Thermodynamic

2026-1

S3-2

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Ideal and Real Gases

UTEC
UNIVERSIDAD DE INGENIERÍA Y TECNOLOGÍA

Y.A. Çengel, and M.A. Boles, Thermodynamics, An Engineering Approach, 8th ed. New York, USA: McGraw-Hill Education, 2015.

Recomendaciones generales:

- Leer antes de clase y entender los conceptos o preguntar si es necesario.
- Practicar bastante:
  - *Ejercicios de clase
  - *Asesorías
  - *Ejercicios del libro resueltos y los de final de capitulo
- Los quizzes virtuales y gradescope úsenlos para aprender de forma honesta (se puede inferir).
- Tengan grupos de estudio y apóyense mutuamente.
- Crear sus propias notas estudio y formulario.
- Son 4 horas de clase en la semana (asistir y ser puntuales, perder alguna es atrasarse mucho)
- Cada hora de clase son 3 horas de estudio por fuera mínimo.
- En la ppt de la semana 1 están todos los links claves para el curso.

Thermodynamics _ Evaluation

COMPONENTE	%
PARCIAL	20
FINAL	30
C	50
APROBACIÓN: 11/20	

SEMANA 1	TAREA VIRTUAL	SE CALIFICA AUTOMATICO NO NECESITA PROCEDIMIENTO
SEMANA 2	TAREA VIRTUAL	
SEMANA 3	TAREA VIRTUAL	.
SEMANA 4	**TAREA INDIVIDUAL 1** + EVALUACION_ AULA1	TAREA INDIVIDUAL: Esta parte incluye subir un archivo con la solución EVALUACION_ AULA: SEMANAS 1-2
SEMANA 5	TAREA VIRTUAL+ EVALUACION_ AULA2	EVALUACION_ AULA: SEMANAS 1-3
SEMANA 6	TAREA VIRTUAL**+TAREA INDIVIDUAL 2**	
SEMANA 7	TAREA VIRTUAL+ EVALUACION_ AULA3	EVALUACION_ AULA: SEMANAS 1-6
SEMANA 8	**PARCIAL**	
SEMANA 9	EVALUACION_ AULA4+**TAREA INDIVIDUAL 3 +Tarea grupal 1**	EVALUACION_ AULA: SEMANAS 1-8
SEMANA 10	TAREA VIRTUAL	
SEMANA 11	TAREA VIRTUAL	
SEMANA 12	TAREA VIRTUAL+ EVALUACION_ AULA5	EVALUACION_ AULA: SEMANAS 1-11
SEMANA 13	TAREA VIRTUAL**+TAREA INDIVIDUAL 4 + Tarea grupal 2**	
SEMANA 14	TAREA VIRTUAL+EVALUACION_ AULA6	EVALUACION_ AULA : SEMANAS 1-13
SEMANA 15		
SEMANA 16	**FINAL**	

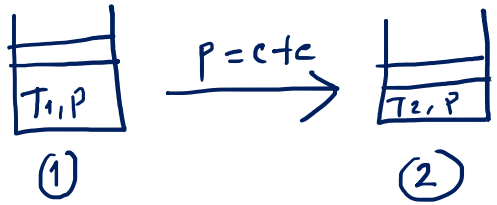
***LAS TAREAS VIRTUALES O LOS GRADESCOPE (TAREA INDIVIDAL) se abren lunes 2pm y se cierran sábado media noche. La tarea virtual se presenta hasta un máximo de 3 veces.**

EVALUACION_ AULA: es un quiz de 20 min aprox. en aula.

Session 5: Apply the ideal gas model for thermodynamic analysis using the equation of state and **estimating properties such as internal energy and enthalpy.**

Session 6: Determine the properties (P-V-T) of a real gas with the application of the reduced temperature, the reduced pressure and the compressibility diagram.

u,h for Ideal Gas?



$\Delta u\left[\frac{kJ}{kg}\right] = u_2 - u_1$?

$T_2 \quad T_1$

$\Delta h\left[\frac{kJ}{kg}\right] = h_2 - h_1$?

TABLE A-22

Ideal Gas Properties of Air

	T(K), h and u(kJ/kg), s° (kJ/kg · K)											
				when $\Delta s = 0^1$							when $\Delta s = 0$	
T	h	u	s°	p_r	v_r	T	h	u	s°	p_r	v_r
200	199.97	142.56	1.29559	0.3363	1707.	450	451.80	322.62	2.11161	5.775	223.6
210	209.97	149.69	1.34444	0.3987	1512.	460	462.02	329.97	2.13407	6.245	211.4
220	219.97	156.82	1.39105	0.4690	1346.	470	472.24	337.32	2.15604	6.742	200.1
230	230.02	164.00	1.43557	0.5477	1205.	480	482.49	344.70	2.17760	7.268	189.5
240	240.02	171.13	1.47824	0.6355	1084.	490	492.74	352.08	2.19876	7.824	179.7

TABLE A-23

Ideal Gas Properties of Selected Gases

	Enthalpy $\bar{h}(T)$ and internal energy $\bar{u}(T)$, in kJ/kmol. Absolute entropy at 1 atm $\bar{s}^\circ(T)$, in kJ/kmol · K.															
	Carbon Dioxide, CO_2 ($\bar{h}_f^\circ = -393{,}520$ kJ/kmol)			Carbon Monoxide, CO ($\bar{h}_f^\circ = -110{,}530$ kJ/kmol)			Water Vapor, H_2O ($\bar{h}_f^\circ = -241{,}820$ kJ/kmol)			Oxygen, O_2 ($\bar{h}_f^\circ = 0$ kJ/kmol)			Nitrogen, N_2 ($\bar{h}_f^\circ = 0$ kJ/kmol)			
T(K)	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	T(K)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
220	6,601	4,772	202.966	6,391	4,562	188.683	7,295	5,466	178.576	6,404	4,575	196.171	6,391	4,562	182.638	220
230	6,938	5,026	204.464	6,683	4,771	189.980	7,628	5,715	180.054	6,694	4,782	197.461	6,683	4,770	183.938	230
240	7,280	5,285	205.920	6,975	4,979	191.221	7,961	5,965	181.471	6,984	4,989	198.696	6,975	4,979	185.180	240
250	7,627	5,548	207.337	7,266	5,188	192.411	8,294	6,215	182.831	7,275	5,197	199.885	7,266	5,188	186.370	250
260	7,979	5,817	208.717	7,558	5,396	193.554	8,627	6,466	184.139	7,566	5,405	201.027	7,558	5,396	187.514	260
270	8,335	6,091	210.062	7,849	5,604	194.654	8,961	6,716	185.399	7,858	5,613	202.128	7,849	5,604	188.614	270

Is there another way?

$$du = c_v(T)\,dT$$

$$dh = c_p(T)\,dT$$

$\frac{kJ}{kg}$

M.J. Moran, H.N. Shapiro, D.D. Boettner, M.B. Bailey, Fundamentals of Engineering Thermodynamics, 10th ed. New Jersey, USA: John Wiley & Sons, 2014.

NAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF IDEAL GASES

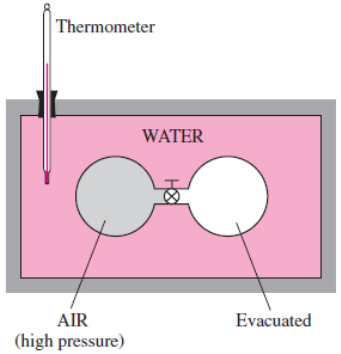


FIGURE 4–22
Schematic of the experimental apparatus used by Joule.

u= u(T, v) y tome su diferencial total:

$$du = \left(\frac{\partial u}{\partial T}\right)_v dT + \left(\frac{\partial u}{\partial v}\right)_T dv \qquad c_v = \left(\frac{\partial u}{\partial T}\right)_v$$

$$du = c_v\, dT + \left(\frac{\partial u}{\partial v}\right)_T dv$$

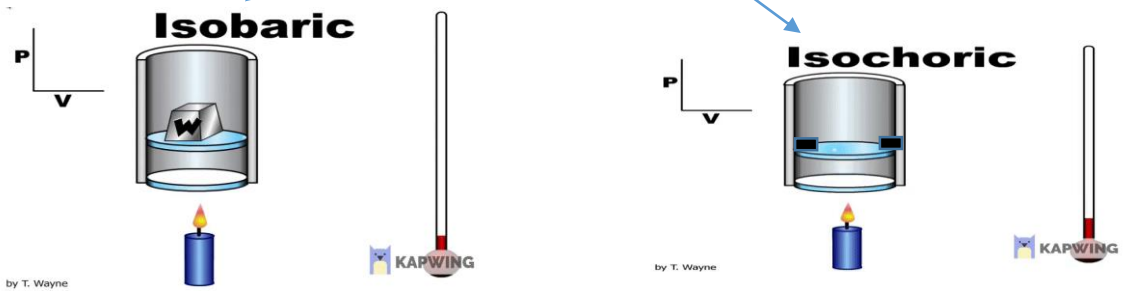
$$\left\{ \begin{array}{l} h = u + Pv \\ Pv = R_g T \end{array} \right\}$$

$$h = u + R_g T \Rightarrow \mathbf{h = f(T)} \Rightarrow h = F(T,P), \quad dh = c_p\, dT$$

$m = 1$ kg
$\Delta T = 1°C$
Specific heat = 5 kJ/kg·°C

5 kJ

Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.



c_p c_v

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INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF IDEAL GASES

For ideal gases: $Pv = R_g T$

$$h = u + Pv = u + RT \rightarrow u = h - RT$$

$$\therefore \Delta \boldsymbol{u} = \Delta \boldsymbol{h} - \boldsymbol{R}\Delta \boldsymbol{T}$$

$$c_p = c_v + R_g \qquad (\mathrm{kJ/kg \cdot K})$$

$$\bar{c}_p = \bar{c}_v + R_u \qquad (\mathrm{kJ/kmol \cdot K})$$

demonstrated that for I.G. :

$$du = c_v(T)\, dT$$

$$dh = c_p(T)\, dT$$

Y.A. Çengel, and M.A. Boles, Thermodynamics, An Engineering Approach, 8th ed. New York, USA: McGraw-Hill Education, 2015.

4–5 ▪ INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF SOLIDS AND LIQUIDS

A substance whose specific volume (or density) is constant is called an **incompressible substance**. The specific volumes of solids and liquids essentially remain constant during a process (Fig. 4–33). Therefore, liquids and solids can be approximated as incompressible substances without sacrificing much in accuracy. The constant-volume assumption should be taken to imply that the energy associated with the volume change is negligible compared with other forms of energy. Otherwise, this assumption would be ridiculous for studying the thermal stresses in solids (caused by volume change with temperature) or analyzing liquid-in-glass thermometers.

It can be mathematically shown that (see Chap. 12) the constant-volume and constant-pressure specific heats are identical for incompressible substances (Fig. 4–34). Therefore, for solids and liquids, the subscripts on c_p and c_v can be dropped, and both specific heats can be represented by a single symbol c. That is,

$$c_p = c_v = c \tag{4–32}$$

This result could also be deduced from the physical definitions of constant-volume and constant-pressure specific heats. Specific heat values for several common liquids and solids are given in Table A–3.

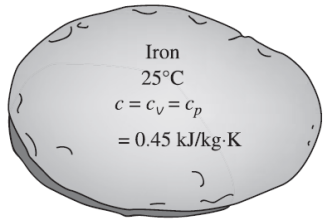


FIGURE 4–34
The c_v and c_p values of incompressible substances are identical and are denoted by c.

Internal Energy Changes

Like those of ideal gases, the specific heats of incompressible substances depend on temperature only. Thus, the partial differentials in the defining equation of c_v can be replaced by ordinary differentials, which yield

$$du = c_v dT = c(T)\, dT \tag{4–33}$$

The change in internal energy between states 1 and 2 is then obtained by integration:

$$\Delta u = u_2 - u_1 = \int_1^2 c(T)\, dT \quad \text{(kJ/kg)} \tag{4–34}$$

The variation of specific heat c with temperature should be known before this integration can be carried out. For small temperature intervals, a c value at the average temperature can be used and treated as a constant, yielding

$$\Delta u \cong c_{avg}(T_2 - T_1) \quad \text{(kJ/kg)} \tag{4–35}$$

Enthalpy Changes

Using the definition of enthalpy $h = u + Pv$ and noting that v = constant, the differential form of the enthalpy change of incompressible substances can be determined by differentiation to be

$$dh = du + v\, dP + P\, \overbrace{dv}^{0} = du + v\, dP \tag{4–36}$$

Integrating,

$$\Delta h = \Delta u + v\, \Delta P \cong c_{avg}\, \Delta T + v\, \Delta P \quad \text{(kJ/kg)} \tag{4–37}$$

For *solids*, the term $v\, \Delta P$ is insignificant and thus $\Delta h = \Delta u \cong c_{avg} \Delta T$. For *liquids*, two special cases are commonly encountered:

1. *Constant-pressure processes,* as in heaters ($\Delta P = 0$): $\Delta h = \Delta u \cong c_{avg} \Delta T$
2. *Constant-temperature processes,* as in pumps ($\Delta T = 0$): $\Delta h = v\, \Delta P$

For a process between states 1 and 2, the last relation can be expressed as $h_2 - h_1 = v(P_2 - P_1)$. By taking state 2 to be the compressed liquid state at a given T and P and state 1 to be the saturated liquid state at the same temperature, the enthalpy of the compressed liquid can be expressed as

$$h_{@\,P,T} \cong h_{f\,@\,T} + v_{f\,@\,T}(P - P_{sat\,@\,T}) \tag{4–38}$$

as discussed in Chap. 3. This is an improvement over the assumption that the enthalpy of the compressed liquid could be taken as h_f at the given temperature (that is, $h_{@\,P,T} \cong h_{f\,@\,T}$). However, the contribution of the last term is often very small, and is neglected. (Note that at high temperature and pressures, Eq. 4–38 may overcorrect the enthalpy and result in a larger error than the approximation $h \cong h_{f\,@\,T}$.)

2. The difference between c_p and c_v approaches zero as the absolute temperature approaches zero.
3. The two specific heats are identical for truly incompressible substances since v = constant. The difference between the two specific heats is very small and is usually disregarded for substances that are *nearly* incompressible, such as liquids and solids.

INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF IDEAL GASES

$$du = c_v(T)\, dT$$

$$dh = c_p(T)\, dT$$

Note that the d*u* and d*h* relations given previously are not restricted to any kind of process. They are valid for all processes.

HOW TO EVALUATE INTERNAL ENERGY AND ENTHALPYOF IDEAL GASES?

Equivalentes en terminos de precisión

$\Delta h =$

1. Tabulated data and calculating Δh: Tables A-22 y Table A-23

$\Delta h = h_2(T_2) - h_1(T_1)$

2. Using expression for $c_p(T)$ and integrating: Table A-21

→ Cp variable con la T

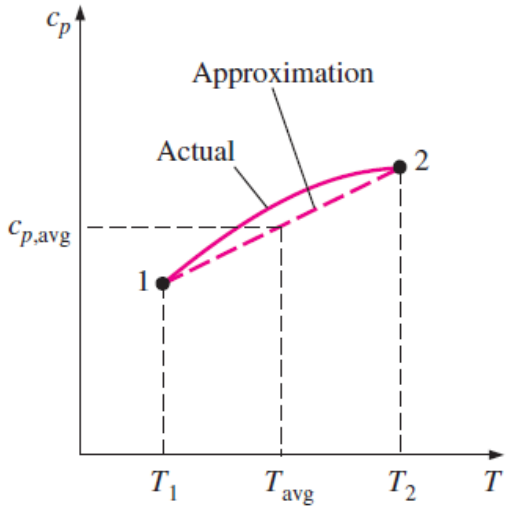
$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T)\, dT \qquad (\text{kJ/kg})$$

$$= \int \underbrace{(2T + 3T^2)}_{C_p(T)} dT$$

3. Using c_{p_avg} and and integrating Table A-20

$\Delta h = C_{p\_avg}\, \Delta T$

→ Asume Cp cte con la T



OJO: Intervalos pequeños de T
de lo contrario toca usar el
método 2.

HOW TO EVALUATE INTERNAL ENERGY AND ENTHALPYOF IDEAL GASES?

Equivalentes en terminos de precisión

$\Delta h =$

1. Tabulated data and calculating Δh: Tables A-22 y Table A-23

$\Delta h = h_2(T_2) - h_1(T_1)$

2. Using expression for $c_p(T)$ and integrating: Table A-21

Cp variable con la T

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T)\, dT \qquad \text{(kJ/kg)}$$

$= \int \underbrace{(2T + 3T^2)}_{C_p(T)} dT$

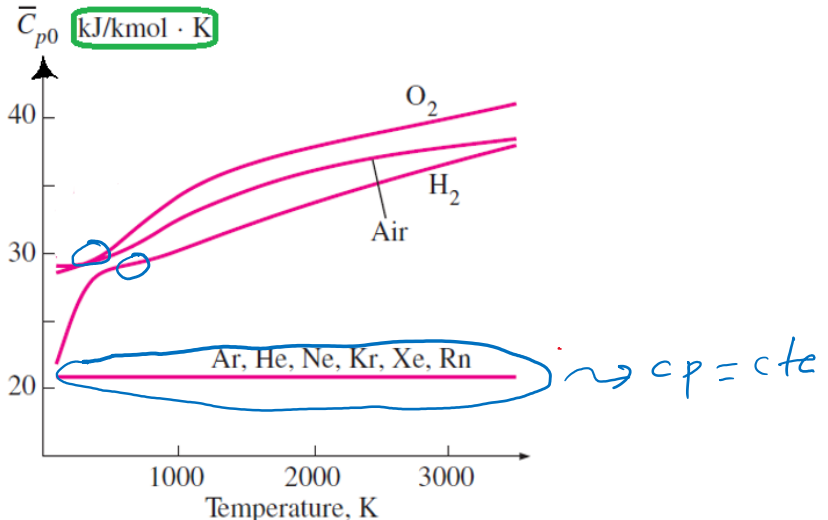
3. Using c_{p_avg} and and integrating Table A-20

$\Delta h = C_{p\_avg}\, \Delta T$ → Asume Cp cte con la T

4. Using c_p constant and and integrating: Table A-20

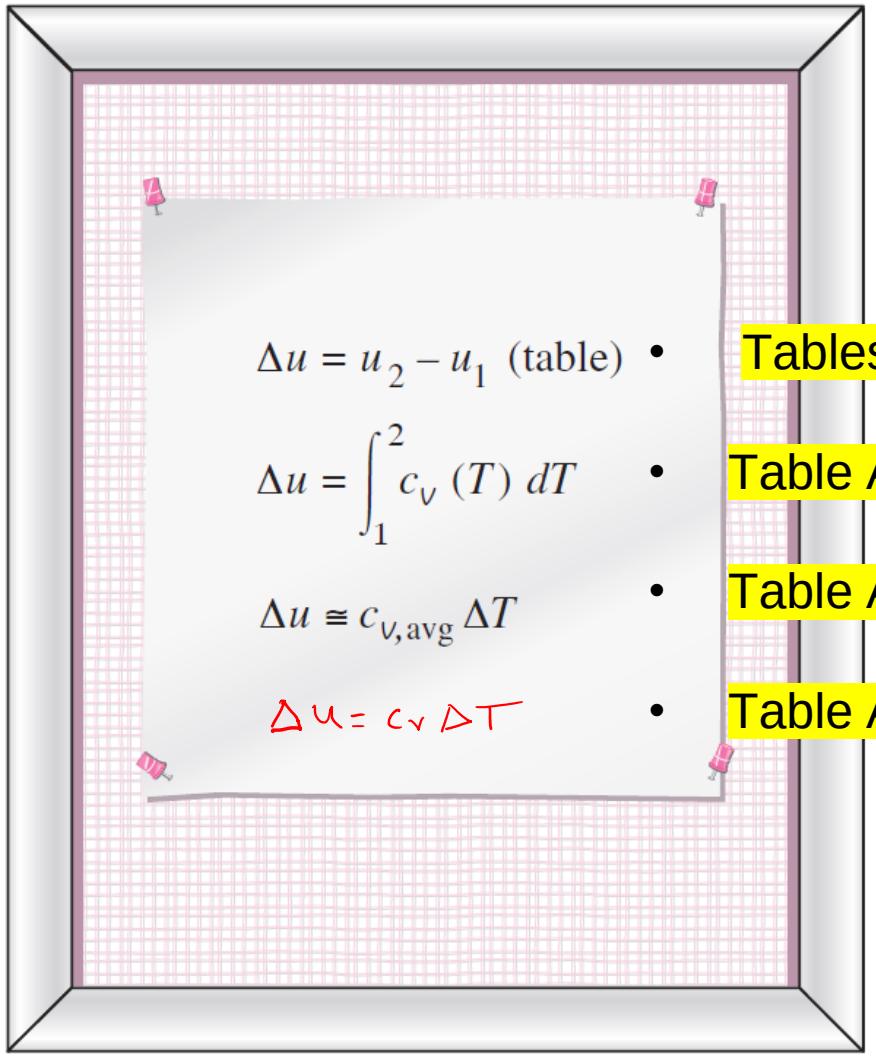
$\Delta h = c_p\, \Delta T \rightarrow h = cpT$

Asume Cp cte con la T



→ cp = cte

In the same way.....



- $\Delta u = u_2 - u_1$ (table) • Tables A-22 y Table A-23
- $\Delta u = \int_1^2 c_v\,(T)\,dT$ • Table A-21 → C_p variable → ver ejemplo 9-1
- $\Delta u \cong c_{v,\text{avg}}\,\Delta T$ • Table A-20 → C_v cte
- $\Delta u = c_v \Delta T$ • Table A-20 → C_v cte

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8.1 Determine the enthalpy change *h* of nitrogen(N_2), in **kJ/kg**, as it is heated from **400** to **800** K, using **(*a*)** the empirical specific heat equation as a function of temperature (Table A–21), **(*b*)** the c_p value at the average temperature (Table A–20), and **(*c*)** the c_p value at 400K (Table A–20). **(d)** Using the table A-23.

a) c_p as function of temperature – Table A-21

TABLE A-21

Variation of $\bar{c}_p$ with Temperature for Selected Ideal Gases

$$\frac{\bar{c}_p}{\bar{R}} = \alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4$$ → Adimensional

T is in K, equations valid from 300 to 1000 K

Gas	α	$\beta \times 10^3$	$\gamma \times 10^6$	$\delta \times 10^9$	$\varepsilon \times 10^{12}$
CO	3.710	−1.619	3.692	−2.032	0.240
CO_2	2.401	8.735	−6.607	2.002	0
H_2	3.057	2.677	−5.810	5.521	−1.812
H_2O	4.070	−1.108	4.152	−2.964	0.807
O_2	3.626	−1.878	7.055	−6.764	2.156
N_2	3.675	−1.208	2.324	−0.632	−0.226
Air	3.653	−1.337	3.294	−1.913	0.2763
SO_2	3.267	5.324	0.684	−5.281	2.559
CH_4	3.826	−3.979	24.558	−22.733	6.963
C_2H_2	1.410	19.057	−24.501	16.391	−4.135
C_2H_4	1.426	11.383	7.989	−16.254	6.749
Monatomic gases[a]	2.5	0	0	0	0

$$\Delta\bar{h} = \int \bar{c}_p dT$$ → kJ/kmol

$\bar{R} = 8.314 \frac{kJ}{kPa \cdot m^3 / kmol \cdot K}$

$$\Delta\bar{h} = \int_{400}^{800} \bar{R}(\alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4) dT$$

$$\Delta\bar{h} = \bar{R}\left[\alpha T + \beta\frac{T^2}{2} + \gamma\frac{T^3}{3} + \delta\frac{T^4}{4} + \varepsilon\frac{T^5}{5}\right]_{400}^{800}$$

$$\Delta\bar{h} = \bar{R}\left[3.675(800-400) - 1.208\times10^{-3}\left(\frac{800^2-400^2}{2}\right) + 2.324\times10^{-6}\left(\frac{800^3-400^3}{3}\right) - 0.632\times10^{-9}\left(\frac{800^4-400^4}{4}\right) - 0.226\times10^{-12}\left(\frac{800^5-400^5}{5}\right)\right]$$

$$\Delta\bar{h} = \bar{R}[1452.1104][=]\frac{\text{kJ}}{\text{k}mol} \qquad \Delta h = \frac{8.314}{28.01}\times 1452.1104\frac{\text{kJ}}{\text{kg}} \quad = \mathbf{431.0191}\,\frac{\mathbf{kJ}}{\mathbf{kg}}$$

b) c_p at an average temperature =(800+400)/2 = 600K

TABLE A-20

Ideal Gas Specific Heats of Some Common Gases (kJ/kg · K)

Temp. K	c_p	c_v	k	c_p	c_v	k	c_p	c_v	k	Temp. K
	Air			Nitrogen, N_2			Oxygen, O_2			
250	1.003	0.716	1.401	1.039	0.742	1.400	0.913	0.653	1.398	250
300	1.005	0.718	1.400	1.039	0.743	1.400	0.918	0.658	1.395	300
350	1.008	0.721	1.398	1.041	0.744	1.399	0.928	0.668	1.389	350
400	1.013	0.726	1.395	1.044	0.747	1.397	0.941	0.681	1.382	400
450	1.020	0.733	1.391	1.049	0.752	1.395	0.956	0.696	1.373	450
500	1.029	0.742	1.387	1.056	0.759	1.391	0.972	0.712	1.365	500
550	1.040	0.753	1.381	1.065	0.768	1.387	0.988	0.728	1.358	550
600	1.051	0.764	1.376	1.075	0.778	1.382	1.003	0.743	1.350	600
650	1.063	0.776	1.370	1.086	0.789	1.376	1.017	0.758	1.343	650
700	1.075	0.788	1.364	1.098	0.801	1.371	1.031	0.771	1.337	700
750	1.087	0.800	1.359	1.110	0.813	1.365	1.043	0.783	1.332	750
800	1.099	0.812	1.354	1.121	0.825	1.360	1.054	0.794	1.327	800
900	1.121	0.834	1.344	1.145	0.849	1.349	1.074	0.814	1.319	900
1000	1.142	0.855	1.336	1.167	0.870	1.341	1.090	0.830	1.313	1000

$$\Delta h = \int c_p dT = c_{p,avg}(\Delta T)$$

$$\Delta h = 1.075\times(800-400) = \mathbf{430}\,\frac{\mathbf{kJ}}{\mathbf{kg}}$$

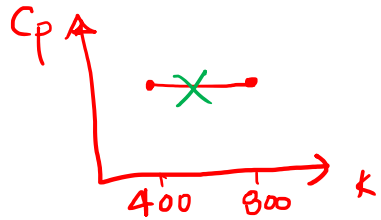
c) c_p at 400K

TABLE A-20

Ideal Gas Specific Heats of Some Common Gases (kJ/kg · K)

Temp. K	c_p	c_v	k	c_p	c_v	k	c_p	c_v	k	Temp. K
	Air			Nitrogen, N_2			Oxygen, O_2			
250	1.003	0.716	1.401	1.039	0.742	1.400	0.913	0.653	1.398	250
300	1.005	0.718	1.400	1.039	0.743	1.400	0.918	0.658	1.395	300
350	1.008	0.721	1.398	1.041	0.744	1.399	0.928	0.668	1.389	350
400	1.013	0.726	1.395	1.044	0.747	1.397	0.941	0.681	1.382	400
450	1.020	0.733	1.391	1.049	0.752	1.395	0.956	0.696	1.373	450
500	1.029	0.742	1.387	1.056	0.759	1.391	0.972	0.712	1.365	500
550	1.040	0.753	1.381	1.065	0.768	1.387	0.988	0.728	1.358	550
600	1.051	0.764	1.376	1.075	0.778	1.382	1.003	0.743	1.350	600
650	1.063	0.776	1.370	1.086	0.789	1.376	1.017	0.758	1.343	650
700	1.075	0.788	1.364	1.098	0.801	1.371	1.031	0.771	1.337	700
750	1.087	0.800	1.359	1.110	0.813	1.365	1.043	0.783	1.332	750
800	1.099	0.812	1.354	1.121	0.825	1.360	1.054	0.794	1.327	800
900	1.121	0.834	1.344	1.145	0.849	1.349	1.074	0.814	1.319	900
1000	1.142	0.855	1.336	1.167	0.870	1.341	1.090	0.830	1.313	1000

$$\Delta h = \int c_p dT = c_p(\Delta T)$$



$$\Delta h = 1.044 \times (800 - 400) = \mathbf{417.6}\,\frac{\mathbf{kJ}}{\mathbf{kg}}$$

d) Ideal gas enthalpy

TABLE A-23

Ideal Gas Properties of Selected Gases

Enthalpy $\bar{h}(T)$ and internal energy $\bar{u}(T)$, in kJ/kmol. Absolute entropy at 1 atm $\bar{s}^\circ(T)$, in kJ/kmol · K.

T(K)	Carbon Dioxide, CO_2 ($\bar{h}_f^\circ$ = −393,520 kJ/kmol)			Carbon Monoxide, CO ($\bar{h}_f^\circ$ = −110,530 kJ/kmol)			Water Vapor, H_2O ($\bar{h}_f^\circ$ = −241,820 kJ/kmol)			Oxygen, O_2 ($\bar{h}_f^\circ$ = 0 kJ/kmol)			Nitrogen, N_2 ($\bar{h}_f^\circ$ = 0 kJ/kmol)			T(K)
	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	
400	13,372	10,046	225.225	11,644	8,319	206.125	13,356	10,030	198.673	11,711	8,384	213.765	11,640	8,314	200.071	400
800	32,179	25,527	257.408	23,844	17,193	227.162	27,896	21,245	223.693	24,523	17,872	235.810	23,714	17,061	220.907	800

$$\Delta \bar{h} = \bar{h}_2 - \bar{h}_1$$

$$\Delta \bar{h} = 23714 - 11640 = 12074\,\frac{\text{kJ}}{\text{kmol}}$$

$$\Delta h = 12074\,\frac{\text{kJ}}{\text{kmol}} \times \frac{1}{28.01}\,\frac{\text{kmol}}{\text{kg}}$$

$$\Delta h = \mathbf{431.0603}\,\frac{\mathbf{kJ}}{\mathbf{kg}}$$

M.J. Moran, H.N. Shapiro, D.D. Boettner, M.B. Bailey, Fundamentals of Engineering Thermodynamics, 10th ed. New Jersey, USA: John Wiley & Sons, 2014.

9.1. Determine the internal energy change *u* of carbon dioxide, in kJ/kg, as it is heated from 300 to 900 K, using **(*a*)** the empirical specific heat equation as a function of temperature (Table A–21), **(*b*)** the c_v value at the average temperature (Table A–20), and **(*c*)** the c_v value at room temperature (300K) (Table A–20). **(d)** Using the table A-23.

a) c_p as function of temperature – Table A-21

TABLE A-21

Variation of $\bar{c}_p$ with Temperature for Selected Ideal Gases

$$\frac{\bar{c}_p}{\bar{R}} = \alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4$$

T is in K, equations valid from 300 to 1000 K

Gas	α	$\beta \times 10^3$	$\gamma \times 10^6$	$\delta \times 10^9$	$\varepsilon \times 10^{12}$
CO	3.710	−1.619	3.692	−2.032	0.240
CO_2	2.401	8.735	−6.607	2.002	0
H_2	3.057	2.677	−5.810	5.521	−1.812
H_2O	4.070	−1.108	4.152	−2.964	0.807
O_2	3.626	−1.878	7.055	−6.764	2.156
N_2	3.675	−1.208	2.324	−0.632	−0.226
Air	3.653	−1.337	3.294	−1.913	0.2763
SO_2	3.267	5.324	0.684	−5.281	2.559
CH_4	3.826	−3.979	24.558	−22.733	6.963
C_2H_2	1.410	19.057	−24.501	16.391	−4.135
C_2H_4	1.426	11.383	7.989	−16.254	6.749
Monatomic gases[a]	2.5	0	0	0	0

For ideal gases:

$$h = u + Pv = u + RT \rightarrow\rightarrow u = h - RT$$

$$\therefore \Delta \boldsymbol{u} = \Delta \boldsymbol{h} - \boldsymbol{R}\Delta \boldsymbol{T}$$

$$\Delta \bar{h} = \int \bar{c}_p dT$$

$$\Delta \bar{h} = \int_{300}^{900} \bar{R}(\alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4) dT$$

$$\Delta \bar{h} = \bar{R}\left[\alpha T + \beta \frac{T^2}{2} + \gamma \frac{T^3}{3} + \delta \frac{T^4}{4} + \varepsilon \frac{T^5}{5}\right]_{300}^{900}$$

$$\Delta\bar{h} = \bar{R}\left[2.401(900-300) + 8.735\times10^{-3}\left(\frac{900^2-300^2}{2}\right) - 6.607\times10^{-6}\left(\frac{900^3-300^3}{3}\right) + 2.002\times10^{-9}\left(\frac{900^4-300^4}{4}\right) + 0.000\times10^{-12}\left(\frac{900^5-300^5}{5}\right)\right]$$

$$\Delta\bar{h} = \bar{R}[3363.486] \ldots . \Delta h = \frac{8.314}{44.01}\times 3363.486\frac{\text{kJ}}{\text{kg}} = \mathbf{635.4016}\frac{\mathbf{kJ}}{\mathbf{kg}}$$

$$\therefore \Delta u = \Delta h - R\Delta T = 635.40 - \frac{8.314}{44.01}\times(900-300) = \mathbf{522.0546}\frac{\mathbf{kJ}}{\mathbf{kg}}$$

b) c_v at an average temperature = 600K

TABLE A-20

Ideal Gas Specific Heats of Some Common Gases (kJ/kg · K)

	c_p	c_v	k	c_p	c_v	k	c_p	c_v	k	
Temp. K	Carbon Dioxide, CO_2			Carbon Monoxide, CO			Hydrogen, H_2			Temp. K
250	0.791	0.602	1.314	1.039	0.743	1.400	14.051	9.927	1.416	250
300	0.846	0.657	1.288	1.040	0.744	1.399	14.307	10.183	1.405	300
350	0.895	0.706	1.268	1.043	0.746	1.398	14.427	10.302	1.400	350
400	0.939	0.750	1.252	1.047	0.751	1.395	14.476	10.352	1.398	400
450	0.978	0.790	1.239	1.054	0.757	1.392	14.501	10.377	1.398	450
500	1.014	0.825	1.229	1.063	0.767	1.387	14.513	10.389	1.397	500
550	1.046	0.857	1.220	1.075	0.778	1.382	14.530	10.405	1.396	550
600	1.075	0.886	1.213	1.087	0.790	1.376	14.546	10.422	1.396	600
650	1.102	0.913	1.207	1.100	0.803	1.370	14.571	10.447	1.395	650
700	1.126	0.937	1.202	1.113	0.816	1.364	14.604	10.480	1.394	700
750	1.148	0.959	1.197	1.126	0.829	1.358	14.645	10.521	1.392	750
800	1.169	0.980	1.193	1.139	0.842	1.353	14.695	10.570	1.390	800
900	1.204	1.015	1.186	1.163	0.866	1.343	14.822	10.698	1.385	900
1000	1.234	1.045	1.181	1.185	0.888	1.335	14.983	10.859	1.380	1000

$$\Delta u = \int c_v dT = c_{v,avg}(\Delta T)$$

$$\Delta u = 0.886\times(600) = \mathbf{531.6}\frac{\mathbf{kJ}}{\mathbf{kg}}$$

c) c_v at room temperature = 300K

TABLE A-20

Ideal Gas Specific Heat

	c_p	c_v
Temp. K	Carbon Dioxide, CO_2	
250	0.791	0.602
300	0.846	0.657

$$\Delta u = \int c_v dT = c_{v,avg}(\Delta T)$$

$$\Delta u = 0.657 \times (600) = \mathbf{394.2}\,\frac{\mathbf{kJ}}{\mathbf{kg}}$$

d) Ideal gas internal energy

TABLE A-23

Ideal Gas Properties of Selected Gases

Enthalpy $\bar{h}(T)$ and internal energy $\bar{u}(T)$, in kJ/kmol. Absolute entropy at 1 atm $\bar{s}^\circ(T)$, in kJ/kmol · K.

	Carbon Dioxide, CO_2 ($\bar{h}_f^\circ = -393{,}520$ kJ/kmol)			Carbon Monoxide, CO ($\bar{h}_f^\circ = -110{,}530$ kJ/kmol)			Water Vapor, H_2O ($\bar{h}_f^\circ = -241{,}820$ kJ/kmol)		
T(K)	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$
300	9,431	6,939	213.915	8,723	6,229	197.723	9,966	7,472	188.928
900	37,405	29,922	263.559	27,066	19,583	230.957	31,828	24,345	228.321

$$\Delta u = \int c_v dT = u_2 - u_1$$

$$\Delta u = 29922 - 6939 = 22983\,\frac{\text{kJ}}{\text{kmol}}$$

$$\Delta u = 22983\,\frac{\text{kJ}}{\text{kmol}} \times \frac{1}{44.01}\,\frac{\text{kmol}}{\text{kg}}$$

$$\Delta u = \mathbf{522.2222}\,\frac{\mathbf{kJ}}{\mathbf{kg}}$$

4–5 ▪ INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF SOLIDS AND LIQUIDS

A substance whose specific volume (or density) is constant is called an **incompressible substance**. The specific volumes of solids and liquids essentially remain constant during a process (Fig. 4–33). Therefore, liquids and solids can be approximated as incompressible substances without sacrificing much in accuracy. The constant-volume assumption should be taken to imply that the energy associated with the volume change is negligible compared with other forms of energy. Otherwise, this assumption would be ridiculous for studying the thermal stresses in solids (caused by volume change with temperature) or analyzing liquid-in-glass thermometers.

It can be mathematically shown that (see Chap. 12) the constant-volume and constant-pressure specific heats are identical for incompressible substances (Fig. 4–34). Therefore, for solids and liquids, the subscripts on c_p and c_v can be dropped, and both specific heats can be represented by a single symbol c. That is,

$$c_p = c_v = c \tag{4–32}$$

This result could also be deduced from the physical definitions of constant-volume and constant-pressure specific heats. Specific heat values for several common liquids and solids are given in Table A–3.

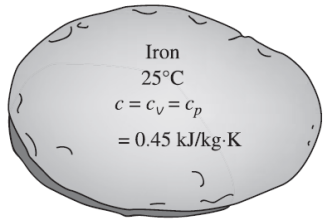


FIGURE 4–34
The c_v and c_p values of incompressible substances are identical and are denoted by c.

Internal Energy Changes

Like those of ideal gases, the specific heats of incompressible substances depend on temperature only. Thus, the partial differentials in the defining equation of c_v can be replaced by ordinary differentials, which yield

$$du = c_v dT = c(T)\, dT \tag{4–33}$$

The change in internal energy between states 1 and 2 is then obtained by integration:

$$\Delta u = u_2 - u_1 = \int_1^2 c(T)\, dT \quad \text{(kJ/kg)} \tag{4–34}$$

The variation of specific heat c with temperature should be known before this integration can be carried out. For small temperature intervals, a c value at the average temperature can be used and treated as a constant, yielding

$$\Delta u \cong c_{avg}(T_2 - T_1) \quad \text{(kJ/kg)} \tag{4–35}$$

Enthalpy Changes

Using the definition of enthalpy $h = u + Pv$ and noting that v = constant, the differential form of the enthalpy change of incompressible substances can be determined by differentiation to be

$$dh = du + v\, dP + P\, \overbrace{dv}^{0} = du + v\, dP \tag{4–36}$$

Integrating,

$$\Delta h = \Delta u + v\, \Delta P \cong c_{avg}\, \Delta T + v\, \Delta P \quad \text{(kJ/kg)} \tag{4–37}$$

For *solids*, the term $v\, \Delta P$ is insignificant and thus $\Delta h = \Delta u \cong c_{avg} \Delta T$. For *liquids*, two special cases are commonly encountered:

1. *Constant-pressure processes,* as in heaters ($\Delta P = 0$): $\Delta h = \Delta u \cong c_{avg} \Delta T$
2. *Constant-temperature processes,* as in pumps ($\Delta T = 0$): $\Delta h = v\, \Delta P$

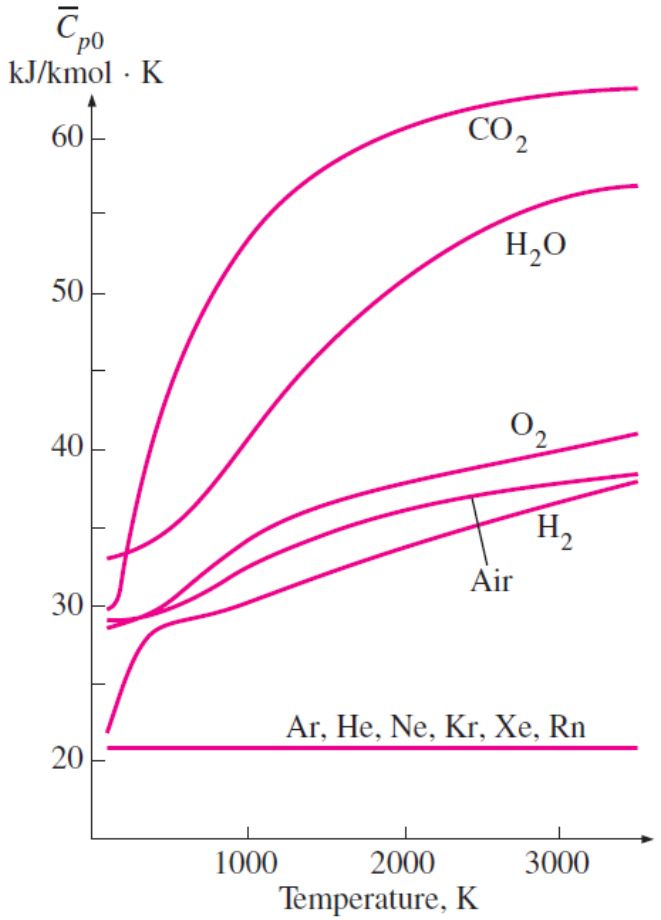
For a process between states 1 and 2, the last relation can be expressed as $h_2 - h_1 = v(P_2 - P_1)$. By taking state 2 to be the compressed liquid state at a given T and P and state 1 to be the saturated liquid state at the same temperature, the enthalpy of the compressed liquid can be expressed as

$$h_{@P,T} \cong h_{f\,@\,T} + v_{f\,@\,T}(P - P_{\text{sat}\,@\,T}) \tag{4–38}$$

as discussed in Chap. 3. This is an improvement over the assumption that the enthalpy of the compressed liquid could be taken as h_f at the given temperature (that is, $h_{@\,P,T} \cong h_{f\,@\,T}$). However, the contribution of the last term is often very small, and is neglected. (Note that at high temperature and pressures, Eq. 4–38 may overcorrect the enthalpy and result in a larger error than the approximation $h \cong h_{f\,@\,T}$.)

2. The difference between c_p and c_v approaches zero as the absolute temperature approaches zero.
3. The two specific heats are identical for truly incompressible substances since v = constant. The difference between the two specific heats is very small and is usually disregarded for substances that are *nearly* incompressible, such as liquids and solids.

At low pressures, all real gases approach ideal-gas behavior, and therefore their specific heats depend on temperature only.



Y.A. Çengel, and M.A. Boles, Thermodynamics, An Engineering Approach, 8th ed. New York, USA: McGraw-Hill Education, 2015.

Y.A. Çengel, and M.A. Boles, Thermodynamics, An Engineering Approach, 8th ed. New York, USA: McGraw-Hill Education, 2015.

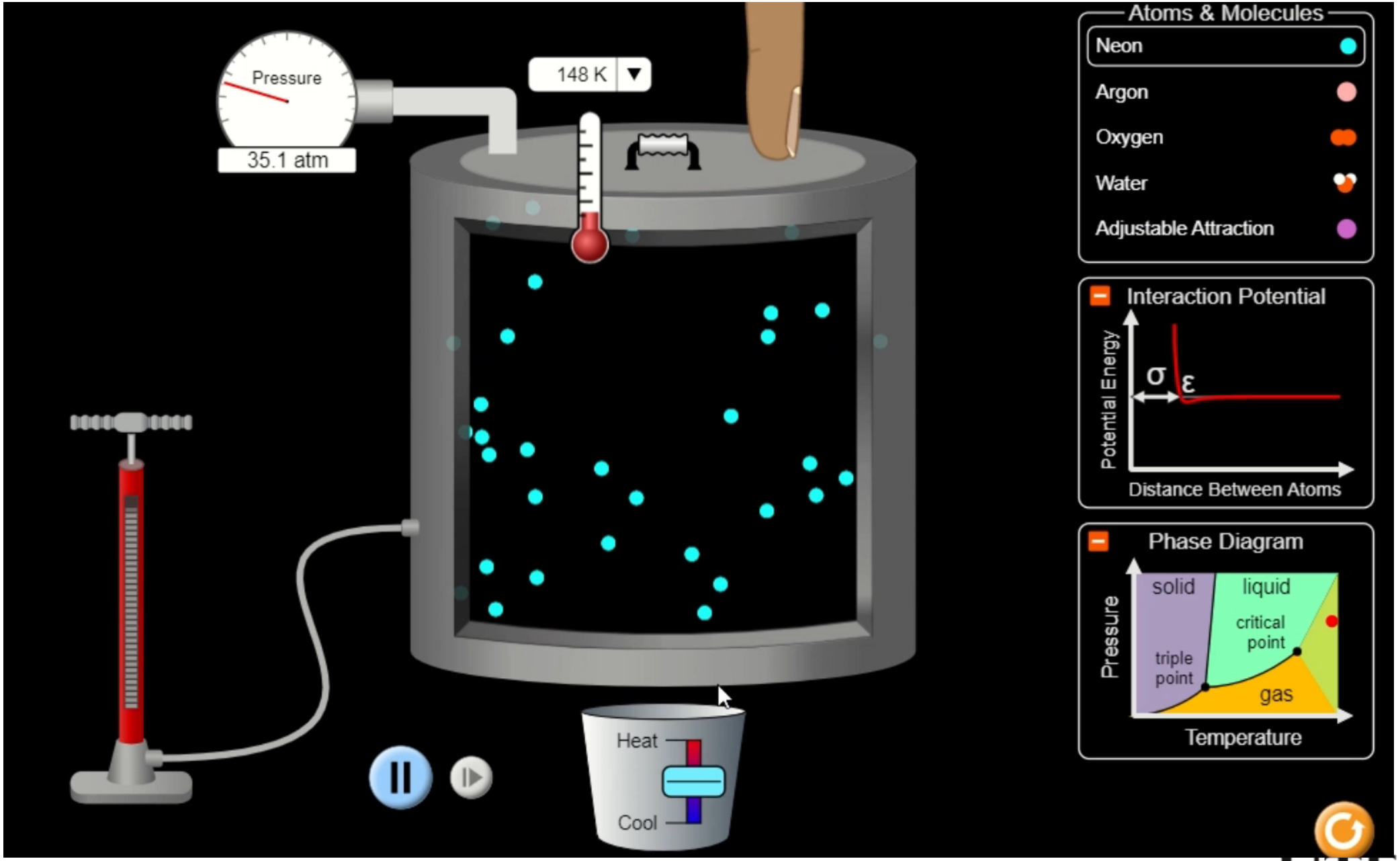
1 2.58

$$\frac{V_{final}}{T_{final}} = \frac{V_{initial}}{T_{initial}}$$

$$\therefore \frac{V_{final}}{V_{initial}} = \frac{T_{final}}{T_{initial}}$$

$$\therefore ratio\ of\ \frac{V_{final}}{V_{initial}} = \frac{77K}{300K} = 0.26$$

https://www.youtube.com/watch?v=4d0FA8yImt0&t=312s



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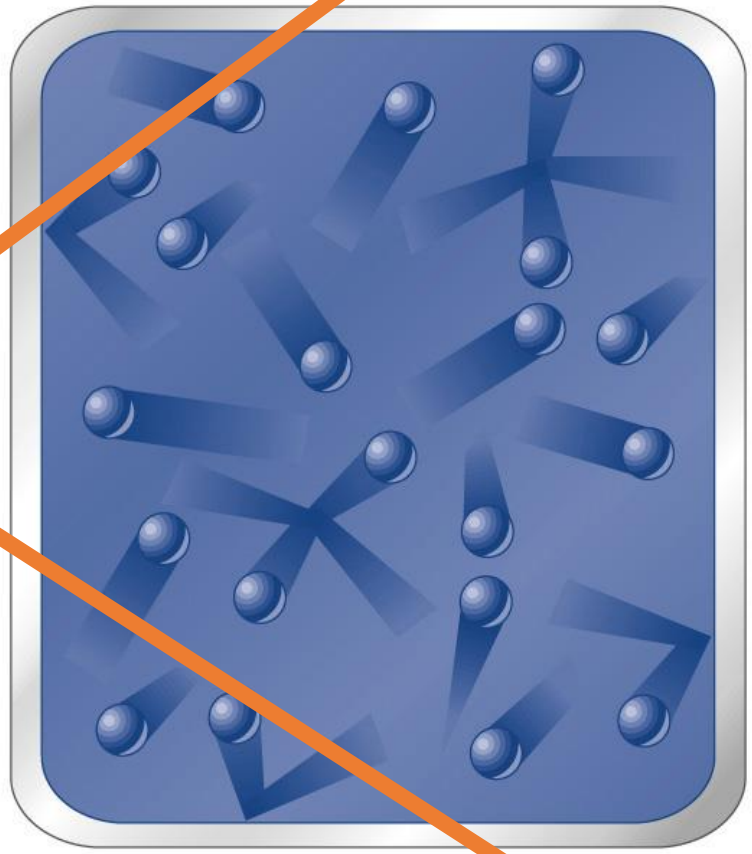
Kinetic Molecular Theory

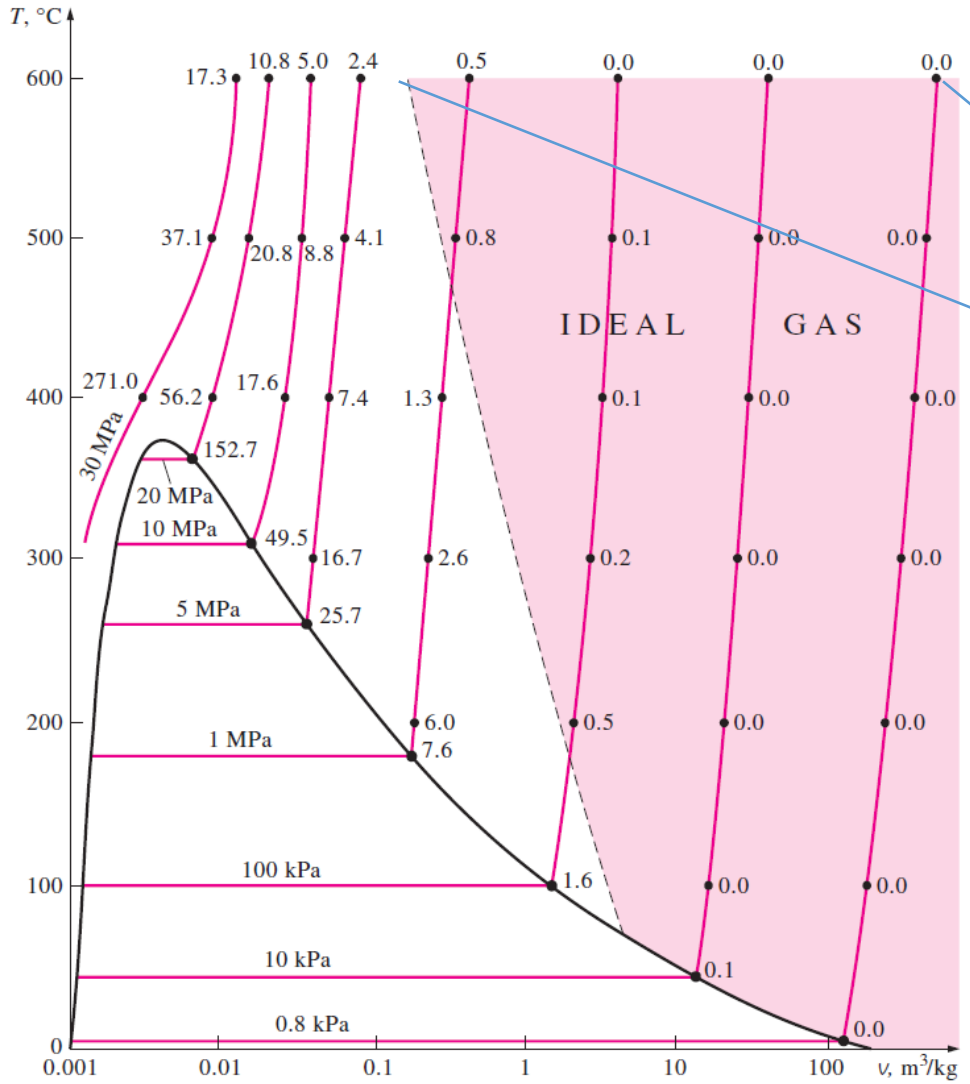
- Particles are point masses in constant, random, straight line motion.
- Particles are separated by great distances.
- Collisions are rapid and elastic.
- No force between particles.
- Total energy remains constant.



Cuando un vapor sobrecalentado se aproxima a gas ideal?

En general a bajas presiones y altas temperaturas!

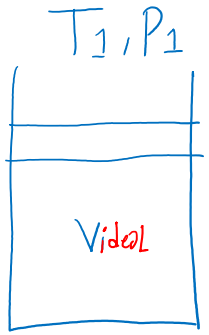
Is Water Vapor an Ideal Gas?



Percentage of error ($[|v_{table} - v_{ideal}|/v_{table}]$ 100) involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with less than 1 percent error

K = °C + 273

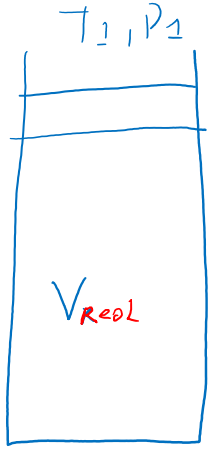
Y.A. Çengel, and M.A. Boles, Thermodynamics, An Engineering Approach, 8th ed. New York, USA: McGraw-Hill Education, 2015.



$PV_i = nRT$ (1)

$V_i = \frac{nRT}{P}$

$Z = \frac{V_R}{V_i}$



$PV_R = Z\,nRT$ (2)

$V_R = \frac{Z\,nRT}{P}$ / para que $V_R > V_i$ $Z > 1$ → dominan las F. repulsivas a T_1, P_1 para ese gas

Análogamente a otro T_i, P_i pueden dominar las F. atractivas y $Z < 1 \Rightarrow V_R < V_i$

Análogamente si $V_R < V_i \Rightarrow Z < 1$ dominan las Fuerzas atractivas

Under what conditions am I closest to ideality??

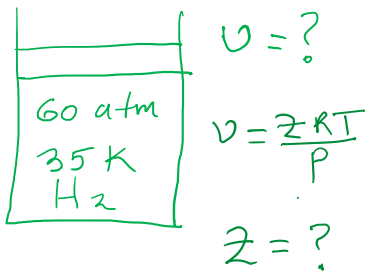
$PV = ZnRT$

$\bar{V} = \frac{V}{n}$

$P\bar{V} = ZRT$

$PV = ZnRT$

$Z = \frac{PV}{RT}$



$V = ?$

$V = \frac{ZRT}{P}$

$Z = ?$

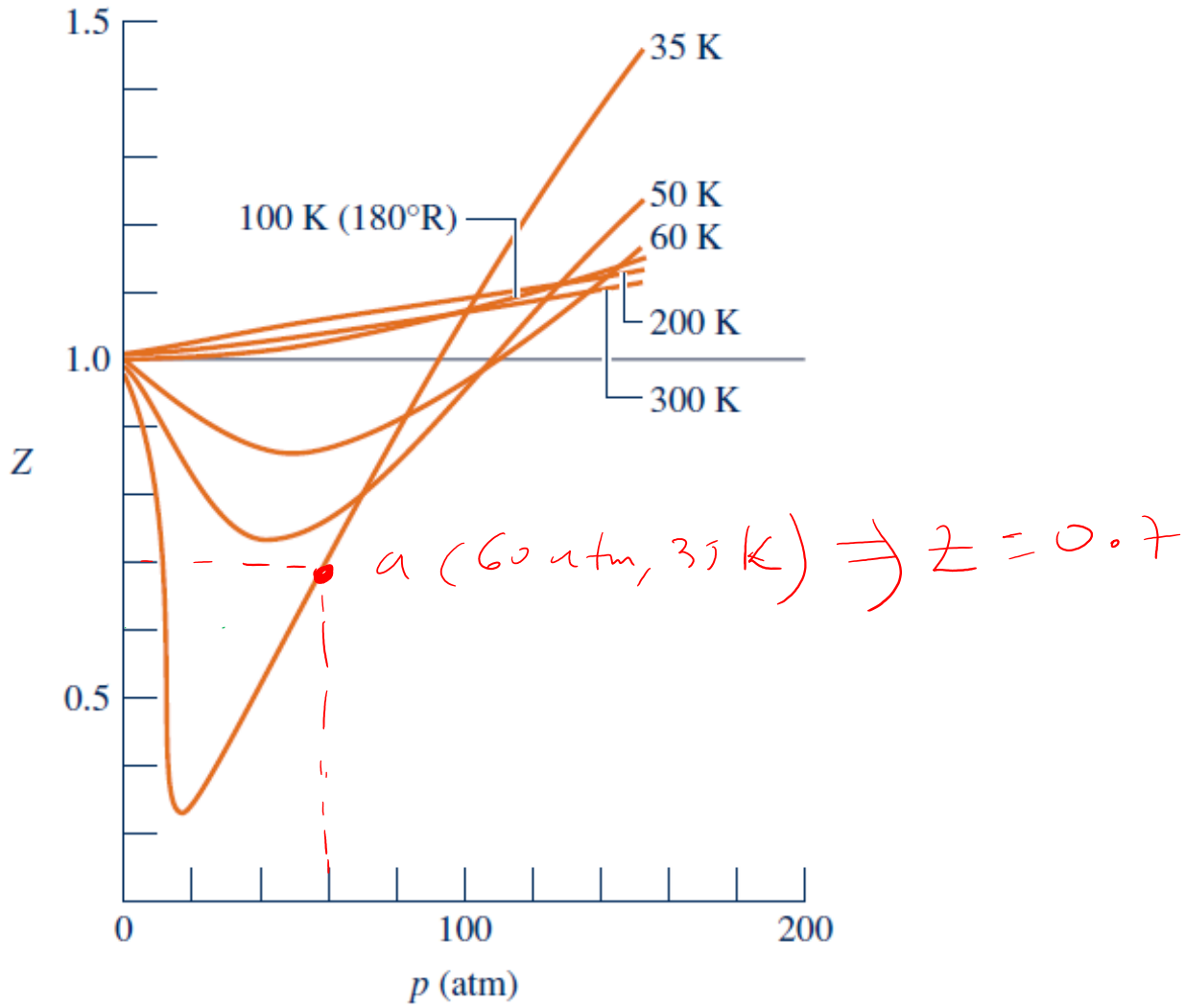


Fig. 3.11 Variation of the compressibility factor of *hydrogen* with pressure at constant temperature.

Critical properties_Can you see something curious ?

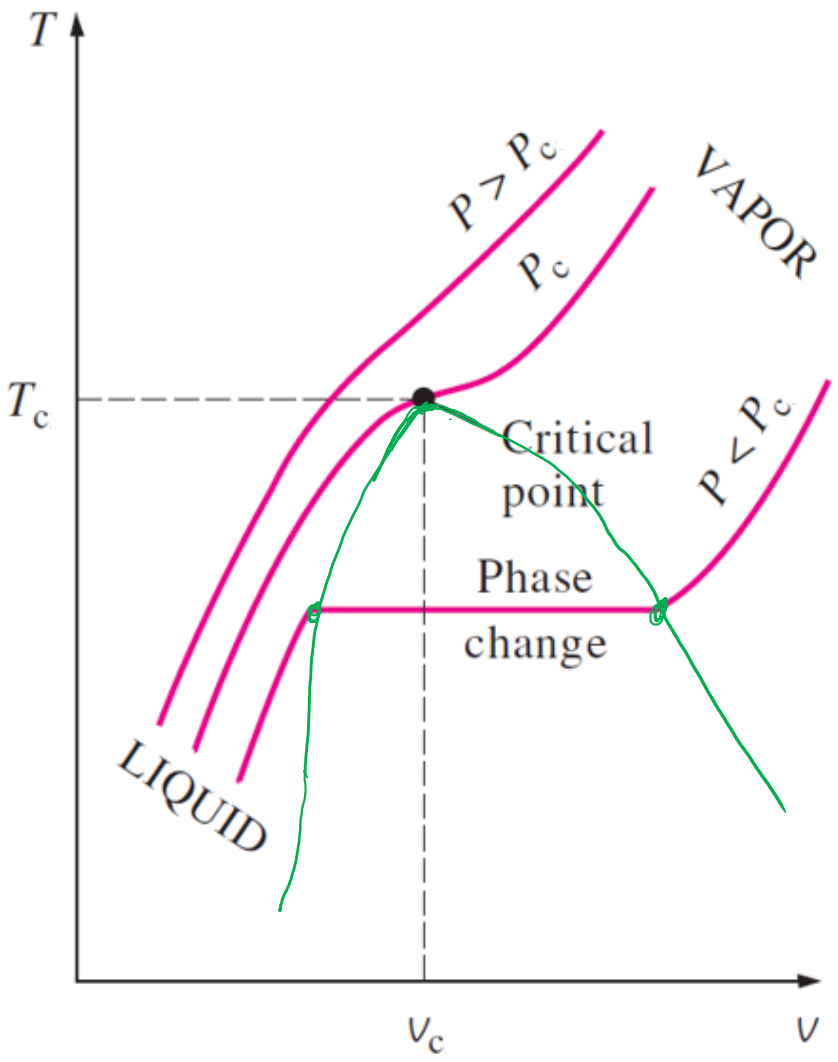


TABLE A-1

Atomic or Molecular Weights and Critical Properties of Selected Elements and Compounds

Substance	Chemical Formula	M (kg/kmol)	T_c (K)	p_c (bar)	$Z_c = \frac{p_c v_c}{R T_c}$
Acetylene	C_2H_2	26.04	309	62.8	0.274
Air (equivalent)	—	28.97	133	37.7	0.284
Ammonia	NH_3	17.03	406	112.8	0.242
Argon	Ar	39.94	151	48.6	0.290
Benzene	C_6H_6	78.11	563	49.3	0.274
Butane	C_4H_{10}	58.12	425	38.0	0.274
Carbon	C	12.01	—	—	—
Carbon dioxide	CO_2	44.01	304	73.9	0.276
Carbon monoxide	CO	28.01	133	35.0	0.294
Copper	Cu	63.54	—	—	—
Ethane	C_2H_6	30.07	305	48.8	0.285
Ethanol	C_2H_5OH	46.07	516	63.8	0.249
Ethylene	C_2H_4	28.05	283	51.2	0.270
Helium	He	4.003	5.2	2.3	0.300
Hydrogen	H_2	2.016	33.2	13.0	0.304
Methane	CH_4	16.04	191	46.4	0.290
Methanol	CH_3OH	32.04	513	79.5	0.220
Nitrogen	N_2	28.01	126	33.9	0.291
Octane	C_8H_{18}	114.22	569	24.9	0.258
Oxygen	O_2	32.00	154	50.5	0.290
Propane	C_3H_8	44.09	370	42.7	0.276
Propylene	C_3H_6	42.08	365	46.2	0.276
Refrigerant 12	CCl_2F_2	120.92	385	41.2	0.278
Refrigerant 22	$CHClF_2$	86.48	369	49.8	0.267
Refrigerant 134a	CF_3CH_2F	102.03	374	40.7	0.260
Sulfur dioxide	SO_2	64.06	431	78.7	0.268
Water	H_2O	18.02	647.3	220.9	0.233

Y.A. Çengel, and M.A. Boles, Thermodynamics, An Engineering Approach, 8th ed. New York, USA: McGraw-Hill Education, 2015.

We can extrapolate the last result as follow:

Gases behave differently at a given temperature and pressure, but they behave very much the same at temperatures and pressures normalized with respect to their critical temperatures and pressures. The normalization is done as:

$$P_R = \frac{P}{P_c} \quad \text{and} \quad T_R = \frac{T}{T_c}$$

Here P_R is called the educed pressure and T_R the reduced temperature. The Z factor for all gases is approximately the same at the same reduced pressure and temperature (This is called the principle of corresponding states) In particular when $P = P_c$ and $T = Tc$, $Z \approx 0.3$.

So We can use and universal graph for Z !!!!!!

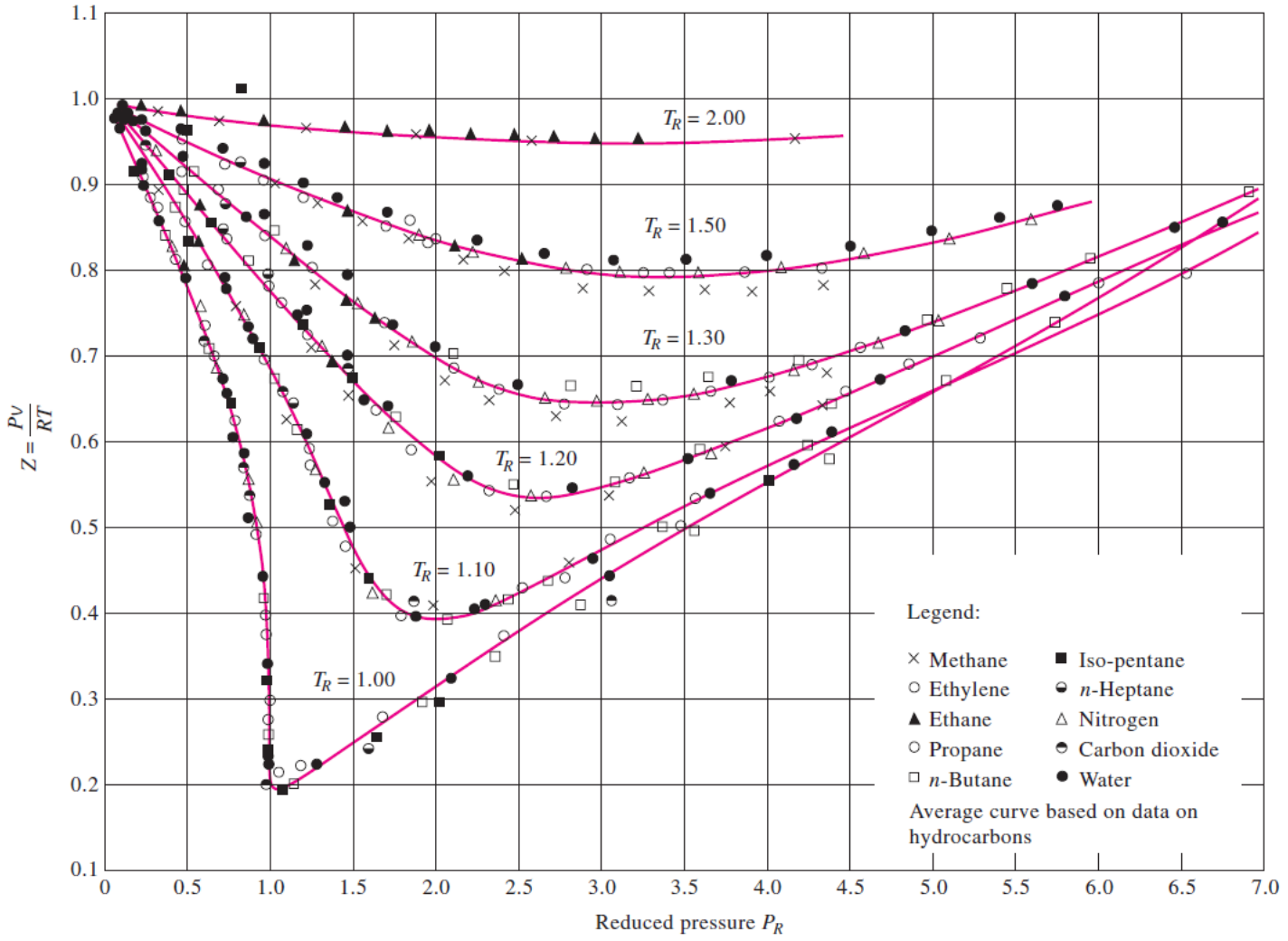


FIGURE Comparison of Z factors for various gases.

Y.A. Çengel, and M.A. Boles, Thermodynamics, An Engineering Approach, 8th ed. New York, USA: McGraw-Hill Education, 2015.

Pseudo-reduced volume

$$v'_R = \frac{\bar{v}}{\bar{R}\,T_c/p_c} = \frac{v}{R\,T_c/p_c}$$

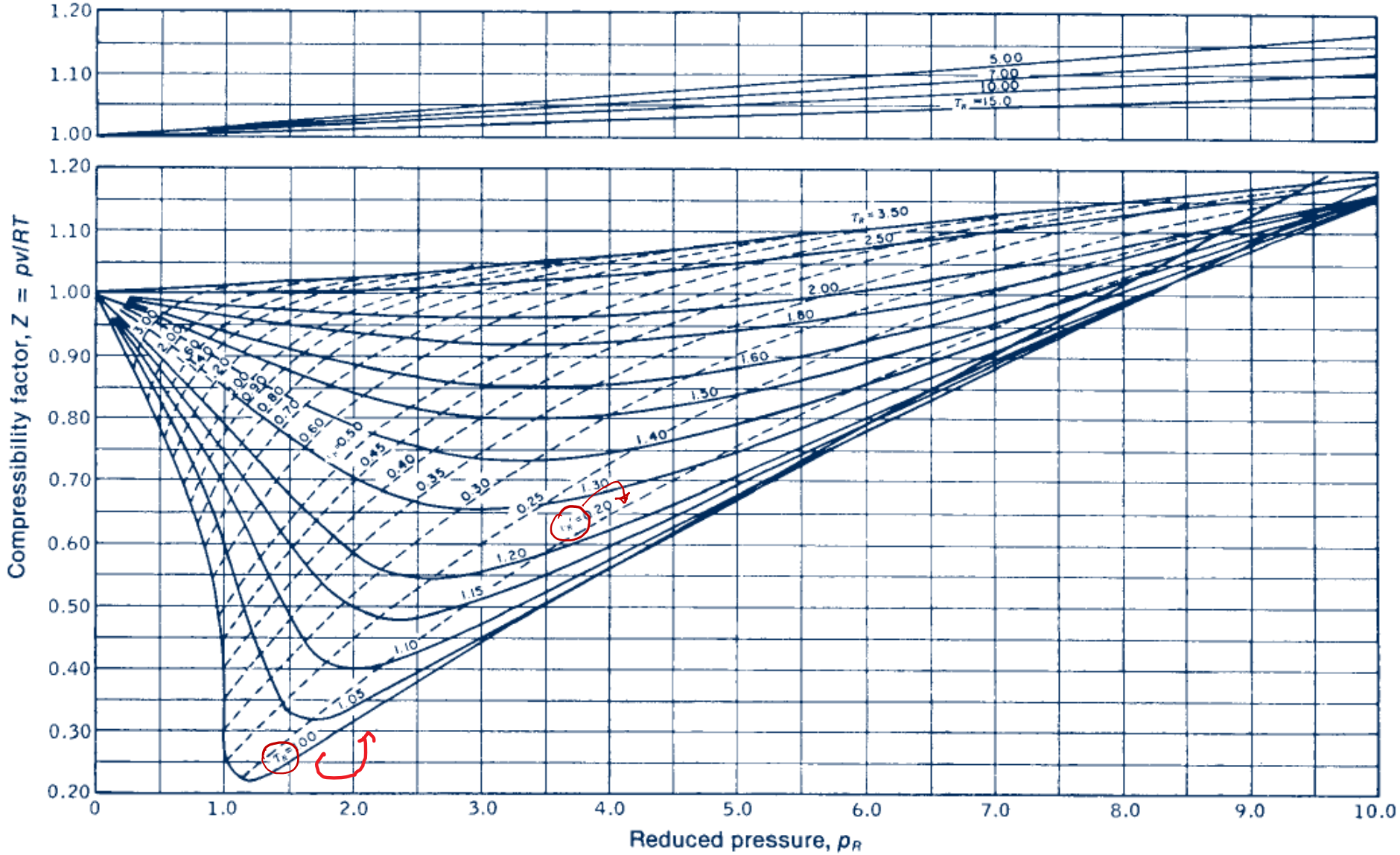


Figure A-2 Generalized compressibility chart, $p_R \leq 10.0$. *Source:* E. F. Obert, *Concepts of Thermodynamics*, McGraw-Hill, New York, 1960.

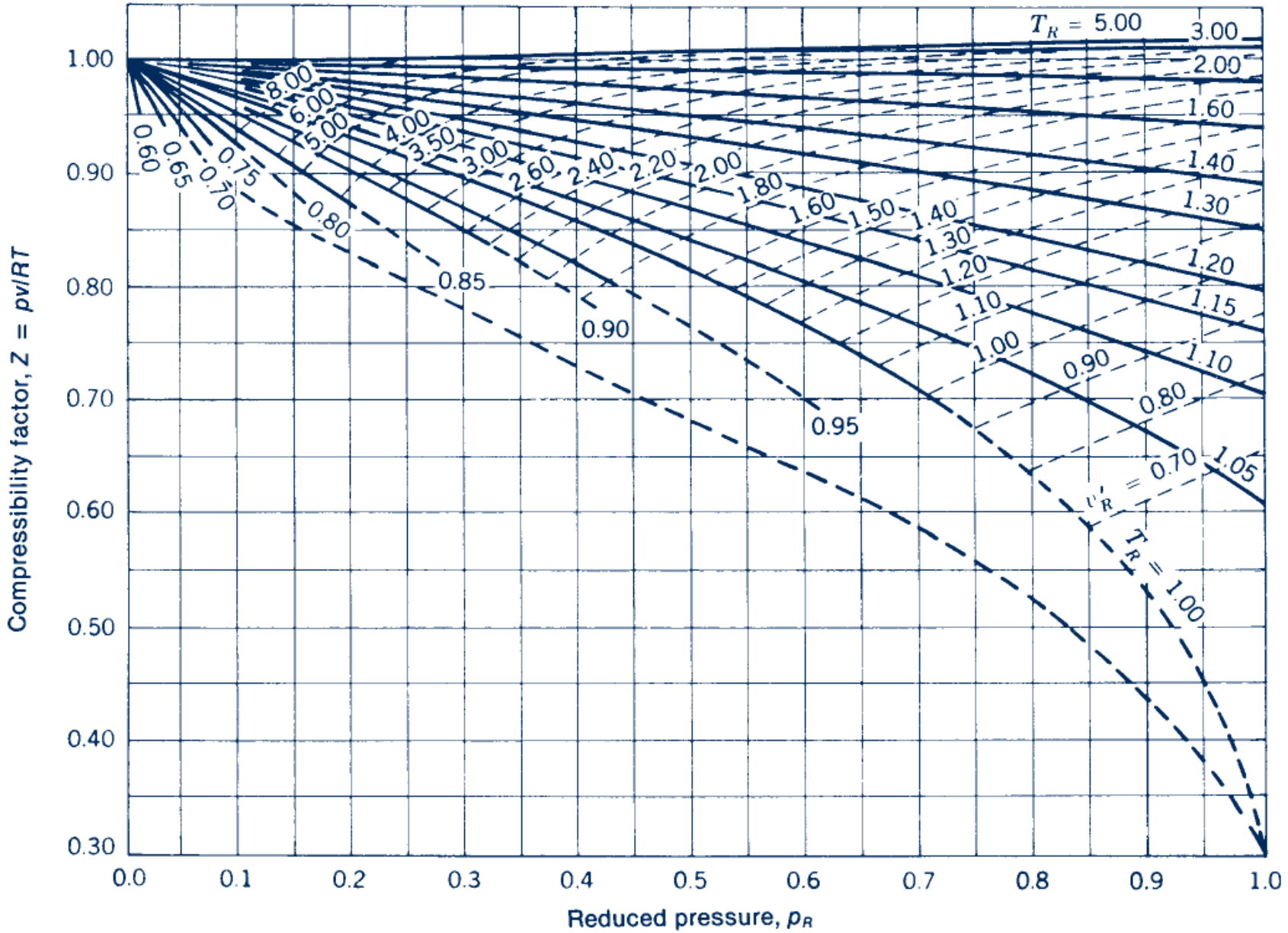
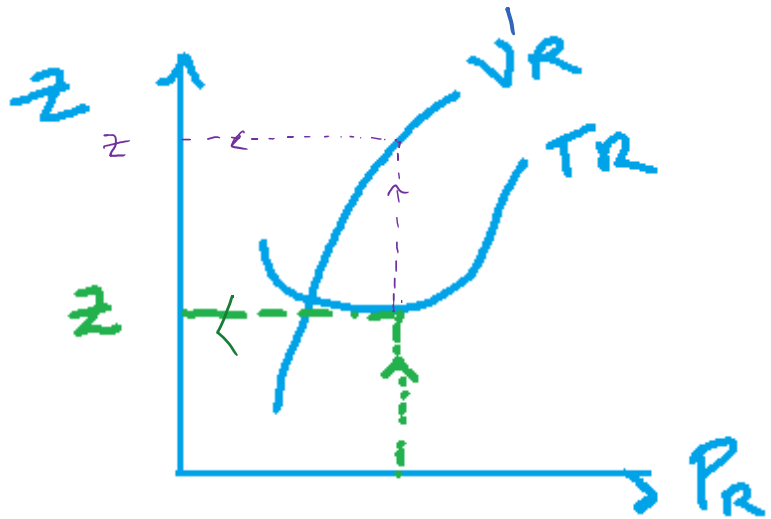


Figure A-1 Generalized compressibility chart, $p_R \leq 1.0$. *Source:* E. F. Obert, *Concepts of Thermodynamics*, McGraw-Hill, New York, 1960.

$$PV = zmR_{\text{spec}}T$$

$$PV = zRT$$

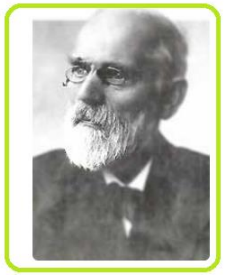
$$R_{\text{spec}} = \frac{\bar{R}}{M}$$



van der Waals equation

$$p = \frac{\overline{R}T}{\overline{v} - b} - \frac{a}{\overline{v}^2}$$

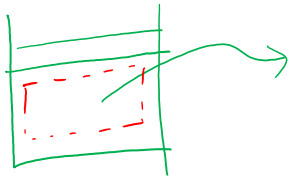
(11.2)



Johannes Van der Waals
(1837/11/23 - 1923/03/08)
Johannes Diderik Van der Waals

Físico holandés, premiado con el Nobel

10.1. Argon (Ar) is at a pressure of 97.2 bar at a temperature of 196.3 K. What is the number of moles in a 100-liter container? Compare the result using **a)** the equation of ideal gas a and **b)** the equation of ideal gas with correction of the compressibility factor.



- $PV = n\bar{R}T$
- $PV = ZnRT$

b) Using the equation of ideal gas

$$n = \frac{PV}{\bar{R}T} = \frac{97.2 \times 10^2[Kpa] \times 0.1[m^3]}{8.314 \times 196.3[K]}$$

$$\boldsymbol{n = 0.5956\ \text{kmol} = 595.6\ \text{moles}}$$

$R =$
- 0.0831447 bar · m^3/kmol · K
- 8.31447 kPa · m^3/kmol · K
- 8.31447 kJ/kmol · K
- 0.082057 L·atm·K^{-1}·mol^{-1}
- 8.205745×10^{-5} m^3·atm·K^{-1}·mol^{-1}
- 8.314472 L·kPa·K^{-1}·mol^{-1}
- 8.314472 m^3·Pa·K^{-1}·mol^{-1}
- 82.05745 cm^3·atm·K^{-1}·mol^{-1}
- 8.314472 J·K^{-1}·mol^{-1}

10.1. Argon is at a pressure of 97.2 bar at a temperature of 196.3 K. What is the number of moles in a 100-liter container? Compare the result using the general equation of ideal gas a) with and b) without correction of the compressibility factor.

a) with correction of the compressibility factor

TABLE A-1

Atomic or Molecular Weights and Critical Properties of Selected Elements and Compounds

Substance	Chemical Formula	M (kg/kmol)	T_c (K)	p_c (bar)	$Z_c = \frac{p_c v_c}{R T_c}$
Acetylene	C_2H_2	26.04	309	62.8	0.274
Air (equivalent)	—	28.97	133	37.7	0.284
Ammonia	NH_3	17.03	406	112.8	0.242
Argon	Ar	39.94	151	48.6	0.290
Benzene	C_6H_6	78.11	563	49.3	0.274
Butane	C_4H_{10}	58.12	425	38.0	0.274

$$p_R = \frac{p}{p_c} = \frac{97.2}{48.6} = 2$$

$$T_R = \frac{T}{T_c} = \frac{196.3}{151} = 1.3$$

M.J. Moran, H.N. Shapiro, D.D. Boettner, M.B. Bailey, Fundamentals of Engineering Thermodynamics, 10th ed. New Jersey, USA: John Wiley & Sons, 2014.

$$p_R = \frac{p}{p_c} = \frac{97.2}{48.6} = 2 \qquad T_R = \frac{T}{T_c} = \frac{196.3}{151} = 1.3$$

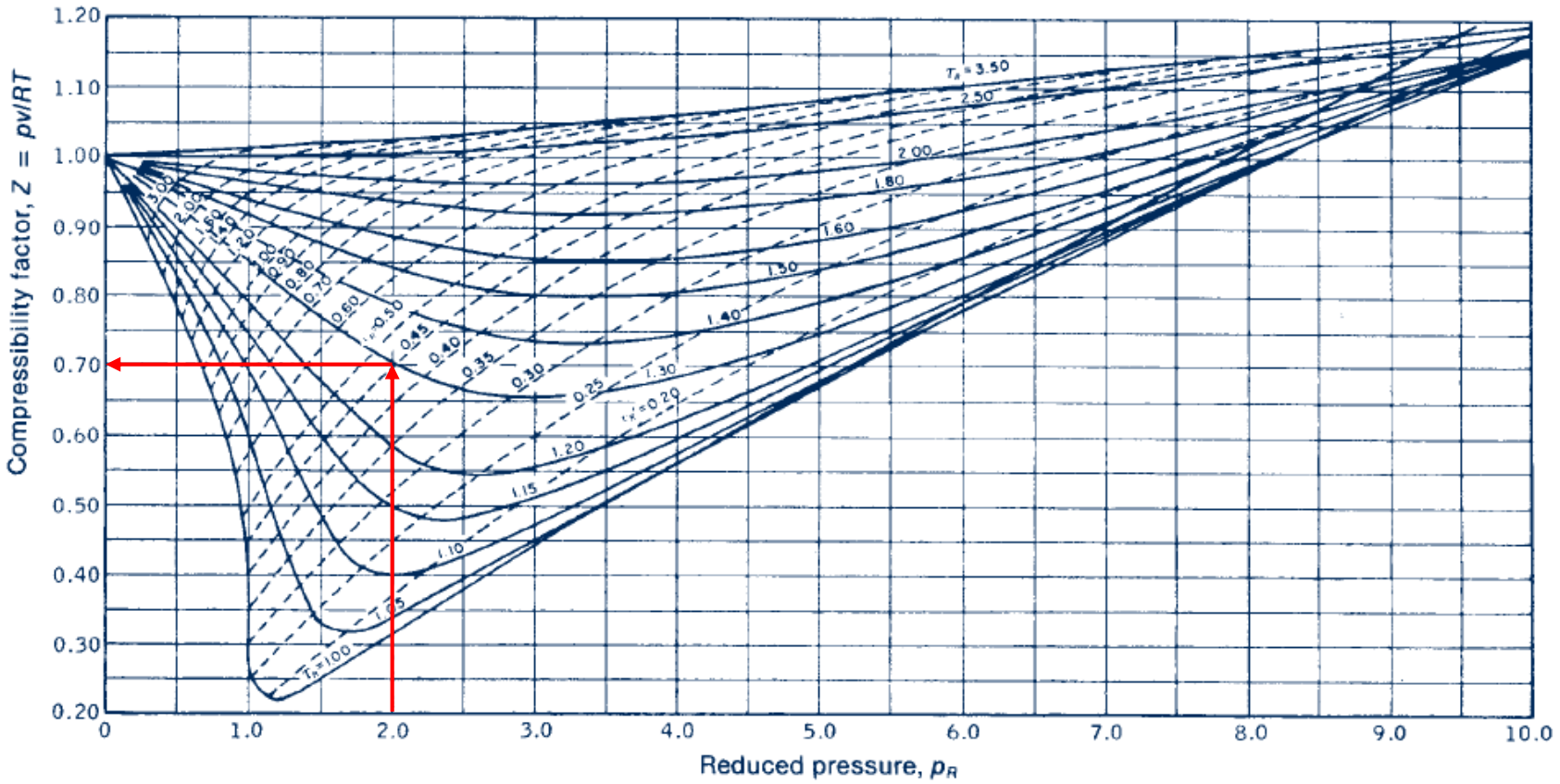


Figure A-2 Generalized compressibility chart, $p_R \leq 10.0$. *Source*: E. F. Obert, *Concepts of Thermodynamics*, McGraw-Hill, New York, 1960.

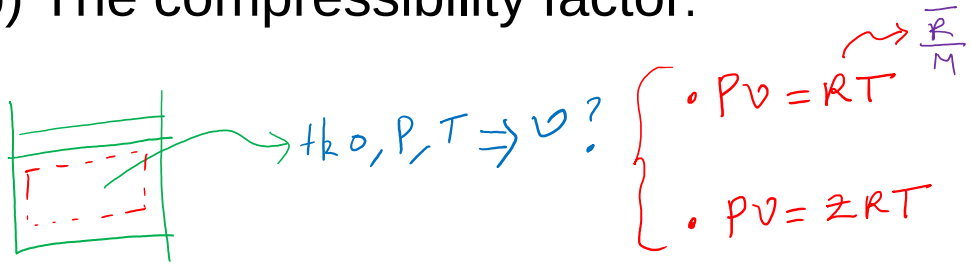
Compressibility Factor Correction:

$$n = \frac{PV}{Z\bar{R}T} = \frac{97.2 \times 10^2 \times 0.1}{0.7 \times 8.314 \times 196.3}$$

$$\boldsymbol{n = 0.8508 \text{ kmol} = 850.8 \text{ moles}}$$

M.J. Moran, H.N. Shapiro, D.D. Boettner, M.B. Bailey, Fundamentals of Engineering Thermodynamics, 10th ed. New Jersey, USA: John Wiley & Sons, 2014.

10.2´. Determine the specific volume of the superheated water vapor in m^3/ kg, at 200 bar and 1346 ºC, a) Using the ideal gas state equation. b) The compressibility factor.



a) Ideal Gas Equation:

$$v = \frac{\bar{R}T}{PM} = \frac{8.314 \times (1346 + 273.15)[K]}{200 \times 100[kPa] \times 18.02[kg/kmol]} = 0.03735 \frac{\mathrm{m}^3}{\mathrm{kg}}$$

b) The compressibility factor:

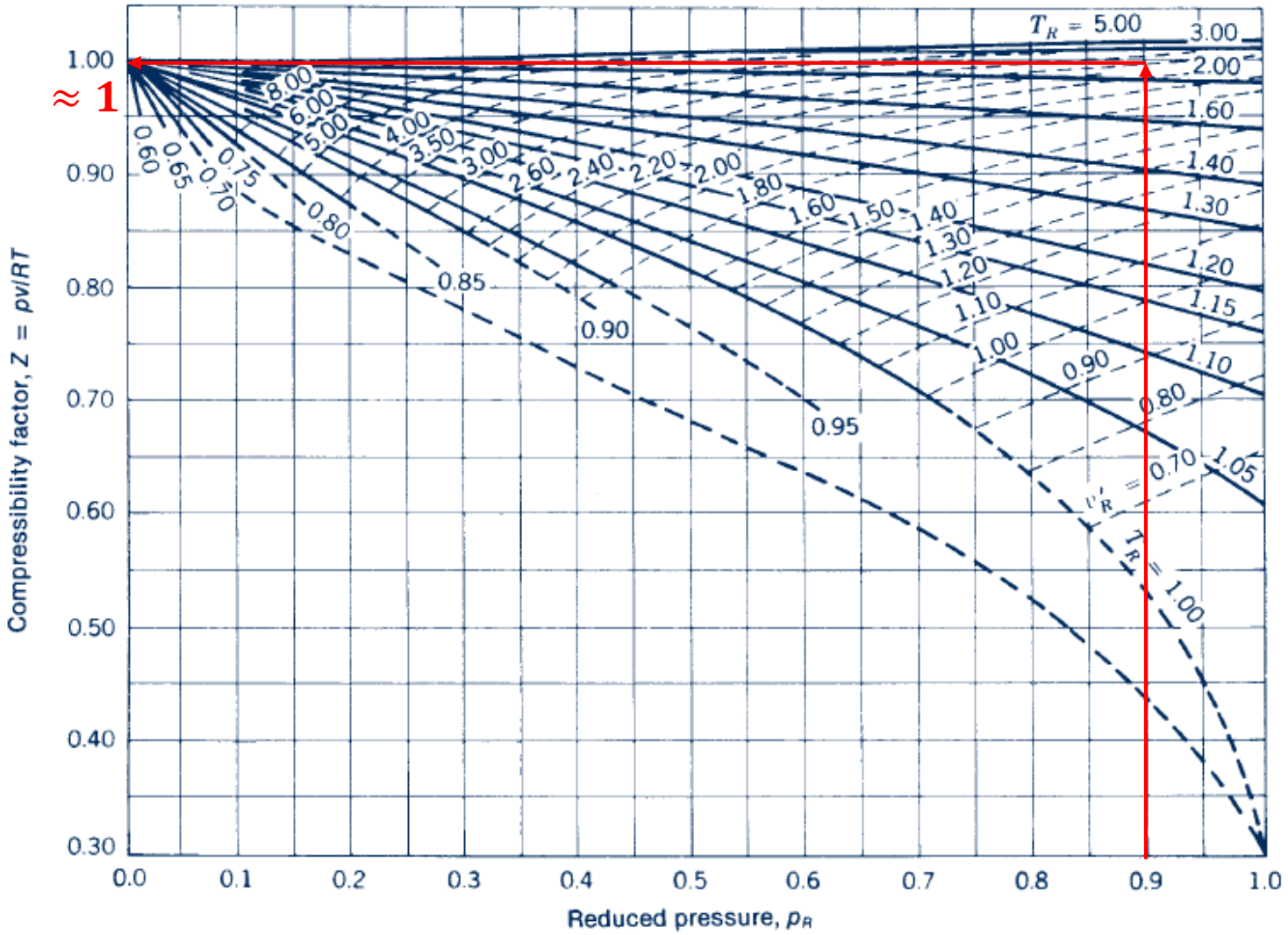
TABLE A-1

Atomic or Molecular Weights and Critical Properties of Selected Elements and Compounds

Substance	Chemical Formula	M (kg/kmol)	T_c (K)	p_c (bar)	$Z_c = \frac{p_c v_c}{RT_c}$
Water	H_2O	18.02	647.3	220.9	0.233

$$T_R = \frac{T}{T_c} = \frac{1346 + 273.15}{647.3} = 2.50$$

$$p_R = \frac{p}{p_c} = \frac{200}{220.9} = 0.90$$



b) Specific volume with Compressibility Factor Correction:

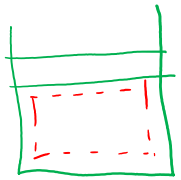
$$\boldsymbol{v} = \frac{Z\bar{R}T}{PM} = \frac{1 \times 8.314 \times (1346 + 273.15)}{200 \times 100 \times 18.02}$$

$$= 0.037\mathbf{35}\,\frac{\boldsymbol{m^3}}{\boldsymbol{kg}}$$

Pero si es vapor sobrecalentado porque usar los dos métodos anteriores?

M.J. Moran, H.N. Shapiro, D.D. Boettner, M.B. Bailey, Fundamentals of Engineering Thermodynamics, 10th ed. New Jersey, USA: John Wiley & Sons, 2014.

12.2. A 0.01677-m^3 tank contains 1 kg of refrigerant-134a at 110°C. Determine the pressure of the refrigerant [kPa], using **(*a*)** the ideal-gas equation, **(*b*)** the generalized compressibility chart, and **(*c*)** the refrigerant tables.



R134a, V, m, T → P ?

- $PV = mRT$ → $R = \frac{\bar{R}}{m}$
- $PV = ZmRT$
- TABLES
  ↳ semana 2

TABLE A-1

Atomic or Molecular Weights and Critical Properties of Selected Elements and Compounds

Substance	Chemical Formula	M (kg/kmol)	T_c (K)	p_c (bar)	$Z_c = \frac{p_c v_c}{RT_c}$
Propylene	C_3H_6	42.08	365	46.2	0.276
Refrigerant 12	CCl_2F_2	120.92	385	41.2	0.278
Refrigerant 22	$CHClF_2$	86.48	369	49.8	0.267
Refrigerant 134a	CF_3CH_2F	102.03	374	40.7	0.260

a) Ideal gas equation

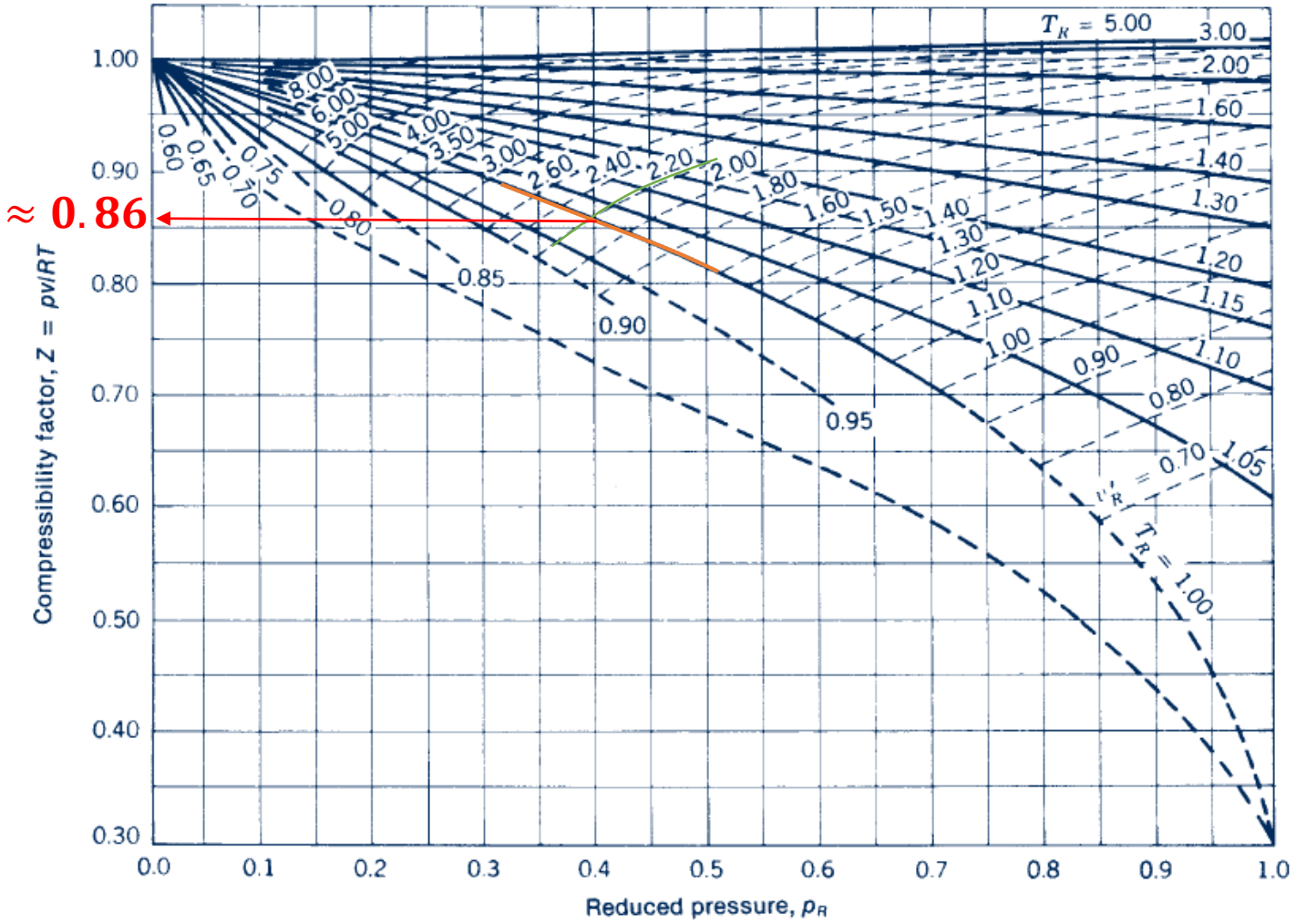
$$PV = m\frac{\bar{R}}{M}T$$

$$P \times 0.01677 = 1 \times \frac{8.314}{102.03} \times (110 + 273.15)$$

$$\boxed{P = 1861.7352\ kPa}$$

b) Compressibility chart

$$v'_R = \frac{\bar{v}}{\bar{R}\,T_c/p_c} = \frac{v}{R_g\,T_c/p_c} = \frac{0.01677/1}{(8.314/102.03)\times 374/4070} = 2.24 \qquad T_R = \frac{T}{T_c} = \frac{110+273}{374} = 1.024$$



$$PV = ZmRT$$

$$P = \frac{ZmRT}{V}$$

$$P = \frac{0.86 \times 1 \times \frac{8.314}{102.03} \times 383.15}{0.01677}$$

$$\boxed{P = 1601.0922\ kPa}$$

c) Table A-12

A 0.01677-m3 tank contains 1 kg of refrigerant-134a at 110°C

$\frac{V}{m} = 0.01677 \frac{m^3}{kg}$

↳ v, T

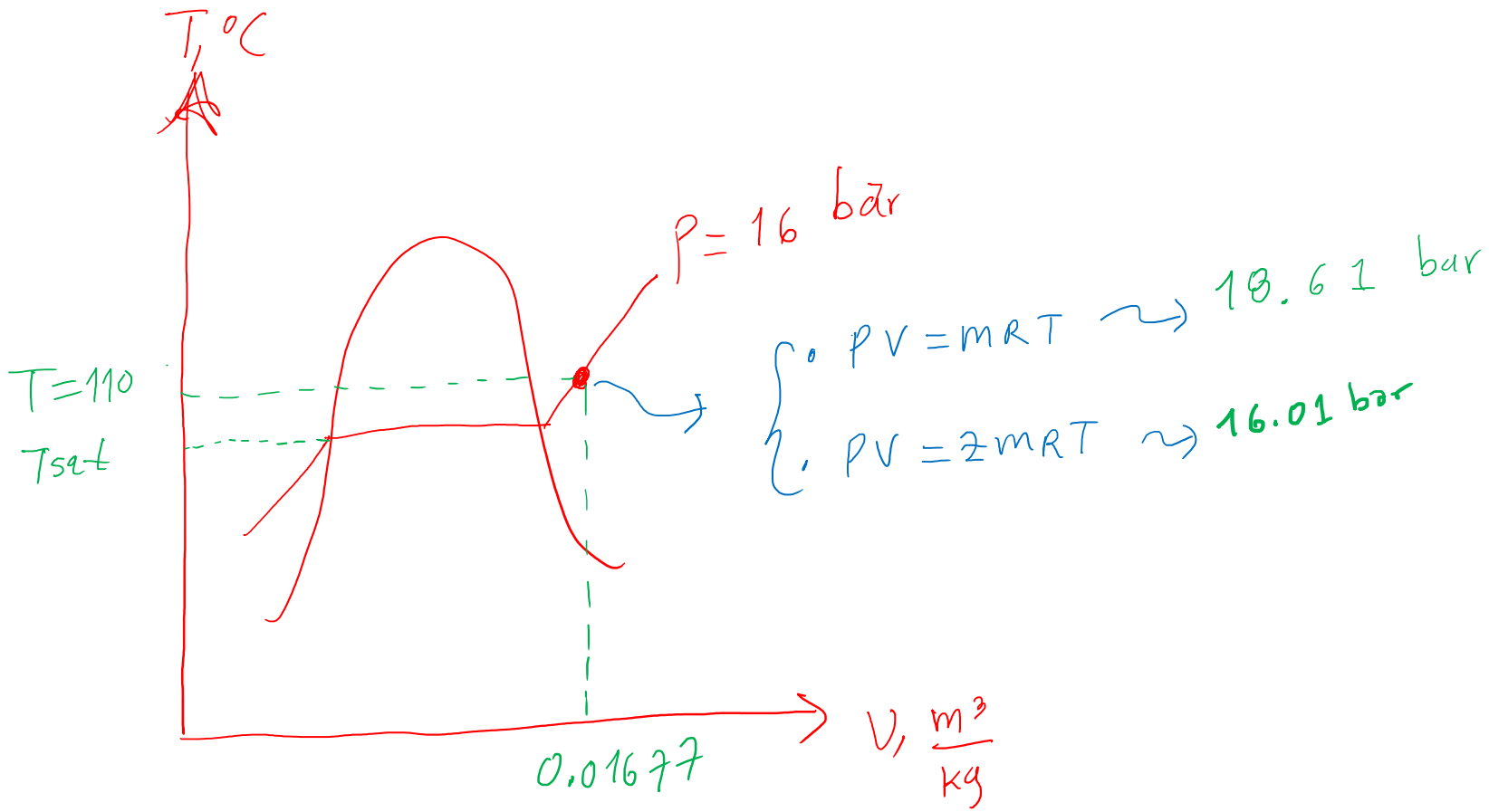
↳ 110 °C

TABLE A-12

(Continued)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 14.0 bar = 1.40 MPa (T_{sat} = 52.43°C)				p = 16.0 bar = 1.60 MPa (T_{sat} = 57.92°C)			
Sat.	0.01405	253.74	273.40	0.9003	0.01208	256.00	275.33	0.8982
60	0.01495	262.17	283.10	0.9297	0.01233	258.48	278.20	0.9069
70	0.01603	272.87	295.31	0.9658	0.01340	269.89	291.33	0.9457
80	0.01701	283.29	307.10	0.9997	0.01435	280.78	303.74	0.9813
90	0.01792	293.55	318.63	1.0319	0.01521	291.39	315.72	1.0148
100	0.01878	303.73	330.02	1.0628	0.01601	301.84	327.46	1.0467
110	0.01960	313.88	341.32	1.0927	0.01677	312.20	339.04	1.0773
120	0.02039	324.05	352.59	1.1218	0.01750	322.53	350.53	1.1069
130	0.02115	334.25	363.86	1.1501	0.01820	332.87	361.99	1.1357
140	0.02189	344.50	375.15	1.1777	0.01887	343.24	373.44	1.1638
150	0.02262	354.82	386.49	1.2048	0.01953	353.66	384.91	1.1912
160	0.02333	365.22	397.89	1.2315	0.02017	364.15	396.43	1.2181
170	0.02403	375.71	409.36	1.2576	0.02080	374.71	407.99	1.2445
180	0.02472	386.29	420.90	1.2834	0.02142	385.35	419.62	1.2704
190	0.02541	396.96	432.53	1.3088	0.02203	396.08	431.33	1.2960
200	0.02608	407.73	444.24	1.3338	0.02263	406.90	443.11	1.3212

Following the tables, the real pressure must be 16bar or 1600kPa



- $PV = mRT \rightsquigarrow 18.61$ bar
- $PV = ZmRT \rightsquigarrow$ **16.01 bar**

13.2 Determine the percent error in the specific volume of superheated ammonia at 20°C and 800 kPa when modeled as an ideal gas. How does this error compare if the generalized compressibility chart is used instead?

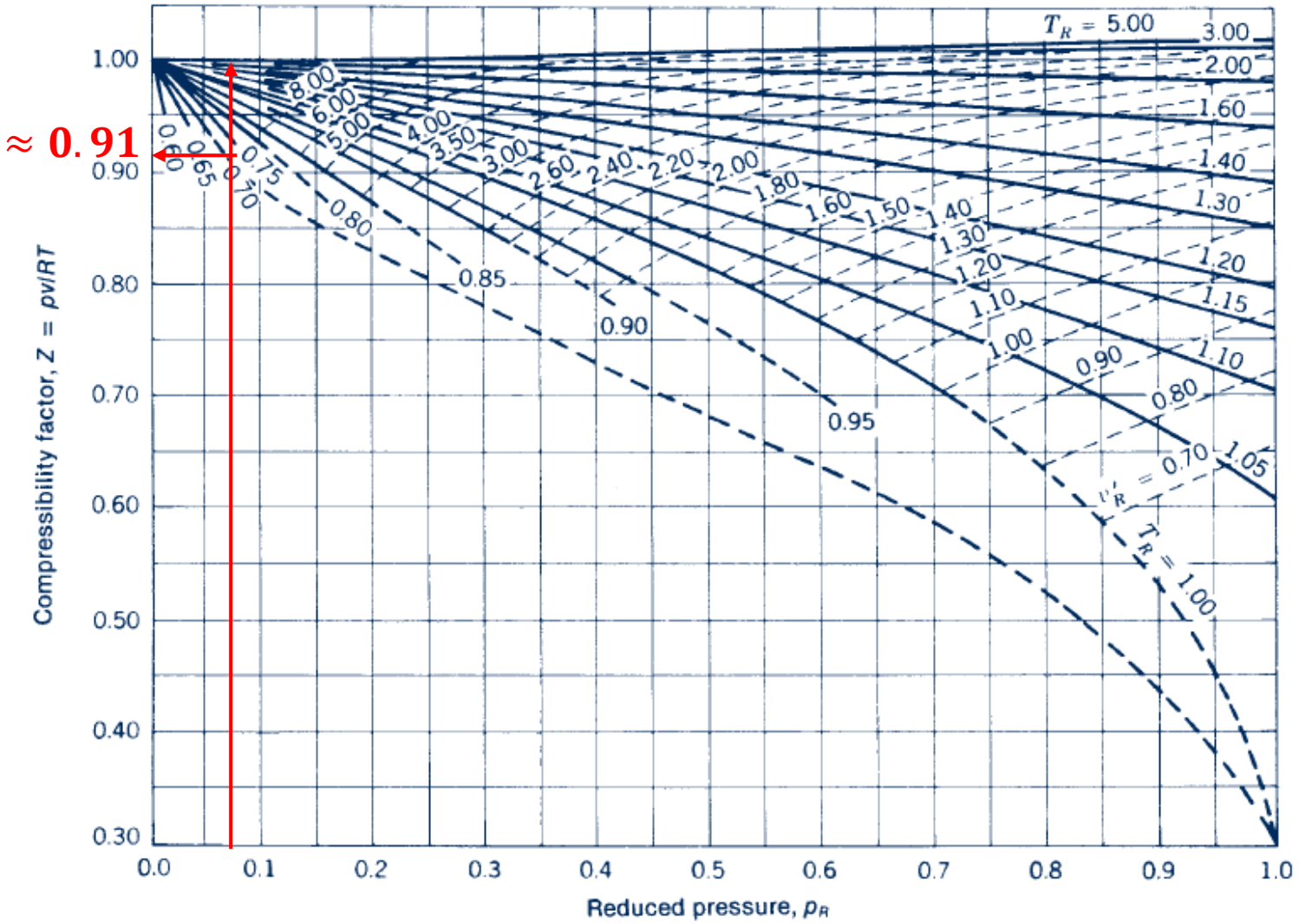
TABLE A-1

Atomic or Molecular Weights and Critical Properties of Selected Elements and Compounds

Substance	Chemical Formula	M (kg/kmol)	T_c (K)	p_c (bar)	$Z_c = \frac{p_c v_c}{RT_c}$
Acetylene	C_2H_2	26.04	309	62.8	0.274
Air (equivalent)	—	28.97	133	37.7	0.284
Ammonia	NH_3	17.03	406	112.8	0.242

Ideal Gas Equation:

$$\frac{V}{m} = \boldsymbol{v} = \frac{RT}{PM} = \frac{8.314 \times (20 + 273.15)[K]}{800[kPa] \times 17.03[kg/kmol]} = 0.1789 \frac{\mathrm{m}^3}{\mathrm{kg}}$$



Specific volume with Compressibility Factor Correction:

$$T_R = \frac{T}{T_c} = \frac{20+273}{406} = 0.722$$

$$p_R = \frac{p}{p_c} = \frac{800}{112.8 \times 100} = 0.0709$$

$$\boldsymbol{v} = \frac{ZRT}{PM} = \frac{0.91 \times 8.314 \times (20+273)}{800 \times 17.03}$$

$$= 0.\mathbf{1628}\,\frac{\boldsymbol{m^3}}{\boldsymbol{kg}}$$

Specific volume from Table A-15:

TABLE A-15

Properties of Superheated Ammonia Vapor

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	$p = 8.0$ bar $= 0.80$ MPa ($T_{sat} = 17.84$°C)			
Sat.	0.15958	1330.64	1458.30	5.1099
20	0.16138	1335.59	1464.70	5.1318
30	0.16948	1357.71	1493.29	5.2277
40	0.17720	1378.77	1520.53	5.3161
50	0.18465	1399.05	1546.77	5.3986
60	0.19189	1418.77	1572.28	5.4763
80	0.20590	1457.14	1621.86	5.6209
100	0.21949	1494.77	1670.37	5.7545
120	0.23280	1532.24	1718.48	5.8801
140	0.24590	1569.89	1766.61	5.9995
160	0.25886	1607.96	1815.04	6.1140
180	0.27170	1646.57	1863.94	6.2243
200	0.28445	1685.83	1913.39	6.3311

$$v_{actual} = 0.16138 \frac{\text{m}^3}{\text{kg}}$$

$$v_{ideal} = 0.1789 \frac{\text{m}^3}{\text{kg}} \rightarrow \% \rightarrow \frac{0.1789 - 0.16138}{0.16138} = +10.8564\%$$

$$v_{Z\ factor} = 0.1628 \frac{\text{m}^3}{\text{kg}} \rightarrow \% \rightarrow \frac{0.1628 - 0.16138}{0.16138} = +0.8799\%$$

The actual specific volume is 0.16138 m3/kg. The compressibility chart method gave a better approximation than ideal gas equation of state, however, it is recommended to use property tables whenever they are available.

Compression Factor (Z)

- Variation of Z with P of a certain gas at varying T

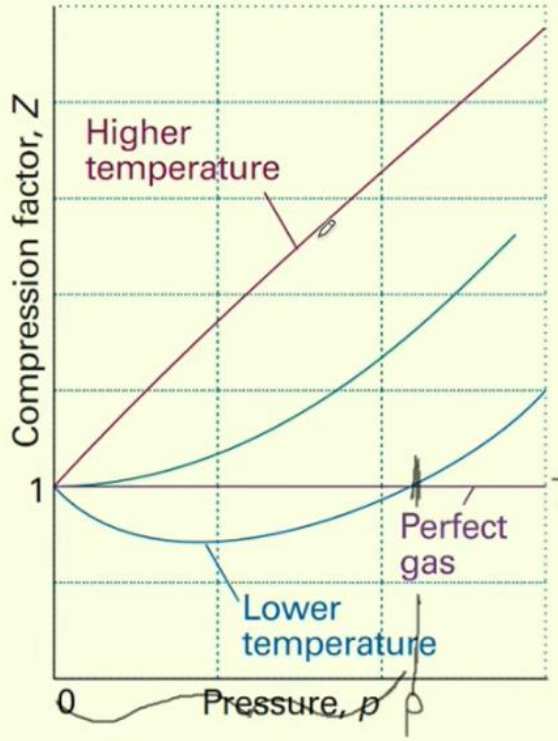


Figure from Atkins, Physical Chemistry, 8th ed.

$Z > 1$: Repulsive forces dominate → dominan fuerzas de repulsión

$Z < 1$: attractive forces dominate → dominan fuerzas de atracción

Thermodynamics _ Evaluation

SEMANA 1	TAREA VIRTUAL	SE CALIFICA AUTOMATICO NO NECESITA PROCEDIMIENTO
SEMANA 2	TAREA VIRTUAL	
SEMANA 3	TAREA VIRTUAL	.
SEMANA 4	**TAREA INDIVIDUAL 1** + EVALUACION_ AULA1	TAREA INDIVIDUAL: Esta parte incluye subir un archivo con la solución EVALUACION_ AULA: SEMANAS 1-2
SEMANA 5	TAREA VIRTUAL+ EVALUACION_ AULA2	EVALUACION_ AULA: SEMANAS 1-3

EJERCICIO DESAFÍO SEMANA 3

OBJETIVO: REPASAR TEMAS BÁSICOS DE SEMANAS 1-2-3

Será resuelto en la asesoría de Rosario, Pueden ver las grabaciones y/o el pdf de la solución en el grupo de WhatsApp.

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PART 1

A rotating system supports a cylinder with a 20 cm² cross-sectional area and 1.2-m length. The cylinder is equipped with a frictionless piston of unknown mass and has stops located at 30 cm from the base. Initially, the cylinder is in horizontal position ($\theta = 0°$), the piston is placed at 15 cm from the base and is full of 2.5 g Nitrogen N_2 **(ideal gas - state 1)**. The system rotates certain angle ($\theta = ?$) until the pressure reaches 1.3bar and the piston is 13 cm from the bottom of the cylinder **(state 2)**. The system continues rotating until it is in vertical position ($\theta = 90°$), the piston is 11 cm from the base and the pressure is 1.4 bar **(state 3)**.

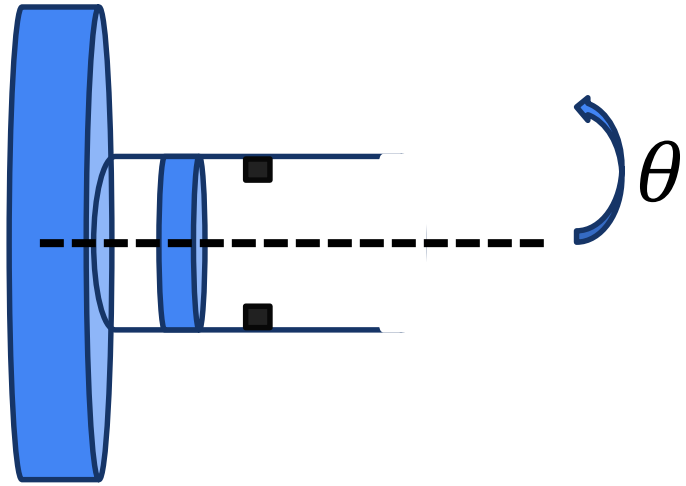


FIGURE 1 - PART 1

Find:

a) Temperature, specific volume and the volume of N_2 in state 1.
b) Temperature, specific volume, volume and the piston mass in state 3.
c) Temperature, specific volume, volume and the angle in state 2 .

PART 2

The cylinder is slowly heated, and the piston starts rising until it gets to the stops **(state 4 – position A)**. The heating continues until the pressure is 130% its previous value **(state 5 – position A)**. An instant after that, the stops breaks because of the excessive force and the piston keeps rising following a reversible polytropic path (n = 1.34) until the piston just touches a linear spring and the pressure is 1.4bar **(state 6 – position B).** The piston goes up compressing the spring until it gets to position C, moment when the temperature is -20°C and the height is 50cm **(state 7 – position C).** Both springs constants are equal.

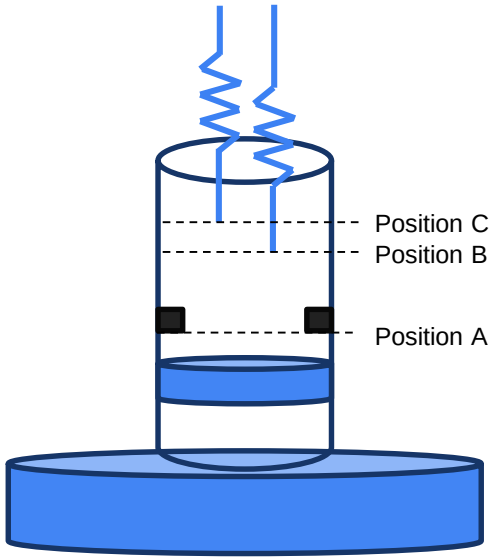


FIGURE 1 - PART 2

Find:

d) Temperature, specific volume and volume in state 4.
e) The force on the stops, the temperature, specific volume and volume in state 5.
f) The specific volume, the volume, the temperature and the height respect to cylinder base in state 6.
g) The specific volume, the volume, the pressure and the spring constant in state 7.

PART 3

The piston keeps going up compressing the second spring (which has the same constant as the first one) until the height of the piston is 80 cm from the base **(state 8)**.

Find:

h) The specific volume, the volume, pressure and temperature in state 8.

i) Plot a P (bar) – v (m3/kg) diagram showing all the states previously mentioned, and the processes from state 3 to state 8.

j) Plot a T (°C) – v (m3/kg) diagram showing all the states previously mentioned, and the processes from state 3 to state 8.

k) Find Δu and Δh for the process 3 to 8 using table A-21 and table A-23. Both results should be found in kJ/kg

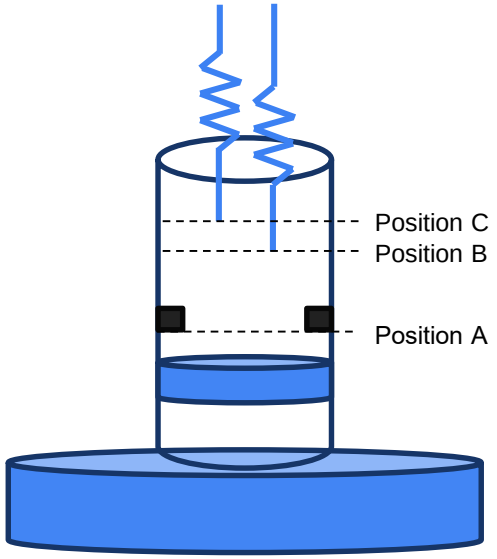
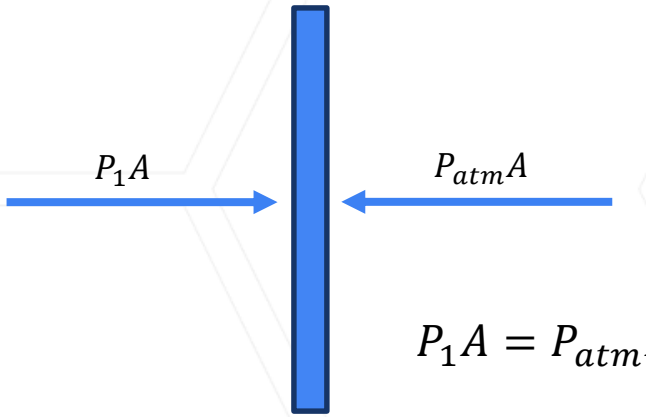


FIGURE 1 - PART 2

a) State 1: FBD for the piston



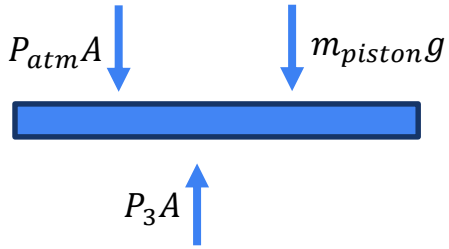
$$P_1A = P_{atm}A \rightarrow P_1 = P_{atm} = 1bar$$

$$V_1 = Ah_1 = 20 \times 10^{-4} \times 0.15 = 3 \times 10^{-4} m^3$$

$$v_1 = \frac{V_1}{m_{N2}} = \frac{3 \times 10^{-4}}{2.5 \times 10^{-3}} = 0.12\, m^3/kg$$

$$T_1 = \frac{P_1V_1}{Rm_{N2}} = \frac{100 \times 3 \times 10^{-4}}{\frac{8.314}{28} \times 2.5 \times 10^{-3}} = 40.4138\, K$$

b) State 3: FBD for the piston



$$P_3A = P_{atm}A + m_{piston}g \rightarrow 1.4 = 1 + \frac{m_{piston} \times 9.81}{(20 \times 10^{-4}) \times 10^5}$$

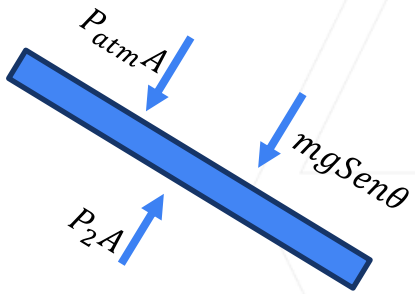
$$m_{piston} = 8.1549kg$$

$$V_3 = Ah_3 = 20 \times 10^{-4} \times 0.11 = 2.2 \times 10^{-4} m^3$$

$$v_3 = \frac{V_3}{m_{N2}} = \frac{2.2 \times 10^{-4}}{2.5 \times 10^{-3}} = 0.0880\, m^3/kg$$

$$T_3 = \frac{P_3V_3}{Rm_{N2}} = \frac{140 \times 2.2 \times 10^{-4}}{\frac{8.314}{28} \times 2.5 \times 10^{-3}} = 41.4915\, K$$

c) State 2: FBD for the piston



$$P_2A = P_{atm}A + m_{piston}gSen\theta \rightarrow 1.3 = 1 + \frac{8.1549 \times 9.81Sen\theta}{(20 \times 10^{-4}) \times 10^5}$$

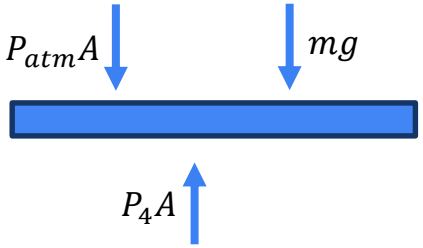
$$Sen\theta = 0.75 \rightarrow \theta = 48.59°$$

$$V_2 = Ah_2 = 20 \times 10^{-4} \times 0.13 = 2.6 \times 10^{-4} m^3$$

$$v_2 = \frac{V_2}{m_{N2}} = \frac{2.6 \times 10^{-4}}{2.5 \times 10^{-3}} = 0.1040\, m^3/kg$$

$$T_2 = \frac{P_2V_2}{Rm_{N2}} = \frac{130 \times 2.6 \times 10^{-4}}{\frac{8.314}{28} \times 2.5 \times 10^{-3}} = 45.5328K$$

d) State 4: FBD for the piston



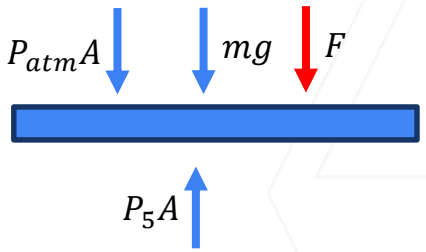
$$P_4A = P_{atm}A + m_{piston}g \rightarrow P_4 = P_3 = 1.4\ bar$$ **(isobaric)**

$$V_4 = Ah_4 = 20 \times 10^{-4} \times 0.30 = 6 \times 10^{-4} m^3$$

$$v_4 = \frac{V_4}{m_{N2}} = \frac{6 \times 10^{-4}}{2.5 \times 10^{-3}} = 0.2400\, m^3/kg$$

$$T_4 = \frac{P_4V_4}{Rm_{N2}} = \frac{140 \times 6 \times 10^{-4}}{\frac{8.314}{28} \times 2.5 \times 10^{-3}} = 113.1585K$$

e) State 5: FBD for the piston



$$P_5A = \overbrace{P_{atm}A + m_{piston}g}^{P_4A} + F \rightarrow F = (P_5 - P_4)A$$

$$F = (130\% \times 1.4 - 1.4) \times 10^5 \times 20 \times 10^{-4} = 84N$$

$$V_5 = V_4 = 6 \times 10^{-4} m^3$$

$$v_5 = \frac{V_5}{m_{N2}} = \frac{6 \times 10^{-4}}{2.5 \times 10^{-3}} = 0.2400\, m^3/kg$$

$$T_5 = \frac{P_5 V_5}{R m_{N2}} = \frac{182 \times 6 \times 10^{-4}}{\frac{8.314}{28} \times 2.5 \times 10^{-3}} = 147.1061K$$

f) State 6: Specific volume for a polytropic process

$$P_5 V_5^n = P_6 V_6^n \rightarrow V_6 = \left(\frac{1.82 \times (6 \times 10^{-4})^{1.34}}{1.40} \right)^{1/1.34}$$

$$V_6 = 7.2977 \times 10^{-4} m^3$$

$$T_6 = \frac{P_6 V_6}{R m_{N2}} = \frac{140 \times 7.2977 \times 10^{-4}}{\frac{8.314}{28} \times 2.5 \times 10^{-3}} = 137.6321K$$

$$v_6 = \frac{V_6}{m_{N2}} = \frac{7.2977 \times 10^{-4}}{2.5 \times 10^{-3}} = 0.2919\, m^3/kg$$

$$h_6 = \frac{V_6}{A} = \frac{7.2977 \times 10^{-4}}{20 \times 10^{-4}} = 0.3649m = 36.49cm$$

g) State 7

$$V_7 = Ah_7 = 20 \times 10^{-4} \times 50 \times 10^{-2} = 10^{-3} m^3$$

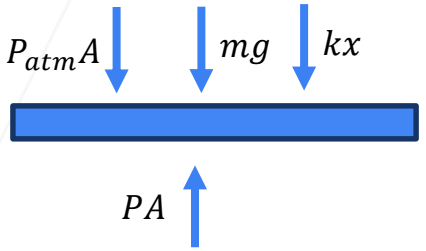
$$v_7 = \frac{Ah_7}{m_{N2}} = \frac{20 \times 10^{-4} \times 50 \times 10^{-2}}{2.5 \times 10^{-3}} = 0.400\, m^3/kg$$

$$T_7 = -20°C = 253.15K$$

$$P_7 = \frac{Rm_{N2}T_7}{V_7} = \frac{\frac{8.314}{28} \times 2.5 \times 10^{-3} \times 253.15}{10^{-3}} = 187.92kPa$$

$$P_7 = 1.8792bar$$

FBD for the piston to find the constant



$$PA = P_{atm}A + m_{piston}g + kx$$

$$P = P_{atm} + \frac{m_{piston}g}{A} + \frac{kx}{A} \times \frac{A}{A}$$

$$P = P_{atm} + \frac{m_{piston}g}{A} + \frac{kV}{A^2}$$

The slope:

$$\frac{k}{A^2} = \frac{(P_7 - P_6)}{m_{N2}(v_7 - v_6)}$$

$$\frac{k}{A^2} = \frac{(1.8792 - 1.4) \times 10^5}{2.5 \times 10^{-3} \times (0.400 - 0.2919)}$$

$$\frac{k}{(20 \times 10^{-4})^2} = \frac{(1.8792 - 1.4) \times 10^5}{2.5 \times 10^{-3} \times (0.400 - 0.2919)}$$

$$k = 709.2914\, N/m$$

h) State 8: Finding first pressure with spring constant

$$V_8 = Ah_8 = 20 \times 10^{-4} \times 80 \times 10^{-2} = 1.6 \times 10^{-3} m^3$$

$$v_8 = \frac{Ah_8}{m_{N2}} = \frac{20 \times 10^{-4} \times 80 \times 10^{-2}}{2.5 \times 10^{-3}} = 0.64\, m^3/kg$$

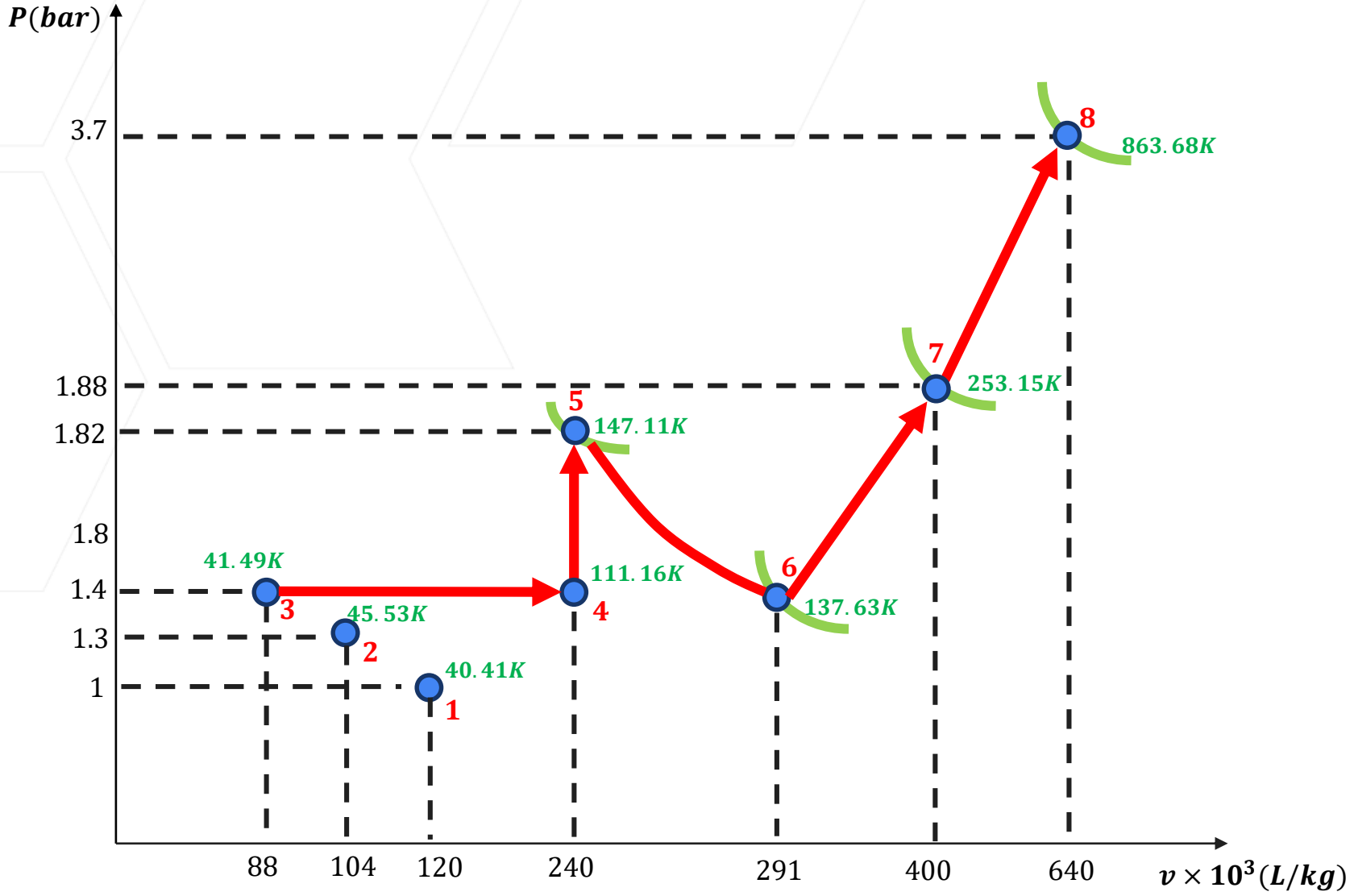
$$\frac{2k}{A^2} = \frac{(P_8 - P_7)}{m_{N2}(v_8 - v_7)} \rightarrow \frac{2 \times 709.2914}{(20 \times 10^{-4})^2} = \frac{(P_8 - 1.8792) \times 10^5}{2.5 \times 10^{-3} \times (0.64 - 0.400)} \rightarrow P_8 = 400.706kPa = 4bar$$

$$P_8 v_8 = RT_8$$

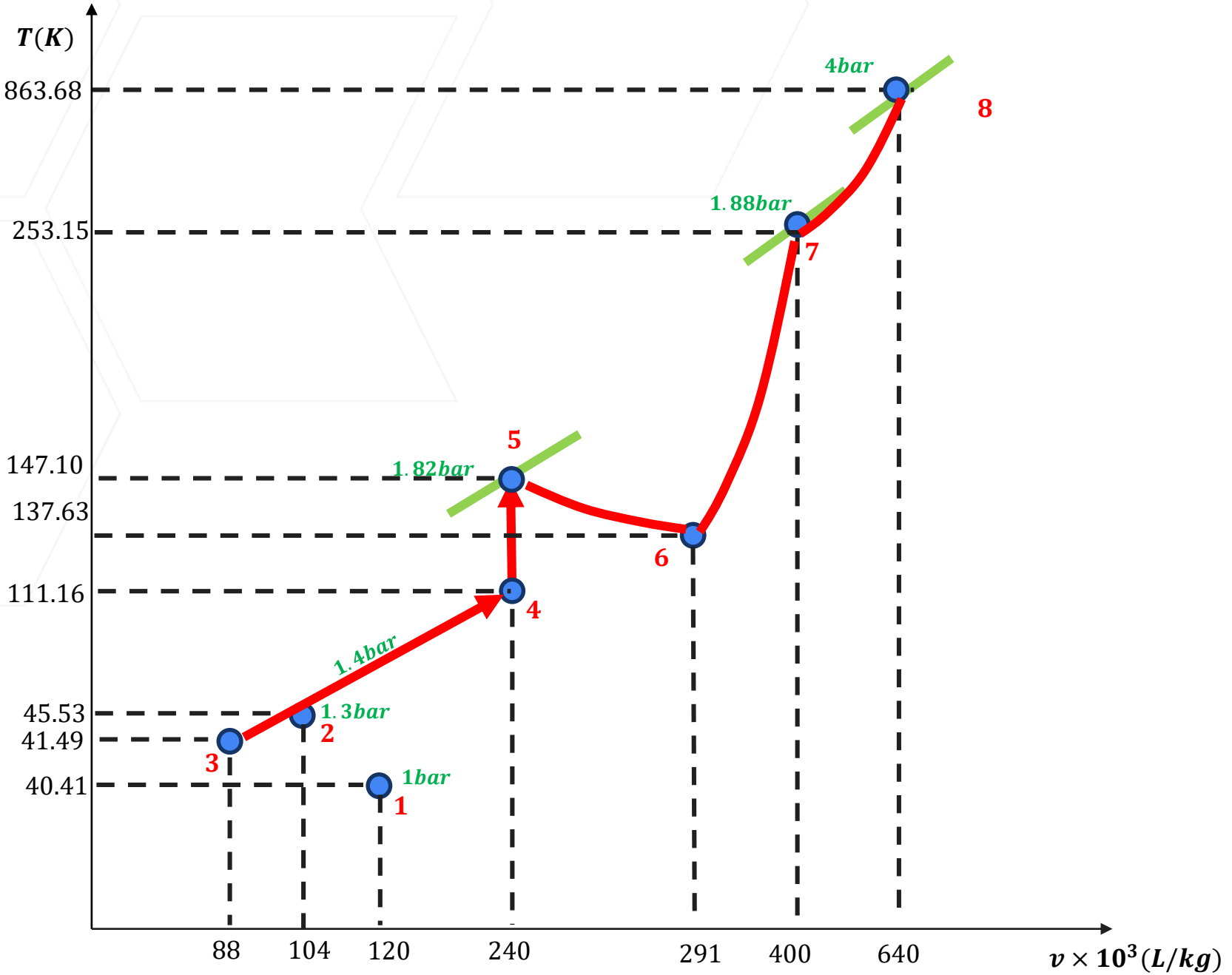
$$400.706 \times 0.64 = \frac{8.314}{28} \times T_8$$

$$T_8 = 863.62K = 590.53°C$$

i) Plot a P (bar) – V (m3/kg) diagram showing all the states previously mentioned, and the processes from state 3 to state 8.



j) Plot a T (°C) – v (m3/kg) diagram showing all the states previously mentioned, and the processes from state 3 to state 8.



k) Find Δu and Δh for the process 3 to 8 using table A-21 and table A-23. Both results should be found in kJ/kg

TABLE A-21

Variation of $\bar{c}_p$ with Temperature for Selected Ideal Gases

$$\frac{\bar{c}_p}{\bar{R}} = \alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4$$

T is in K, equations valid from 300 to 1000 K

Gas	α	$\beta \times 10^3$	$\gamma \times 10^6$	$\delta \times 10^9$	$\varepsilon \times 10^{12}$
N_2	3.675	−1.208	2.324	−0.632	−0.226

$$\Delta h = \int_{T_3}^{T_8} c_p dT = \int_{T_3}^{T_8} R(3.675 - 1.208 \times 10^{-3}T + 2.324 \times 10^{-6}T^2 - 0.632 \times 10^{-9}T^3 - 0.226 \times 10^{-12}T^4)dT$$

$$\frac{\Delta h}{R} = \int_{41.49}^{863.68} (3.675 - 1.208 \times 10^{-3}T + 2.324 \times 10^{-6}T^2 - 0.632 \times 10^{-9}T^3 - 0.226 \times 10^{-12}T^4)dT$$

$$\frac{\Delta h}{8.314/28} = 2961.429 \rightarrow \Delta h = 879.3329 \frac{kJ}{kg}$$

$$\Delta u = \int_{T_3}^{T_8} (c_p - R)dT = \int_{T_3}^{T_8} R(3.675 - 1.208 \times 10^{-3}T + 2.324 \times 10^{-6}T^2 - 0.632 \times 10^{-9}T^3 - 0.226 \times 10^{-12}T^4 - 1)dT$$

$$\frac{\Delta u}{R} = \int_{41.49}^{863.68} (2.675 - 1.208 \times 10^{-3}T + 2.324 \times 10^{-6}T^2 - 0.632 \times 10^{-9}T^3 - 0.226 \times 10^{-12}T^4)dT$$

$$\frac{\Delta u}{8.314/28} = 2139.239 \rightarrow \Delta u = 635.2012 \frac{kJ}{kg}$$

k) Find Δu and Δh for the process 3 to 8 using table A-21 and table A-23. Both results should be found in kJ/kg

Nitrogen, N_2 ($\bar{h}_f^\circ = 0$ kJ/kmol)			
$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	T(K)
0	0	0	0
6,391	4,562	182.638	220
25,610	18,459	223.194	860
25,928	18,695	223.562	870

$$h_8 = \frac{25928 - 25610}{870 - 860}(863.68 - 860) + 25610 = 25727.02\frac{kJ}{kmol} \rightarrow h_8 = \frac{25727.02}{28} = 918.8223\frac{kJ}{kg}$$

$$h_3 = \frac{6391 - 0}{220 - 0}(41.49 - 0) + 0 = 1205.285\frac{kJ}{kmol} \rightarrow h_3 = \frac{1205.285}{28} = 43.0459\frac{kJ}{kg}$$

$$\Delta h = h_8 - h_3 = 918.8223 - 43.0459 = 875.7764\frac{kJ}{kg}$$

$$u_8 = \frac{18695 - 18459}{870 - 860}(863.68 - 860) + 18459 = 18545.85\frac{kJ}{kmol} \rightarrow u_8 = \frac{18545.85}{28} = 662.3517\frac{kJ}{kg}$$

$$u_3 = \frac{4562 - 0}{220 - 0}(41.49 - 0) + 0 = 860.3517\frac{kJ}{kmol} \rightarrow u_3 = \frac{860.3517}{28} = 30.7269\frac{kJ}{kg}$$

$$\Delta u = u_8 - u_3 = 662.3517 - 30.7269 = 631.6249\frac{kJ}{kg}$$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Thanks!