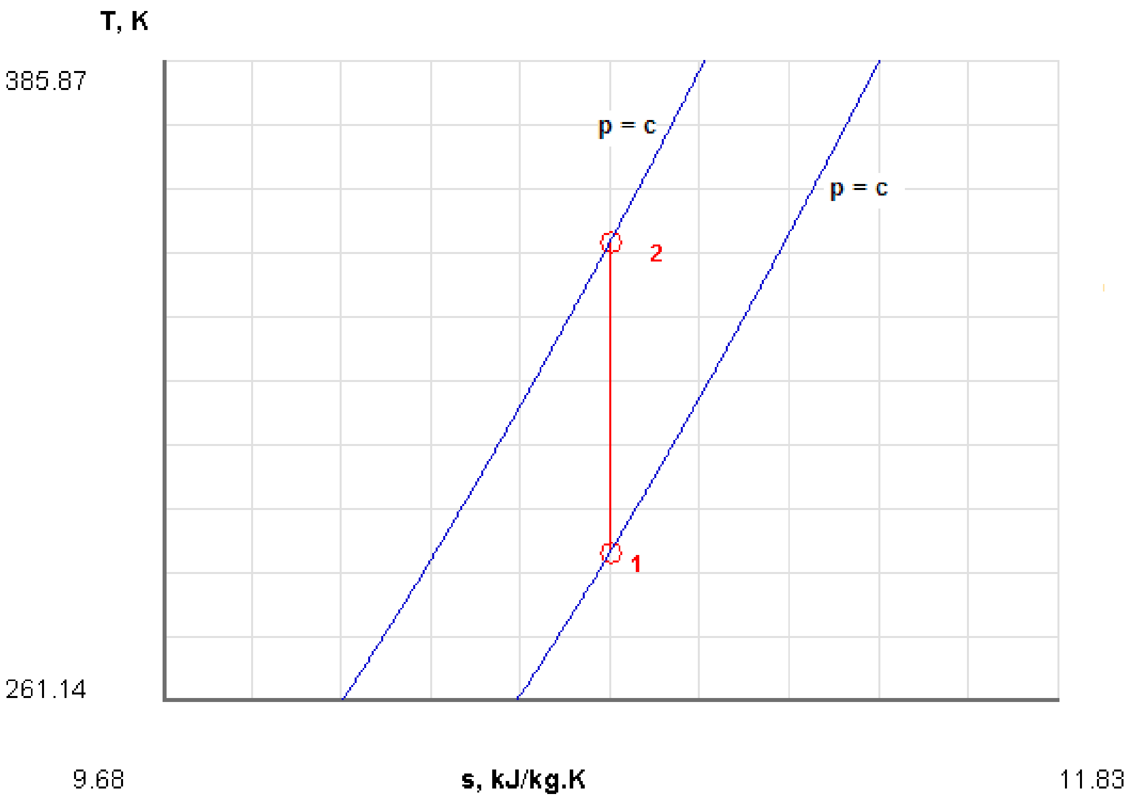
5. Now, click on **SuperCalculate** and go to I/O panel. TEST code etc are available there. Also, we can use the I/O panel as a calculator to calculate the required quantities. Here, the advantage of using I/O panel is that you can transfer the quantities from the States panel just by entering the names of variables:

i.e. We get:

#Exit temp. T2 = 77.64 C = 350.790 K ... Ans.

#Work needed per kg flow, W = m1 * (h2-h1) = 134.168 kJ/kg .... Ans.

6. From the Plots widget, get **T-s diagram**, shown below:



7. **And, the TEST code etc from the I/O panel:**

```
#~~~~~~~~~~~~~~~~~~~~~OUTPUT OF SUPER-CALCULATE

#

#          Daemon Path: States>System>IG-GenMixModel; v-10.ca08

#
```

```
#--------------------Start of TEST-code-----------------------------------------------------------------------

States    {

          State-1: mixture, ;
          Given: { p1= 100.0 kPa; T1= 17.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 1.0 kg; }

          State-2: mixture, ;

          Given: { p2= 250.0 kPa; s2= "s1" kJ/kg.K; Vel2= 0.0 m/s; z2= 0.0 m; m2= "m1" kg; }

          }

#----------------------End of TEST-code-----------------------------------------------------------------------

#******DETAILED OUTPUT:

#

# Mixture composition:

#

# k       MM_k(kg/kmol) m_k(kg)        n_k(kmol)       x_k(m_k/m)      y_k(n_k/n)
#
# Methane(CH4)          16.04   0.75    0.04676 0.75    0.84904
# Ethane(C2H6)          30.07   0.25    0.00831 0.25    0.15096
# Total         18.16   1.0     0.05507

#

# Evaluated States:

#
#         State-1: mixture, > ;
#                 Given: p1= 100.0 kPa; T1= 17.0 deg-C; Vel1= 0.0 m/s;
#                         z1= 0.0 m; m1= 1.0 kg;
#                 Calculated: v1= 1.3285 m^3/kg; u1= -4347.518 kJ/kg; h1= -4214.667 kJ/kg;
#                         s1= 10.7559 kJ/kg.K; g1= -7335.483 kJ/kg; e1= -4347.518 kJ/kg;
#                         j1= -4214.667 kJ/kg; Vol1= 1.3285 m^3; MM1= 18.158 kg/kmol;
#                         c_p1= 2.1414 kJ/kg.K;
#
```

```
#         State-2: mixture, > ;
#                   Given: p2= 250.0 kPa; s2= "s1" kJ/kg.K; Vel2= 0.0 m/s;
#                             z2= 0.0 m; m2= "m1" kg;
#                   Calculated: T2= 77.6401 deg-C; v2= 0.6425 m^3/kg; u2= -4241.1143 kJ/kg;
#                             h2= -4080.4985 kJ/kg; g2= -7853.552 kJ/kg; e2= -4241.1143 kJ/kg;
#                             j2= -4080.4985 kJ/kg; Vol2= 0.6425 m^3; MM2= 18.158 kg/kmol;
#                             c_p2= 2.3029 kJ/kg.K;
#
#--------Property spreadsheet starts:

#

# State  p(kPa)  T(K)    v(m3/kg)        u(kJ/kg)h(kJ/kg)s(kJ/kg)
# 1      100.0   290.2   1.3285          -4347.52        -4214.67        10.756
# 2      250.0   350.8   0.6425          -4241.11        -4080.5         10.756

#

#******CALCULATE VARIABLES: Type in an expression starting with an '=' sign ('= mdot1*(h2-h1)',
'= sqrt(4*A1/PI)', etc.) and press the Enter key)*********

#
```

#Exit temp. T2:

T2 = 350.7901306152344 K ... Ans.

#Work needed per kg flow, W:

m1 * (h2-h1) = 134.16845703125 kJ/kg .... Ans.

==

9.14 REFERENCES:

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Appendix

EES Function to find out the compressibility Factor, Z when Tr and Pr are given:

Recall that we have the compressibility factor chart as shown below:

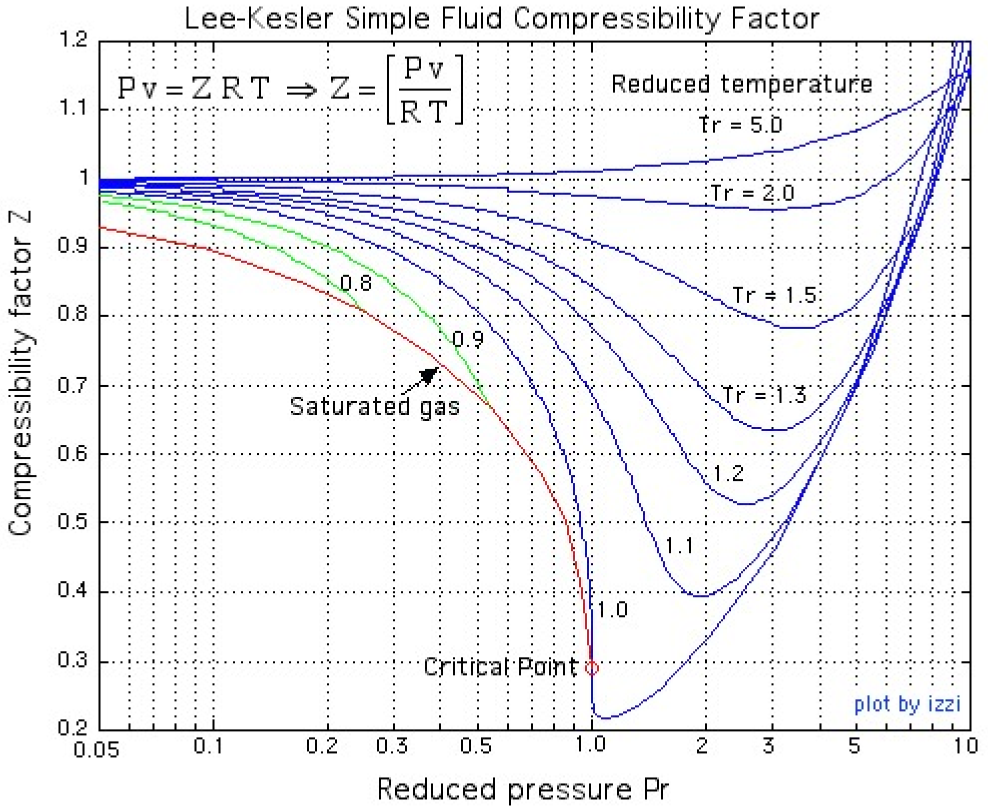


Fig. 9.6 Lee-Kesler compressibility chart [8]

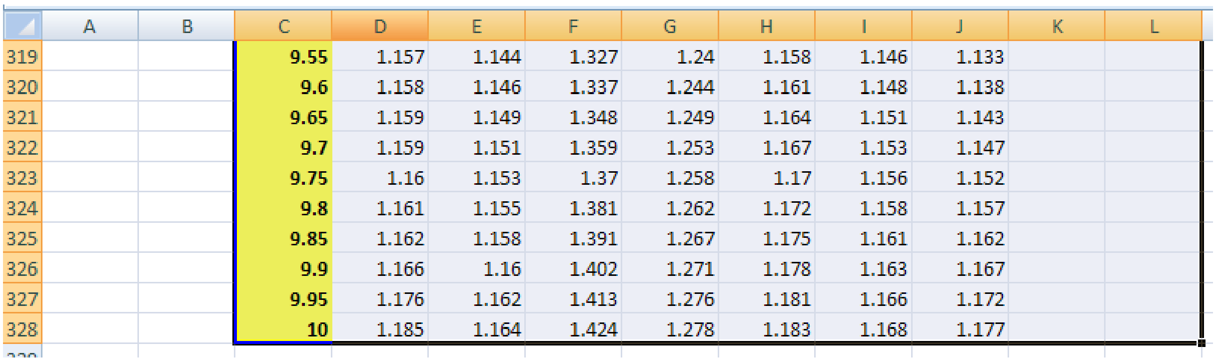
Now, in computer calculations, it is not very convenient to refer to the above graph as and when required. Also, interpolation in this graph is difficult because the x-axis is in logarithmic scale.

Therefore, it is preferable to have an EES Function to calculate Z when Tr and Pr are given. It makes the calculations very easy and simple.

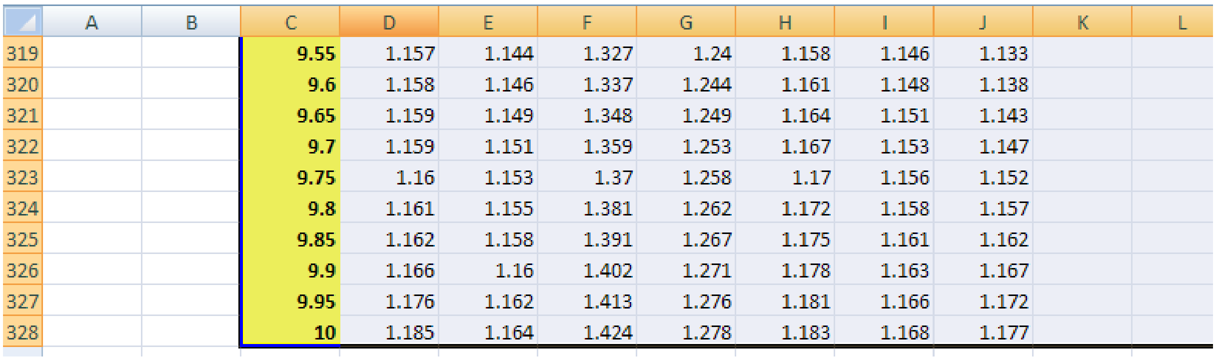
To write the EES Function, following are the steps:

1. Digitize each curve in the above plot using the 'free' software **"Plot Digitizer"** available from http://plotdigitizer.sourceforge.net. It is a Java based program, which is very easy to use.
2. Copy the x-y data produced in PlotDigitizer to EXCEL.
3. Use EES to re-cast the data such that x-axis (i.e. Pr) values are common for all the curves i.e. for Tr = 5, 2, 1.5, …..0.8, by linear interpolation.

4. Set up the final Table in EXCEL as shown below. Table is shown only partially, to conserve space.



	A	B	C	D	E	F	G	H	I	J	K	L
319			9.55	1.157	1.144	1.327	1.24	1.158	1.146	1.133		
320			9.6	1.158	1.146	1.337	1.244	1.161	1.148	1.138		
321			9.65	1.159	1.149	1.348	1.249	1.164	1.151	1.143		
322			9.7	1.159	1.151	1.359	1.253	1.167	1.153	1.147		
323			9.75	1.16	1.153	1.37	1.258	1.17	1.156	1.152		
324			9.8	1.161	1.155	1.381	1.262	1.172	1.158	1.157		
325			9.85	1.162	1.158	1.391	1.267	1.175	1.161	1.162		
326			9.9	1.166	1.16	1.402	1.271	1.178	1.163	1.167		
327			9.95	1.176	1.162	1.413	1.276	1.181	1.166	1.172		
328			10	1.185	1.164	1.424	1.278	1.183	1.168	1.177		



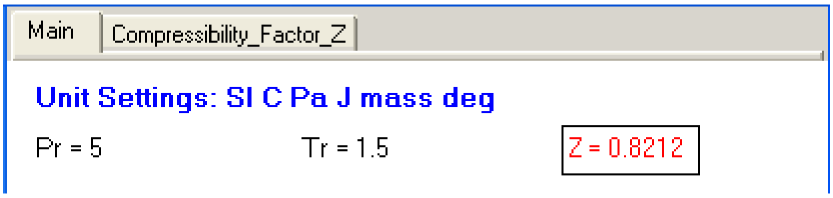
	A	B	C	D	E	F	G	H	I	J	K	L
319			9.55	1.157	1.144	1.327	1.24	1.158	1.146	1.133		
320			9.6	1.158	1.146	1.337	1.244	1.161	1.148	1.138		
321			9.65	1.159	1.149	1.348	1.249	1.164	1.151	1.143		
322			9.7	1.159	1.151	1.359	1.253	1.167	1.153	1.147		
323			9.75	1.16	1.153	1.37	1.258	1.17	1.156	1.152		
324			9.8	1.161	1.155	1.381	1.262	1.172	1.158	1.157		
325			9.85	1.162	1.158	1.391	1.267	1.175	1.161	1.162		
326			9.9	1.166	1.16	1.402	1.271	1.178	1.163	1.167		
327			9.95	1.176	1.162	1.413	1.276	1.181	1.166	1.172		
328			10	1.185	1.164	1.424	1.278	1.183	1.168	1.177		

5. Now, copy this Table as a **Lookup Table** in to EES and name it as 'CompressibilityFactor'.
6. Now, this Table is in a format suitable for 2D interpolation in EES, i.e. top horizontal row gives Tr values: 5 , 2, 1.5 …. 0.8, and left vertical column gives Pr values: 0.05, 0.1, 0.15 …..10. Rest of the numbers in the Table are corresponding Z values.
7. Z value for given Tr and Pr is found out by 2D interpolation in EES using the built-in Function **interpolate2DM.**
8. The simple EES Function to find Z when Tr and Pr are given is now written:

```
$UnitSystem SI Pa C J

FUNCTION Compressibility_Factor_Z(Tr,Pr)

{ Compressibility_Factor_Z  … finds the compressibility factor, given Tr (=T/Tc) and Pr (=P/Pc)}

Compressibility_Factor_Z = Interpolate2DM('CompressibilityFactor',Tr,Pr)
```

```
END

“============================================================”

“Example:”

Tr = 1.5

Pr = 5

“Then, Z is found out by:”

Z = Compressibility_Factor_Z(Tr,Pr)
```

Result:



```
Unit Settings: SI C Pa J mass deg
Pr = 5                Tr = 1.5                Z = 0.8212
```

```
================================================================================
```

Use of the above Function is demonstrated with the following example:

Example: Calculate the density of Nitrogen at 260 bar and 15 C using the compressibility chart.

Following is the EES program:

```
“Data:”

P = 260 “bar”

T = 15+273 “K”

R = 8314/28 “J/kg.K ... Gas const. for N2”

P_c = 33.94”bar...critical pressure for N2....from Table on page 18”

T_C = 126.2”K...critical temp. for N2..from Table on page 18”
```

"Calculations:"

Pr = P/P_c "...reduced pressure"

Tr = T/T_c "....reduced temp."

Z = Compressibility_Factor_Z(Tr,Pr)"....finds compressibility factor, Z …. Using the EES Function written above"

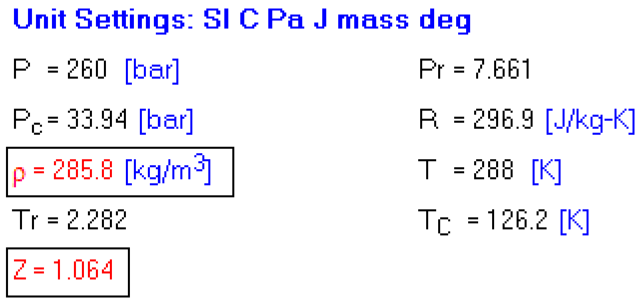
"And, density, rho:"

"rho = P/(Z * R * T) ... where rho is in kg/m^3, P in Pa, R in J/kg.K and T in Kelvin"

"Therefore:"

rho = P *10^5 / (Z * R * T) "....finds rho in kg/m^3"

Results:



```
Unit Settings: SI C Pa J mass deg
P  = 260  [bar]              Pr = 7.661
Pc = 33.94 [bar]             R  = 296.9 [J/kg-K]
ρ = 285.8 [kg/m3]            T  = 288  [K]
Tr = 2.282                   Tc  = 126.2 [K]
Z = 1.064
```

Thus:

Compressibility Factor, Z = 1.064 …. Ans.

Density of N2 = rho = 285.8 kg/m^3 … Ans.

===

To continue…

As we mentioned in the Preface in Part-I, generally, the subject of Thermodynamics is taught over two semesters, under the titles **Basic Thermodynamics** and **Applied Thermodynamics**.

Now, in this book entitled **Basic Thermodynamics: Software Solutions**, presented in four parts, we have solved problems on the topics such as: Units, Pressure, Temperature, Properties of Pure substances, Zeroth Law, Heat and Work, First Law of Thermodynamics for a closed system and for flow processes, Second Law of Thermodynamics, Heat engines, Refrigerators and Heat Pumps, Entropy, Availability and Irreversibility, Real and Ideal gases and Gas mixtures etc.

In the next series of books entitled **Applied Thermodynamics: Software Solutions,** we shall solve problems on the following topics: Thermodynamic relations, Vapour power cycles, Gas power cycles, Refrigeration cycles, Psychrometrics, Reactive Systems and Compressible fluid flow.

At the beginning of each chapter, definitions, Statements and Formulas used are presented. Then, problems are solved using Mathcad, Engineering Equation Solver (EES) or The Expert System on Thermodynamics (TEST).