Thermodynamics
2026-1

S7_2: Control Volume_First law_Unsteady-flow process (Transient)

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NAUDY LOPEZ

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.

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EXÁMENES	FECHAS
EXAMEN PARCIAL	**(MAYO 11)**

TEORIA 1 : 3PM
TEORIA 2 : 5PM

Atentos a las indicaciones por anuncios en canvas para saber todos los detalles

EXAMEN PARCIAL : Todos los temas vistos hasta la semana 6

INDICACIONES GENERALES PARA EL EXAMEN PARCIAL

LEER ESTO ANTES DE DAR EL EXAMEN

- Esta evaluación es individual y presencial
- Fecha y hora del examen parcial:
    - Teoría 1 - 11/05/2026 - 3:00pm a 5:00pm
    - Teoría 2 - 11/05/2026 - 5:00pm a 7:00pm

Sobre la evaluación:

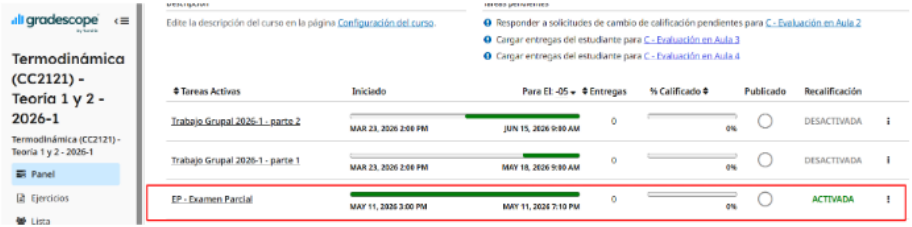
Pueden revisar el detalle de las listas en el siguiente enlace:

https://docs.google.com/spreadsheets/d/107dYActNd4Hb01X4pWy1JXQrGGdG30khNFh3w2V_mMc/edit?usp=drive_link

Además de lo anterior tengan en cuenta las siguientes indicaciones **OBLIGATORIAS:**

1. Traer DNI o carnet estudiantil para identificarse durante el examen.
2. **Solo se permitirá el ingreso al aula con un tiempo máximo de tardanza de 15 minutos** después del inicio de la evaluación.
3. Las tablas de propiedades deben estar impresas y no deben tener nada escrito sobre ellas.
4. Cada estudiante debe traer su calculadora personal, la cual no se puede compartir. No se permite usar el celular como calculadora.
5. Los estudiantes sólo podrán usar un lapicero, un lápiz, un borrador, un corrector, una calculadora y una HOJA (dos páginas) de formulario tamaño A4. Estos formularios no pueden ser impresiones (debe ser a mano), ni fotocopias, ni incluir problemas resueltos. Está prohibido que los estudiantes compartan o intercambien cualquier material una vez que la evaluación se haya iniciado.
6. Cuando se dé la indicación que el tiempo ha terminado, ningún estudiante podrá seguir escribiendo. Si alguien lo hace, su examen será anulado con nota de cero.
7. Una vez terminado el examen se darán 10 minutos adicionales para subir el archivo con la solución en formato PDF al curso "Termodinámica (CC2121) - Teoría 1 y 2 - 2026-1" en la plataforma GRADESCOPE. El ejercicio tendrá el nombre "EP - Examen Parcial".

https://docs.google.com/spreadsheets/d/107dYActNd4Hb01X4pWy1JXQrGGdG30khNFh3w2V_mMc/edit?usp=drive_link



8. Una vez cargado el archivo con la solución, el participante hará entrega de su EXAMEN COMPLETO al encargado de su aula y procederá a retirarse. **No es necesario que indique en qué parte está el desarrollo de cada pregunta, pero puede hacerlo en caso lo considere necesario.**

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OBSERVACIONES PARA TODO EL EXAMEN

- EN CADA PREGUNTA DEL EXAMEN HABRÁN VARIOS ÍTEMS QUE DEBEN SER RESPONDIDOS APROPIADAMENTE
- CADA ÍTEM TIENE UN PUNTAJE EN ESPECÍFICO (QUE ESTÁ INDICADO EN EL ENUNCIADO DE LA PREGUNTA). DE FORMA SIMILAR A LAS TAREAS INDIVIDUALES, **LA CALIFICACIÓN SEGUIRÁ EL CRITERIO TODO O NADA**.
- CADA PREGUNTA DEBE TENER UN DESARROLLO ADECUADO Y COHERENTE, SIGUIENDO LA ESTRUCTURA ECUACIÓN - REEMPLAZO - RESPUESTA. **COLOCAR ÚNICAMENTE RESPUESTAS NO SERÁ CONSIDERADO**. LAS ÚNICAS EXCEPCIONES SERÁN CUANDO SE LES PIDA INFORMACIÓN QUE SE LEE Y SE EXTRAE DIRECTAMENTE DE LAS TABLAS TERMODINÁMICAS.
- SE DEBE UTILIZAR SIEMPRE 4 DECIMALES (COMO MÍNIMO) EN LOS CÁLCULOS.
- NO COLOCAR LAS RESPUESTAS EN LAS UNIDADES SOLICITADAS O NO COLOCAR LAS UNIDADES **DESCUENTA EL 50% DEL PUNTAJE DE LA PREGUNTA**.
- NO **DELIMITAR LOS SISTEMAS (VOLÚMENES DE CONTROL O MASAS DE CONTROL) DESCUENTA EL 50%** DEL PUNTAJE OBTENIDO EN LAS PREGUNTAS QUE IMPLIQUEN SU USO
- EL **ORDEN SERÁ PENALIZADO HASTA CON EL 50%** DEL PUNTAJE TOTAL.
- UNA PREGUNTA CON **EXCESO DE DESORDEN**, QUE IMPIDE OBSERVAR UNA ADECUADA RESOLUCIÓN, **NO SERÁ CORREGIDA**.

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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	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.

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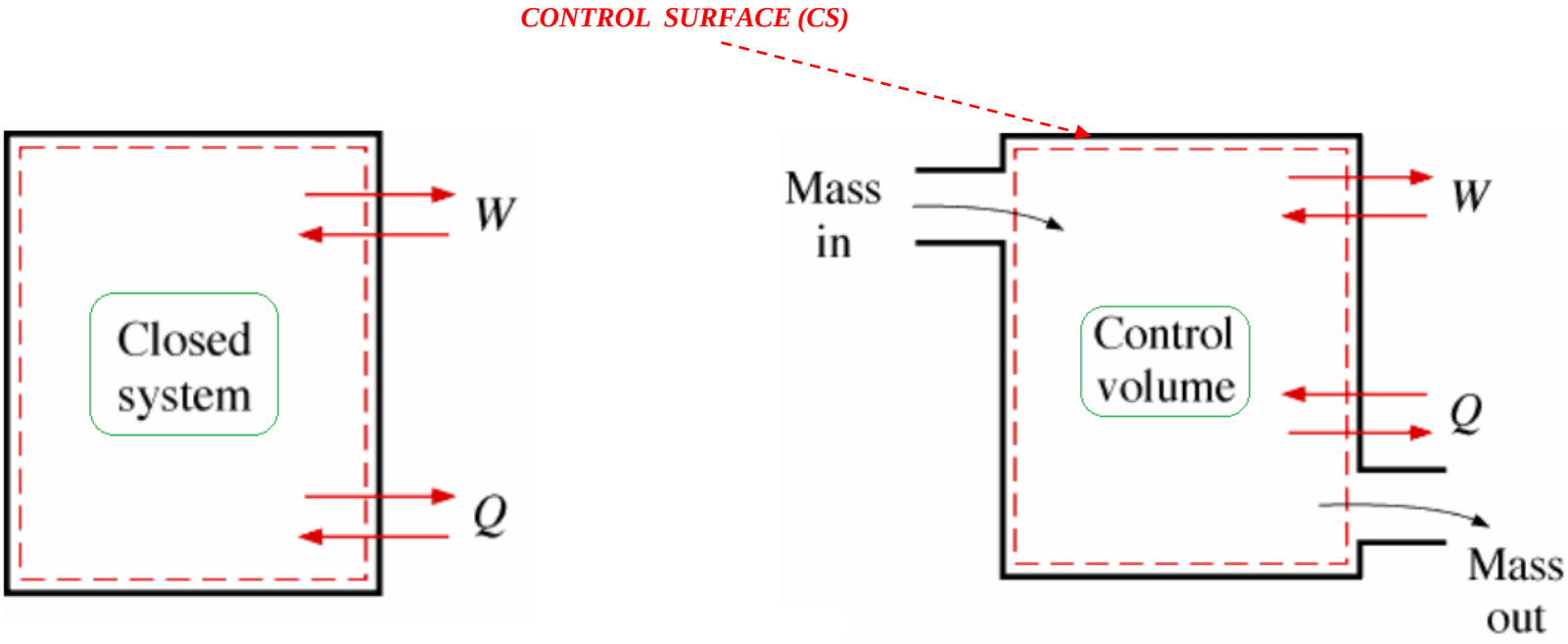
Objectives

Session 13-14: Apply the principle of conservation of energy and mass in open systems operating in a transient state.

Difference Between Closed and Open Systems



SYSTEM

CONTROL VOLUME

(CV)

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First Law_Control Volume

If you don't know $\dot{m}$ you can use equation as alternatives:

Thus for incompressible flow or even for compressible flow where ρ is uniform across A_c,

velocity

$$\dot{m} = \rho V_{avg} A_c \qquad (kg/s)$$

$$\dot{m} = \rho V_{avg} A_c \qquad (kg/s)$$

$\dot{V}$ $\left[\frac{m^3}{s}\right]$

$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}$$

For ideal gases we can also use:

$$P\dot{V} = \frac{\dot{m}\bar{R}T}{M}$$

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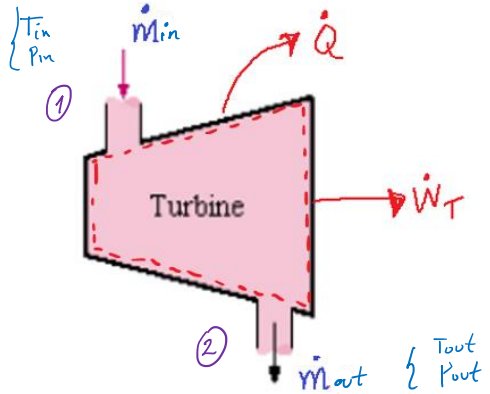
Conditions to analyze an open system:

- Steady state:
  - The mass that enters is equal to the one that leaves (MASS BALANCE)
  - The properties do not change in time (ENERGY BALANCE)

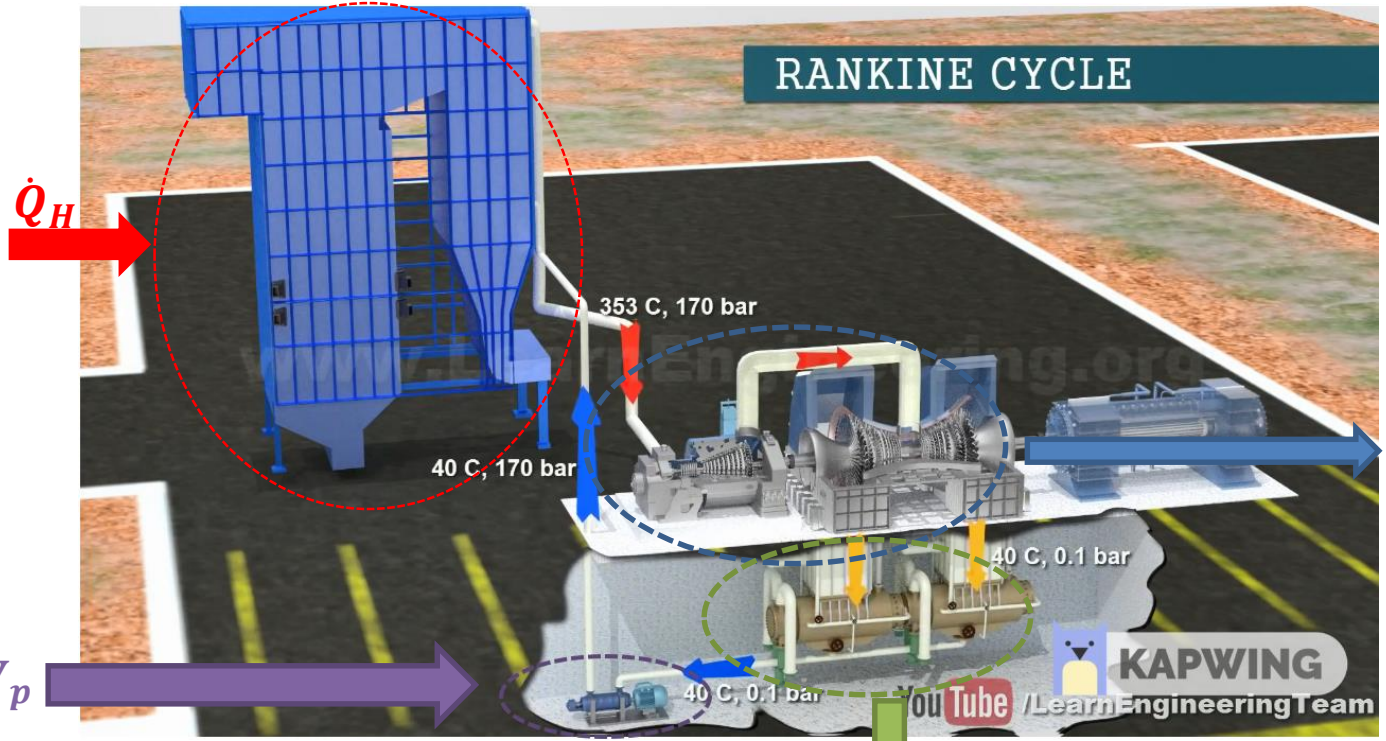


$$\frac{dE_{C.V.}}{dt} = \dot{m}_{in}\left(h_{in} + \frac{1}{2}\mathbf{V}_{in}^2 + gZ_{in}\right) - \dot{m}_{out}\left(h_{out} + \frac{1}{2}\mathbf{V}_{out}^2 + gZ_{out}\right) + \dot{Q}_{C.V.} - \dot{W}_{C.V.} \left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)$$

$$\dot{m}_{in} - \dot{m}_{out} = dm_{CV}/dt \qquad (\text{kg/s})$$

In E.E conditions: $$\frac{dE_{C.V.}}{dt} = \dot{m}\left\{\left(h_{in} + \frac{1}{2}\mathbf{V}_{in}^2 + gZ_{in}\right) - \left(h_{out} + \frac{1}{2}\mathbf{V}_{out}^2 + gZ_{out}\right)\right\} + \dot{Q}_{C.V.} - \dot{W}_{C.V.} \left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)$$

Work-Heat- First Law_Power plant



$\dot{Q}_H$

$\dot{W}_t$

$\dot{W}_p$

$\dot{Q}_L$

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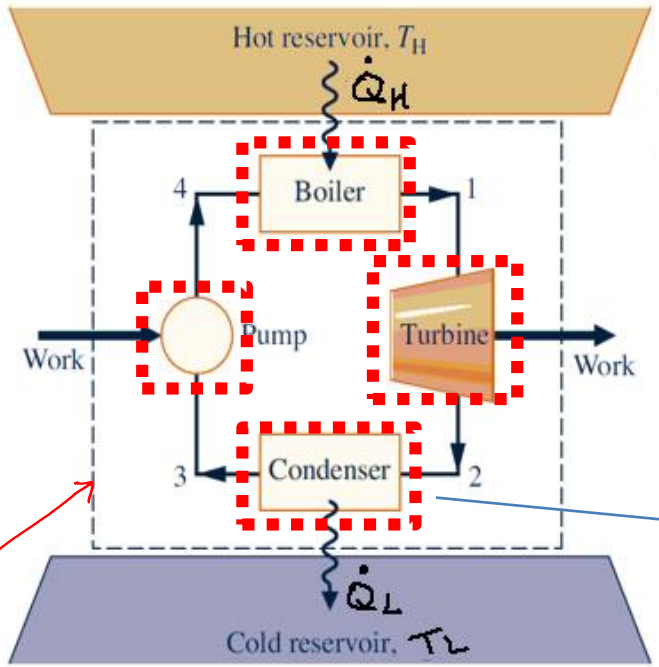
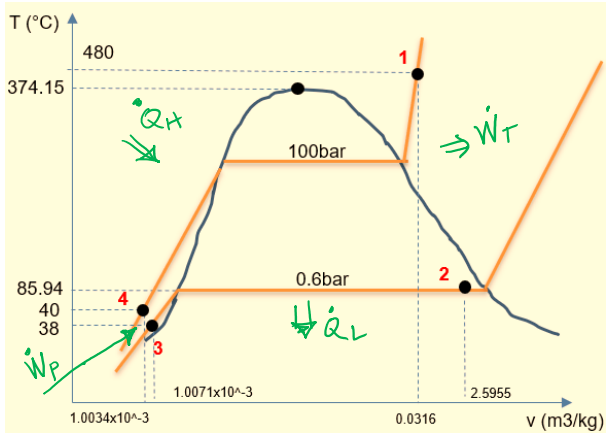
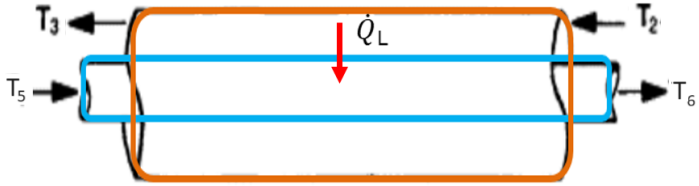
Work-Heat- First Law _ Power plant

$Q_H = Q_{in}$…AND $Q_L = Q_C = Q_{out}$ =







$$\frac{dE_{CV}}{dt} = \sum_{in}\left(\dot{m}_{in}\left(h_{in} + \tfrac{1}{2}V_{in}^2 + gz_{in}\right)\right) - \sum_{out}\left(\dot{m}_{out}\left(h_{out} + \tfrac{1}{2}V_{out}^2 + gz_{out}\right)\right) + \dot{Q}_{CV} - \dot{W}_{CV}$$

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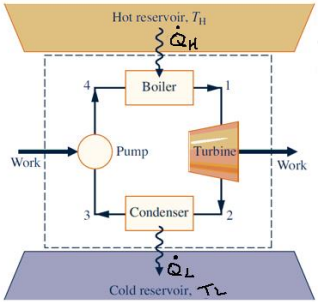
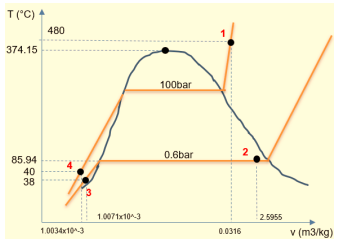
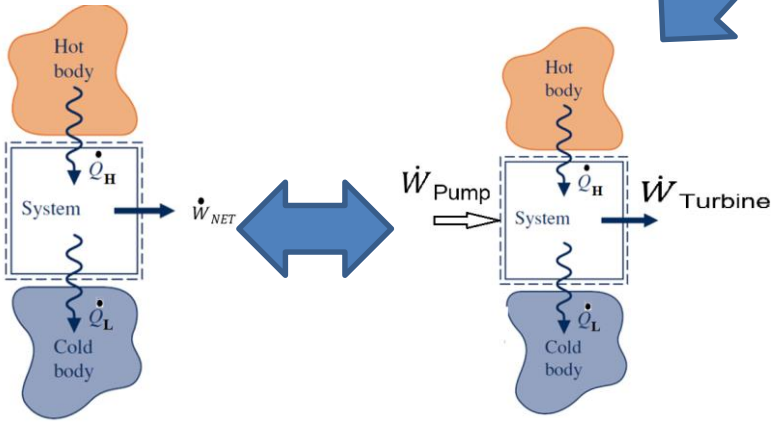
Power Cycles Work-Heat-Firts Law

CONTROL MASS





Mass control



$$\frac{dE}{dt} = \dot{Q}_{NET} - \dot{W}_{NET}$$

$$\eta = \frac{|\dot{W}_T| - |\dot{W}_P|}{|\dot{Q}_H|} = \frac{|\dot{W}_{NET}|}{|\dot{Q}_H|}$$

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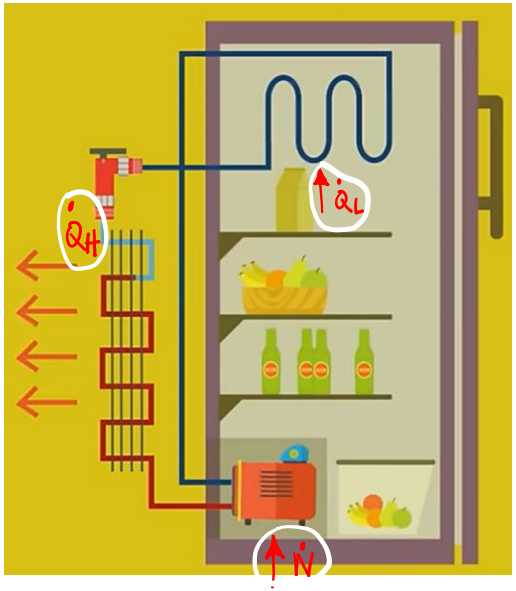
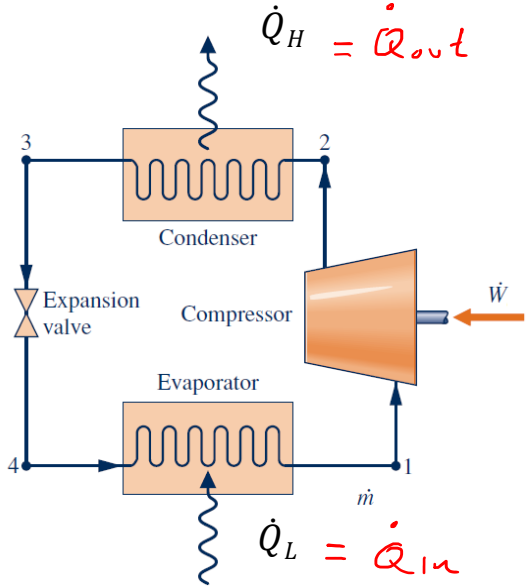
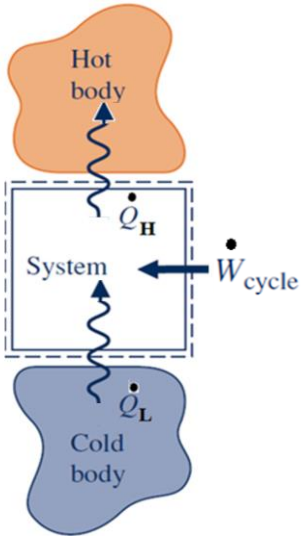
$$\frac{dE_{CV}}{dt} = \sum_{in}\left(\dot{m}_{in}\left(h_{in} + \frac{1}{2}V_{in}^2 + gz_{in}\right)\right) - \sum_{out}\left(\dot{m}_{out}\left(h_{out} + \frac{1}{2}V_{out}^2 + gz_{out}\right)\right) + \dot{Q}_{CV} - \dot{W}_{CV}$$

Refrigeration cycle







$$\mathrm{COP_R} = \boldsymbol{\beta}_R = \left|\frac{\dot{Q}_L}{\dot{W}}\right|$$

$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

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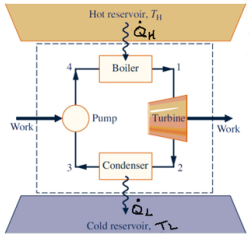
Power Cycles

Work-Heat-First Law

CONTROL MASS

$$\frac{dE}{dt} = \dot{Q}_{NET} - \dot{W}_{NET}$$

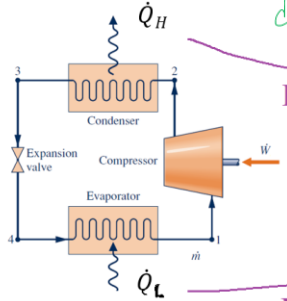


$$\eta = \frac{|\dot{W}_T| - |\dot{W}_P|}{|\dot{Q}_H|} = \frac{|\dot{W}_{NET}|}{|\dot{Q}_H|}$$

Refrigeration cycles

CONTROL MASS

$$\frac{dE}{dt} = \dot{Q}_{NET} - \dot{W}_{NET}$$



For heating

$$\beta_{HP} = \left|\frac{\dot{Q}_H}{\dot{W}}\right|$$

For cooling

$$\beta = \left|\frac{\dot{Q}_L}{\dot{W}}\right|$$

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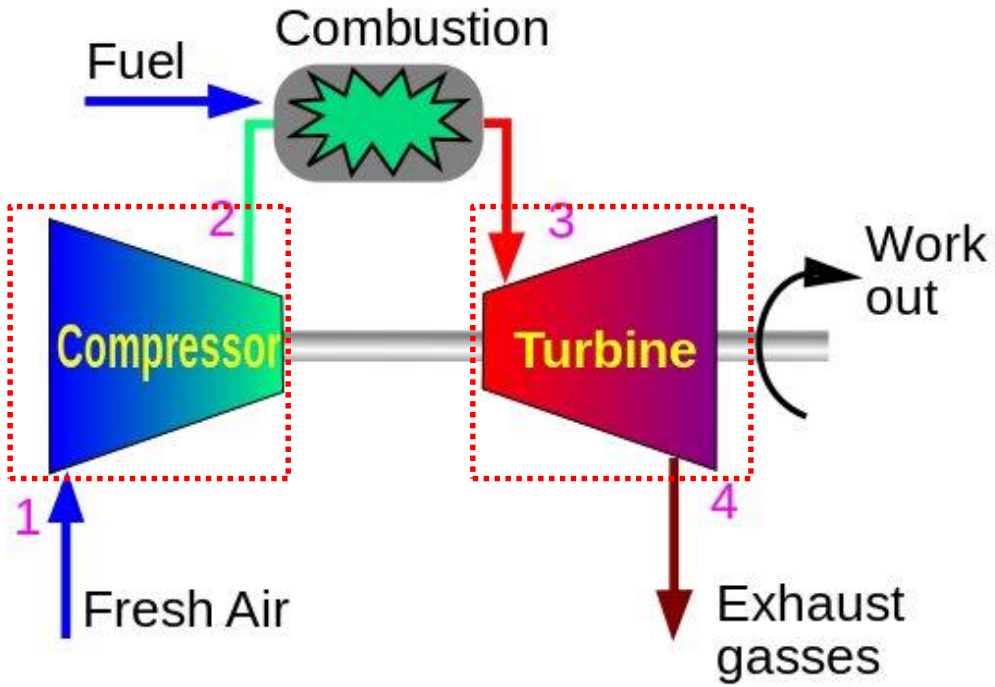

$$\frac{dE_{CV}}{dt} = \sum_{in}\left(\dot{m}_{in}\left(h_{in} + \frac{1}{2}V_{in}^2 + gz_{in}\right)\right) - \sum_{out}\left(\dot{m}_{out}\left(h_{out} + \frac{1}{2}V_{out}^2 + gz_{out}\right)\right) + \dot{Q}_{CV} - \dot{W}_{CV}$$

https://www.turbinesinfo.com/gas-turbines/

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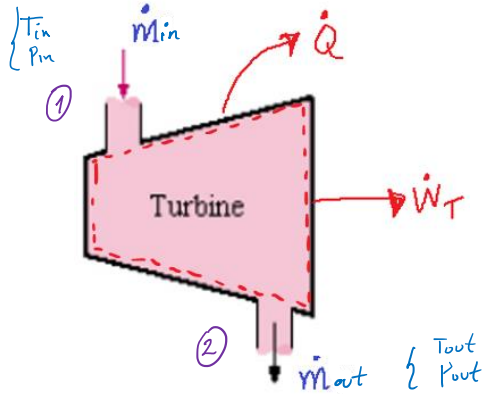
Conditions to analyze an open system:

- Steady state:
  - The mass that enters is equal to the one that leaves (MASS BALANCE)
  - The properties do not change in time (ENERGY BALANCE)
- **Transient: This week**

Steady state



COMO CAMBIAN LAS ECUACIONES ① Y ② PARA TRANSITORIOS?

① $$\frac{dE_{C.V.}}{dt} = \dot{m}_{in}\left(h_{in} + \frac{1}{2}\mathbf{V}_{in}^2 + gZ_{in}\right) - \dot{m}_{out}\left(h_{out} + \frac{1}{2}\mathbf{V}_{out}^2 + gZ_{out}\right) + \dot{Q}_{C.V.} - \dot{W}_{C.V.}$$ $\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)$

② $$\left(\frac{dm}{dt}\right)_{CV} = \dot{m}_{in} - \dot{m}_{out}$$

En transitorio

- Las propiedades cambian con el t en el V.C. $\left\{\frac{dE}{dt} \neq 0\right.$
- La masa cambia en el V.C $\left\{\frac{dm}{dt} \neq 0\right.$

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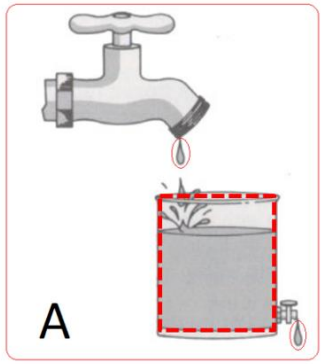
Control Volume_First law

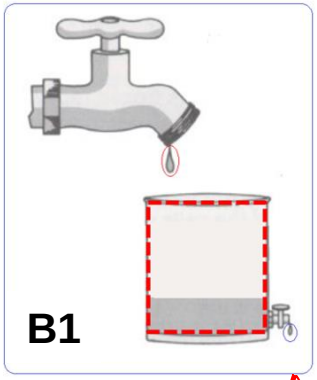
Steady-State

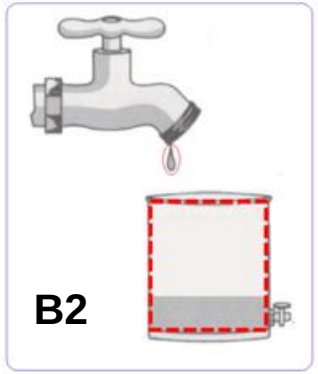


$\frac{dE}{dt} = 0$

$\frac{dm}{dt} = 0$

Unsteady-flow process (Transient)





$\left\{ \begin{array}{l} \frac{dE}{dt} \neq 0 \\ \frac{dm}{dt} \neq 0 \end{array} \right.$

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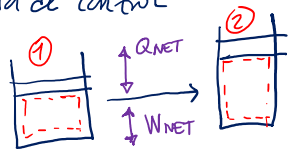
masa de control

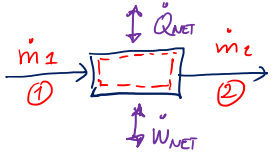


$\Delta U = Q_{NET} - W_{NET}$ / $\frac{dE}{dt} = \dot{Q} - \dot{W}$

↳ $m(u_2 - u_1)$

$m = cte$

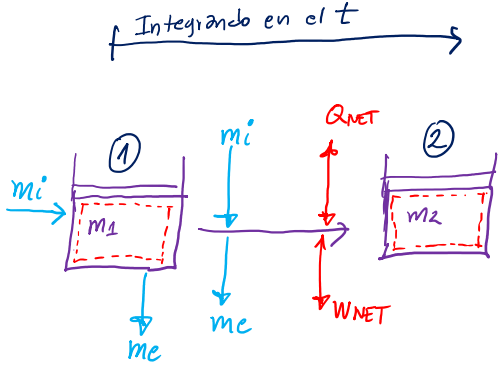
Volumen de control $\begin{cases} \cdot E. \text{ estacionario} \\ \cdot \Delta E_K, \Delta E_P \approx 0 \end{cases}$



$\frac{dE}{dt}^{\circ} = \dot{m}(h_1 - h_2) + \dot{Q}_{NET} - \dot{W}_{NET}$

$\frac{dm}{dt}^{\circ} = \dot{m}_1 - \dot{m}_2$

Volumen de control: Estado transitorio, $\Delta E_K = \Delta E_P \approx 0$



$m_2 - m_1 = m_i - m_e$

$m_2 u_2 - m_1 u_1 = m_i h_i - m_e h_e + Q - W$

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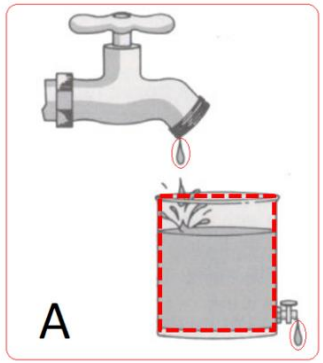
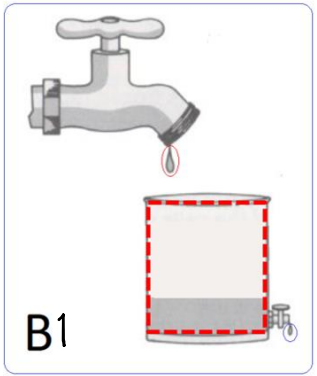
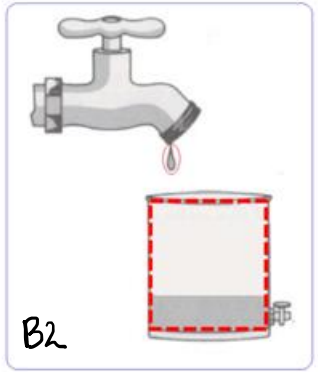
Control Volume_First law

Steady-State



Unsteady-flow process (Transient)





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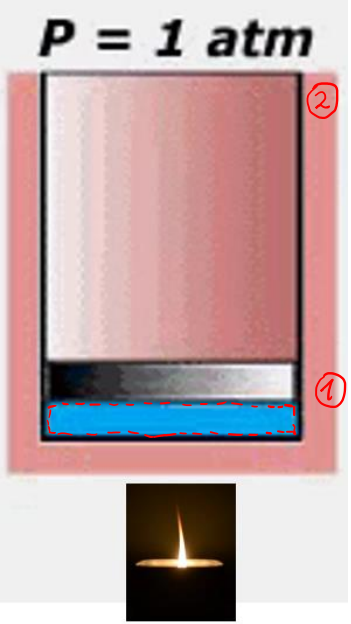
Masa de control



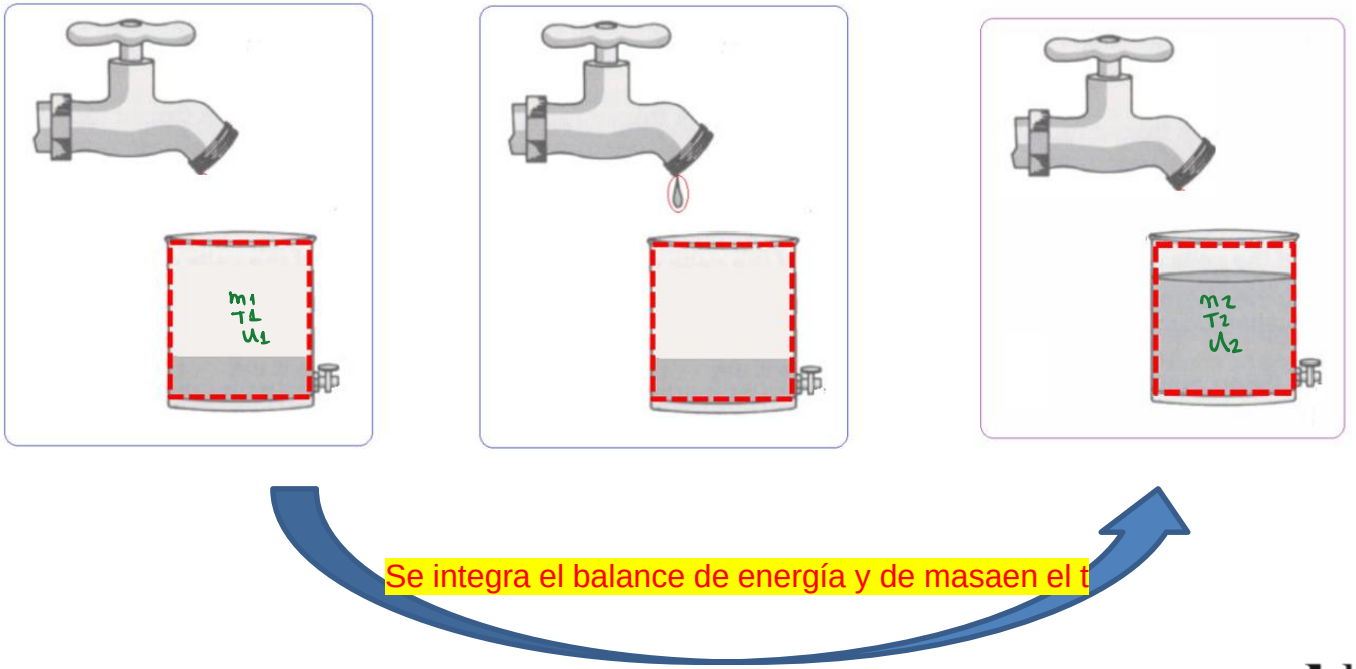
$$\Delta U = Q_{12} - W_{12}$$

El balance lo Hacemos entre el estado inicial y final por eso no está el tiempo.

Algo análogo se hace con el TRANSITORIO

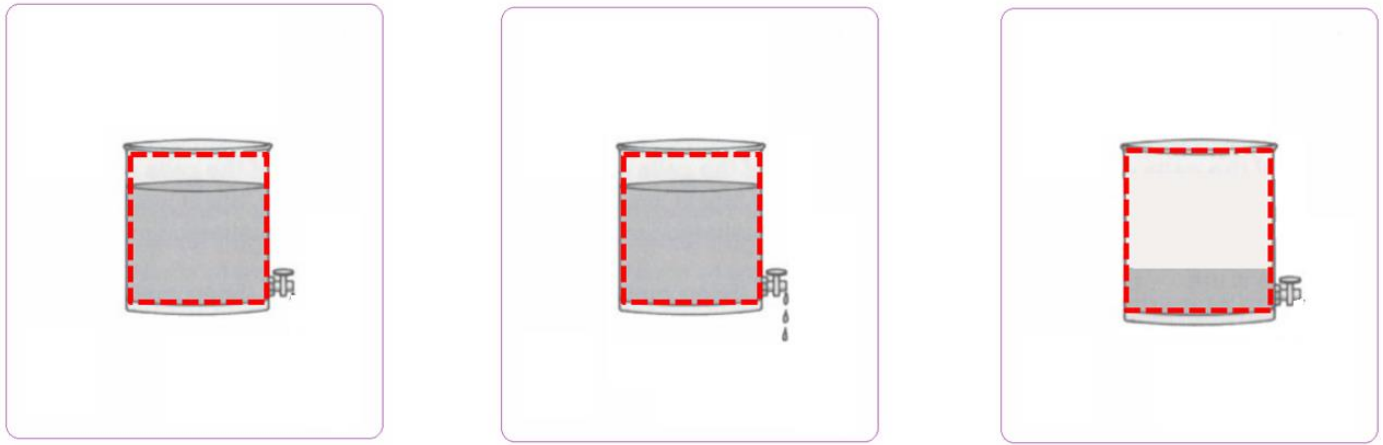
Control Volume_First law

The typical case is the filling or emptying of a tank.



Control Volume_First law

The typical case is the filling or emptying of a tank.



Se integra el balance de energía y de masaen el t

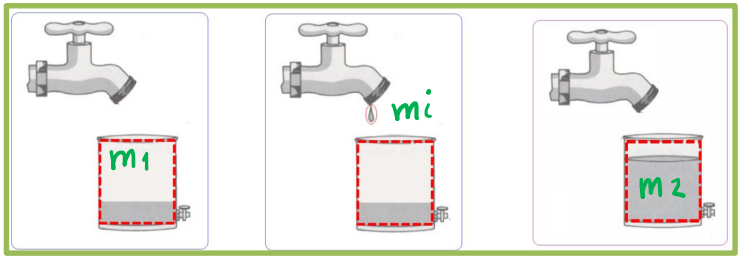
TRANSIENT PROCESS (UNSTEADY STATE PROCESS)

MASS BALANCE

$\neq 0$

$$\left(\frac{dm}{dt}\right)_{CV} = \dot{m}_i - \dot{m}_e$$

Rate form

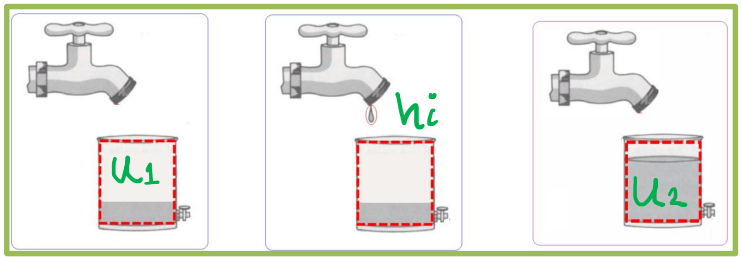


0

$$m_2 - m_1 = m_i - m_e$$

Integrated form

1st LAW_ Control volume



$\neq 0$

$$\left(\frac{dE}{dt}\right)_{CV} = \dot{Q} - \dot{W} + \dot{m}_i(h_i + ke_i + pe_i) - \dot{m}_e(h_e + ke_e + pe_e)$$

Integrated form:

$$E_2 - E_1 = Q_{12} - W_{12} + m_i(h_i + ke_i + pe_i) - m_e(h_e + ke_e + pe_e)$$

$$\Delta U_{12} + \Delta KE_{12} + \Delta PE_{12} = Q_{12} - W_{12} + m_i(h_i + ke_i + pe_i) - m_e(h_e + ke_e + pe_e)$$

$m_2u_2 - m_1u_1$ $\qquad$ 0

$$\Delta U_{12} = Q_{12} - W_{12} + m_i(h_i) - m_e(h_e)$$

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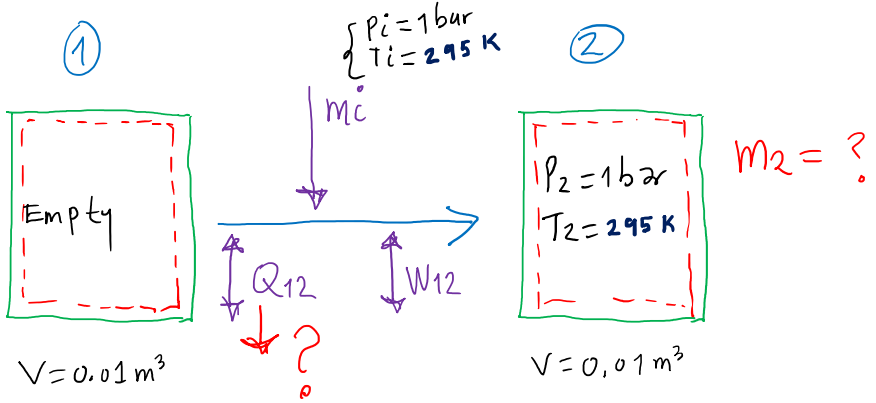
En algunos casos es necesario sacar he (o hi) promedio...

$$h_e = \frac{h_{e,LC} + h_{e,VSC}}{2}$$

Example 3 (transient process 1):

A rigid tank whose volume is 0.01 m^3 is initially evacuated. A pinhole develops in the wall, and air (ideal gas) from the surroundings at 295 K, 1 bar enters until the pressure in the tank is 1 bar. If the final temperature of the air in the tank is 295 K, determine (a) the final mass in the tank, in g, and (b) the heat transfer between the tank contents and the surroundings, in kJ. M_{aire} = 28.97 kg/kmol. Use table A-22.



Mass balance – transient process

$$m_2 - m_1 = m_i - m_e$$

Integrated form

$$m_2 - 0 = m_i - 0$$

$$m_2 = m_i$$

$$m_2 = \frac{P_2 V_2}{R T_2}$$

$$m_2 = \frac{100 \times 0.01}{8.314/28.97 \times 295} = 11.812 \times 10^{-3} kg$$

$$\boxed{m_2 = 11.812 g}$$

Energy balance – transient process

TABLE A-22

Ideal Gas Properties of Air

T(K), h and u(kJ/kg), s° (kJ/kg · K)				when Δs = 0†	
T	h	u	s°	p_r	v_r
295	295.17	210.49	1.68515	1.3068	647.9

$$m_2 u_2 - m_1 u_1 = Q_{12} - W_{12} + m_i(h_i) - m_e(h_e)$$

$$m_2 u_2 - 0 = Q_{12} - 0 + m_2(h_i) - 0$$

$$Q_{12} = m_2 u_2 - m_2(h_i) \qquad m_2 = m_i,\ T_2 = T_i$$

$$Q_{12} = 11.812 \times 10^{-3}[210.49 - 295.17]$$

$$\boxed{Q_{12} = -1.0002\ kJ}$$

Entra ?
sale ?

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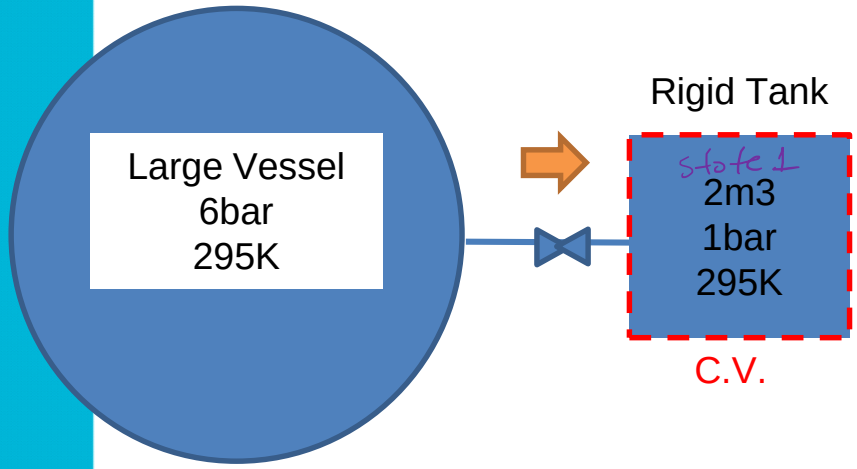
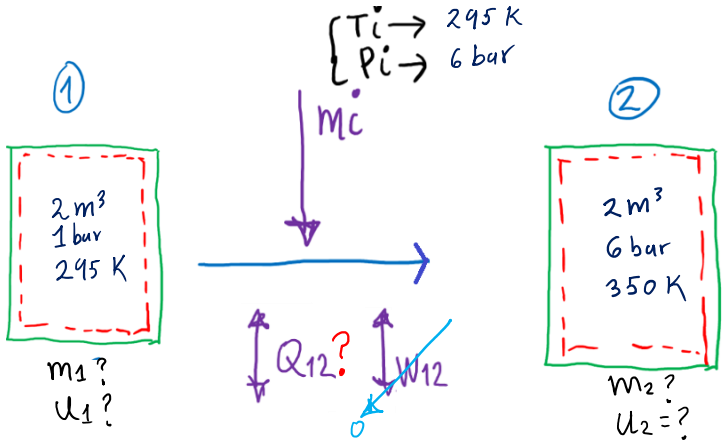
Example 3 (transient process 3):

A rigid tank whose volume is 2 m^3, initially containing air (ideal gas) at 1 bar, 295 K, is connected by a valve to a large vessel holding air (ideal gas) at 6 bar, 295 K. The valve is opened only as long as required to fill the tank with air to a pressure of 6 bar and a temperature of 350 K. Assuming the ideal gas model for the air, determine the heat transfer between the rigid tank and the surroundings, in kJ. M_{aire} = 28.97 kg/kmol. Usar table A22.





Mass balance – transient process

$$m_2 - m_1 = m_i - m_e$$

Integrated form

$$m_2 - m_1 = m_i$$

$$m_1 = \frac{P_1 V}{RT_1} = \frac{100 \times 2}{(8.314/28.97) \times 295} = 2.3624\ kg \qquad m_2 = \frac{P_2 V}{RT_2} = \frac{600 \times 2}{(8.314/28.97) \times 350} = 11.9468\ kg$$

$$m_i = 11.9468 - 2.3624 = 9.5844\ kg$$

Energy balance – transient process

TABLE A-22

Ideal Gas Properties of Air

T(K)	h	u	s° (kJ/kg · K)	when $\Delta s = 0^1$ p_r	v_r
295	295.17	210.49	1.68515	1.3068	647.9
350	350.49	250.02	1.85708	2.379	422.2

$$\Delta U_{12} = Q_{12} - W_{12} + m_i(h_i) - m_e(h_e)$$

$$U_2 - U_1 = Q - 0 + m_i(h_i) - 0$$

$$m_2 u_2 - m_1 u_1 = Q + m_i(h_i)$$

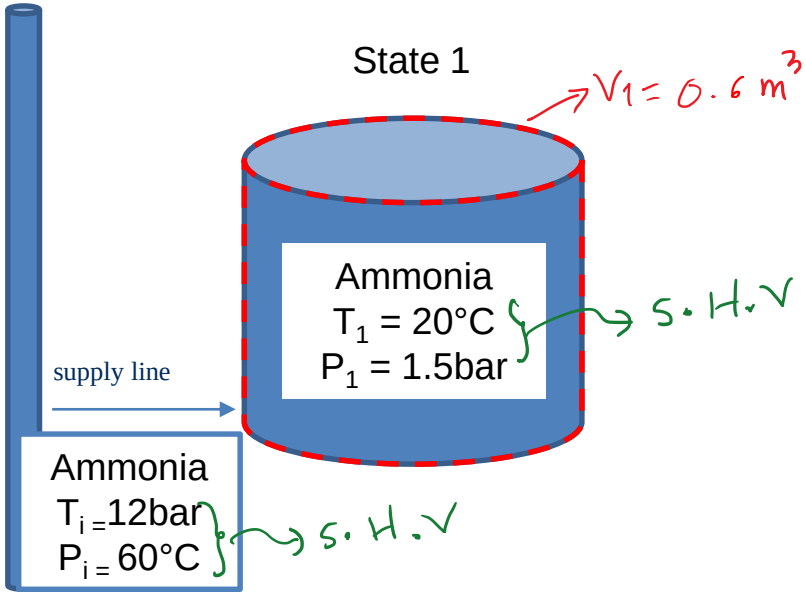
$$11.9468 \times 250.02 - 2.3624 \times 210.49 = Q + 9.5844 \times 295.17$$

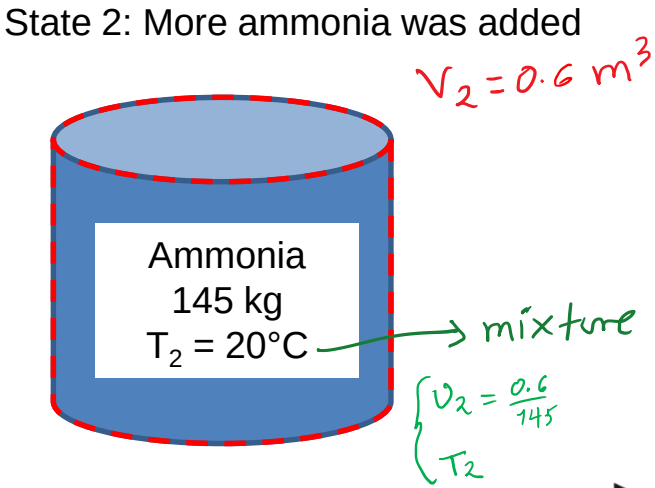
$$-339.34999\ kJ = Q$$

Heat is transferred to the surroundings

Example 2 (transient process 2):

A rigid tank whose volume is 0.6 m3, initially containing ammonia at 20°C, 1.5 bar, is connected by a valve to a large supply line carrying ammonia at 12 bar, 60°C. The valve is opened only as long as required to fill the tank with additional ammonia, bringing the total mass of ammonia in the tank to 145 kg. At state 2, the temperature is 20°C. Determine m_i [kg] and the heat transfer between the tank contents and the surroundings [kJ], ignoring kinetic and potential energy effects.





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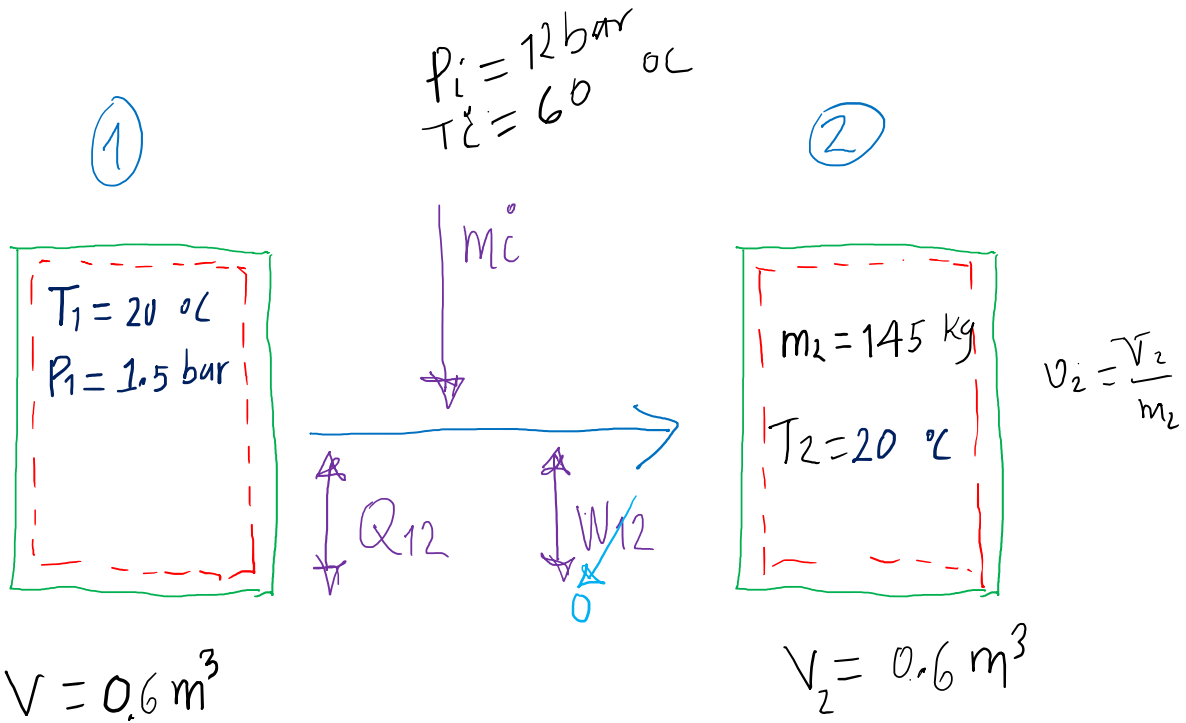
$P_i = 12$ bar
$T_i = 60$ °C
1
2
$\dot{m}_c$
$T_1 = 20$ °C
$P_1 = 1.5$ bar
Q_{12}
W_{12}
0
$m_2 = 145$ kg
$T_2 = 20$ °C
$v_2 = \frac{V_2}{m_2}$
$V = 0.6\ m^3$
$V_2 = 0.6\ m^3$

Properties of Ammonia

TABLE A-15

Properties of Superheated Ammonia Vapor

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
$p = 1.5$ bar $= 0.15$ MPa ($T_{sat} = -25.22°C$)				
20	0.9382	1371.79	1512.51	6.0751

TABLE A-13

Pressure Conversions: 1 bar = 0.1 MPa = 10^2 kPa

Properties of Saturated Ammonia (Liquid–Vapor): Temperature Table

Temp. °C	Press. bar	Specific Volume m³/kg: Sat. Liquid $v_f \times 10^3$	Specific Volume m³/kg: Sat. Vapor v_g	Internal Energy kJ/kg: Sat. Liquid u_f	Internal Energy kJ/kg: Sat. Vapor u_g	Enthalpy kJ/kg: Sat. Liquid h_f	Enthalpy kJ/kg: Evap. h_{fg}	Enthalpy kJ/kg: Sat. Vapor h_g
20	8.5762	1.6386	0.1492	272.86	1331.94	274.26	1185.64	1459.90

TABLE A-15

(Continued)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
$p = 12.0$ bar $= 1.20$ MPa ($T_{sat} = 30.94°C$)				
60	0.12378	1404.54	1553.07	5.2347

State 1:

$P_1 = 1.5bar, T_1 = 20°C$

$v_1 = 0.9382\ m^3/kg$

$u_1 = 1371.79\ kJ/kg$

$\frac{0.6}{0.9382} = m_1 = 0.6395\ kg$

State 2:

$T_2 = 20°C, P_2 = P_{sat} = 8.5762bar$

$v_2 = \frac{0.6}{145} = 0.004138\ m^3/kg$

$x_2 = \frac{0.004138 - 1.6386\times10^{-3}}{0.1492 - 1.6386\times10^{-3}} = 0.01694$

$u_2 = 272.86 + 0.01694(1331.94 - 272.86)$

$u_2 = 290.8008\ kJ/kg$

$u_2 = \frac{V_2}{m_2}$

Inlet:

$P_i = 12bar, T_i = 60°C$

$h_i = 1553.07\ kJ/kg$

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Mass balance – transient process

$$m_2 - m_1 = m_i - m_e$$

Integrated form

$$m_2 - m_1 = m_i$$

$$145 - \frac{0.6}{0.9382} = m_i$$

m_1

$$m_i = 145 - 0.6395 = 144.3605\ kg$$

Energy balance – transient process

$$\Delta U_{12} = Q_{12} - W_{12} + m_i(h_i) - m_e(h_e)$$

$$U_2 - U_1 = Q - 0 + m_i(h_i) - 0$$

$$m_2 u_2 - m_1 u_1 = Q + m_i(h_i)$$

$$145 \times 290.8008 - 0.6395 \times 1371.79 = Q + 144.3605 \times 1553.07$$

$$-182913.1054\ kJ = Q$$

Heat is transferred to the surroundings

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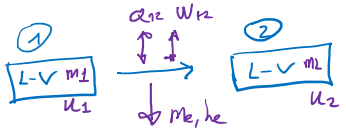
EXAMPLE 2: A 750-L rigid tank, shown in Fig., initially contains water at 250°C, 50% liquid and 50% vapor, by volume. A valve at the bottom of the tank is opened, and saturated liquid is slowly withdrawn. Heat transfer takes place such that the temperature remains constant. Find: The total mass $\mathbf{m_1}$(kg), $\mathbf{x_1}$ y $\mathbf{x_2}$ and the amount of heat transfer required to the state where half the initial mass is withdrawn (kJ).

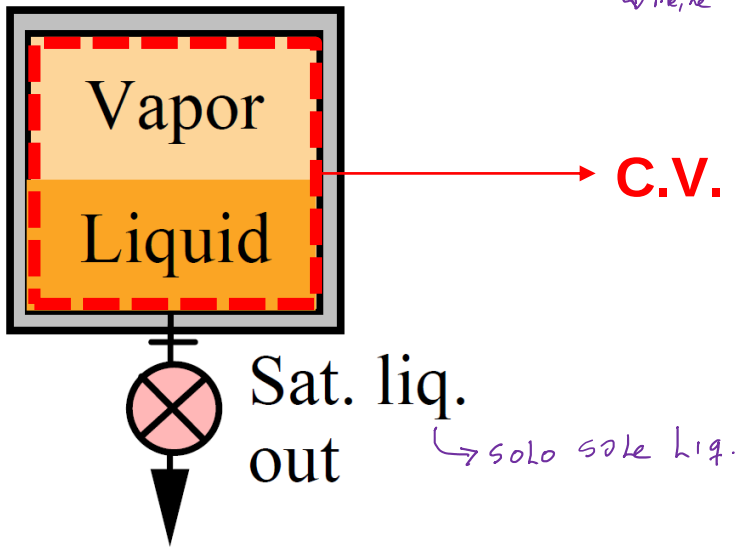


→ solo sale L.S. ⇒ E1 y E2 son mezcla a la misma T, P
↳ he

Estado 1
V = 750 L = 0.750 m³
v_f = 0.375 m³
v_g = 0.375 m³
T_1 = 250 °C
↳ mixture
v_g ✓ v_f ✓
m_g ✓ m_f ✓
$m_1 = m_f + m_g$
$v_1 = \frac{V}{m_1}$
$v_1 = v_f' + x_1 (v_g' - v_f')$
↳ x_1

Estado 2
V = 0.750 m³
$m_2 = m_1/2$
$v_2 = \frac{V}{m_2}$ ✓
$v_2' = v_f' + x_2 (v_g' - v_f')$
x_2 ✓

Con esta inf. hacemos el balance de energía para calcular Q



↳ solo sale Liq. sat.

Solution:

Control Volume: Vessel

Mass Balance (transient process)

$$m_2 - m_1 = m_i - m_e$$

Integrated form

(no inlet)

$$\boldsymbol{m_2 - m_1 = -m_e}$$

Energy Balance (transient process)

$$\Delta U_{12} = Q_{12} - W_{12} + m_i(h_i) - m_e(h_e)$$

Integrated form after neglecting potential and kinetic energy

(no electrical or any other kind of work)

(no inlet)

$$U_2 - U_1 = Q_{12} - m_e(h_e) \longrightarrow \boldsymbol{m_2u_2 - m_1u_1 = Q_{12} - m_eh_e}$$

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State 1: Vapor-liquid mixture at 250°C

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

(*Continued*)

		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg		
Temp. °C	Press. bar	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g
250	39.73	1.2512	0.05013	1080.4	2602.4	1085.4	1716.2	2801.5

$Total\ Volume = 750\text{L} = 0.750\text{m}^3\ (0.375\text{m}^3\ vapor\ and\ 0.375\text{m}^3\ liquid)$

Liquid Mass:

$$m_{L1} = \frac{V_{L1}}{v_L} = \frac{0.375\text{m}^3}{1.2512 \times 10^{-3}\,\text{m}^3/\text{kg}} = 299.71\text{kg}$$

Vapor Mass:

$$m_{V1} = \frac{V_{V1}}{v_v} = \frac{0.375\text{m}^3}{0.05013\,\text{m}^3/\text{kg}} = 7.48\text{kg}$$

$m_1 = m_{L1} + m_{V1} = 307.19\text{kg}$

$m_2 = m_c = \frac{m_1}{2} = 153.595\text{ kg}$

Quality:

$$x_1 = \frac{m_{V1}}{m_{L1} + m_{V1}} = \frac{7.48}{299.71 + 7.48} = 2.43 \times 10^{-2}$$

Internal Energy:

$$u_1 = u_L + x(u_v - u_L) = 1080.4 + 2.43 \times 10^{-2}(2602.4 - 1080.4) = 1117.38\text{kJ/kg}$$

$$m_1 u_1 = (299.71 + 7.48)\text{kg} \times 1117.38\frac{\text{kJ}}{\text{kg}} =$$

343 248 kJ

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State 2: Vapor-liquid mixture at 250°C, half mass withdrawn

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

(*Continued*)

Temp. °C	Press. bar	Specific Volume m^3/kg Sat. Liquid $v_f \times 10^3$	Specific Volume m^3/kg Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Internal Energy kJ/kg Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Enthalpy kJ/kg Evap. h_{fg}	Enthalpy kJ/kg Sat. Vapor h_g
250	39.73	1.2512	0.05013	1080.4	2602.4	1085.4	1716.2	2801.5

Total mass at state 2: $m_2 = (299.71 + 7.48)/2 = 153.595\text{kg}$

Specific volume at state 2:

$$v_2 = \frac{V_2}{m_2} = \frac{0.750\ \text{m}^3}{153.595\ \text{kg}} = 4.883 \times 10^{-3}\ \text{m}^3/\text{kg}$$

But, using quality:

$$v_2 = v_L + x_2(v_v - v_L) = 1.2512 \times 10^{-3} + x_2(0.05013 - 1.2512 \times 10^{-3}) \longrightarrow \boxed{x_2 = 7.43 \times 10^{-2}}$$

Internal Energy:

$$u_2 = u_L + x_2(u_v - u_L) = 1080.4 + 7.43 \times 10^{-2}(2602.4 - 1080.4) = 1193.48\ \text{kJ/kg}$$

$$m_2 u_2 = 153.595\text{kg} \times 1193.48 \frac{\text{kJ}}{\text{kg}} = \quad \textbf{183 313kJ}$$

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Energy Balance (Transient Process):

Pressure Conversions:
1 bar = 0.1 MPa
$= 10^2$ kPa

(*Continued*)

Temp. °C	Press. bar	Specific Volume m^3/kg Sat. Liquid $v_f \times 10^3$	Specific Volume m^3/kg Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Internal Energy kJ/kg Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Enthalpy kJ/kg Evap. h_{fg}	Enthalpy kJ/kg Sat. Vapor h_g
250	39.73	1.2512	0.05013	1080.4	2602.4	1085.4	1716.2	2801.5

$$m_2u_2 - m_1u_1 = Q_{12} - m_eh_e$$

Water leaves the vessel as SATURATED LIQUID

$$183\,313\text{kJ} - 343\,248\text{kJ} = Q_{12} - 153.595\text{kg} \times 1085.4\frac{\text{kJ}}{\text{kg}}$$

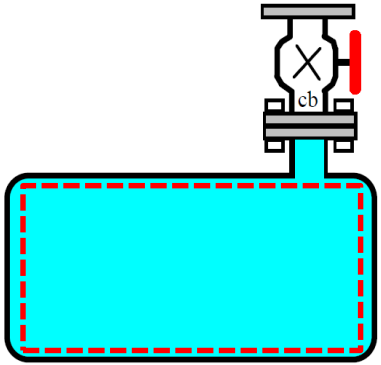
$$\boldsymbol{Q_{12} = 6777.01\ \text{kJ}}$$

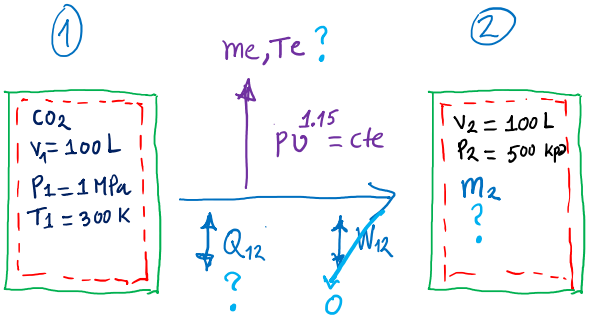
EXAMPLE 4: A 100-L rigid tank contains carbon dioxide gas at 1 MPa, 300 K. A valve is open, and carbon dioxide escapes slowly until the tank pressure has dropped to 500 kPa. At this point the valve is closed. The gas remaining inside the tank may be assumed to have undergone a polytropic expansion $(Pv^n = C)$, with polytropic exponent **n = 1.15**. Find the final mass inside and the heat transferred to the tank during the process. v (espefic volume)

Assumptions: CO_2 has an ideal behaviour

Control Volume: Tank

Mass Balance (transient process):





$$m_2 - m_1 = m_i - m_e$$

$$m_2 u_2 - m_1 u_1 = Q_{12} - W_{12} + m_i(h_i) - m_e(h_e)$$

$$m_2 - m_1 = \cancel{m_i} - m_e \longrightarrow \text{Integrated form}$$

(no inlet)

$$\boldsymbol{m_2 - m_1 = -m_e}$$

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Energy Balance (transient process):

$$\Delta U_{12} = Q_{12} - W_{12} + m_i(h_i) - m_e(h_e)$$

(no electrical or any other kind of work)

(no inlet)

→ Integrated form after neglecting potential and kinetic energy

$$\boldsymbol{m_2u_2 - m_1u_1 = Q_{12} - m_eh_e}$$

STATE 1 (1MPa, 300K):

$$PV = \frac{\boldsymbol{m_1}}{M}\bar{R}T \longrightarrow (1000\text{kPa})(0.1\text{m}^3) = \frac{\boldsymbol{m_1}}{44.01\,\frac{\text{kg}}{\text{kmol}}}\left(8.314\,\frac{\text{kPa.m}^3}{\text{kmol.K}}\right)(300\text{K})$$

$$\boldsymbol{m_1} = 1.764\ \text{kg}$$

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STATE 2 (500kPa, T=?): Polytropic expansion

$$P_1 v_1^n = P_2 \boldsymbol{v_2^n} \longrightarrow \quad (1000\text{kPa})\left(\frac{0.1\text{m}^3}{1.764\text{kg}}\right)^{1.15} = (500\text{kPa})(\boldsymbol{v_2})^{1.15}$$

$$\boldsymbol{v_2} = 0.1036\ \text{m}^3/\text{kg}$$

And the specific volume at state 2 is:

$$v_2 = \frac{V}{\boldsymbol{m_2}} \longrightarrow \quad 0.1036\ \text{m}^3/\text{kg} = \frac{0.1\text{m}^3}{\boldsymbol{m_2}} \longrightarrow \quad \boldsymbol{m_2} = 0.965\ \text{kg}$$

Therefore, temperature at state 2 is:

$$PV = \frac{m_2}{M}\bar{R}\boldsymbol{T_2} \longrightarrow \quad (500\text{kPa})(0.1\text{m}^3) = \frac{0.965\ \text{kg}}{44.01\ \frac{kg}{\text{kmol}}}\left(8.314\ \frac{\text{kPa.m}^3}{\text{kmol.K}}\right)(\boldsymbol{T_2})$$

$$\boldsymbol{T_2} = 274.274\ \text{K}$$

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Finding internal energy and enthalpy for both states from Tables:

STATE 1 (1MPa, 300K)

$$\bar{u}_1 = 6939 \text{ kJ/kmol}$$

STATE 2 (500kPa, 274.274 K)

$$\bar{u}_2 = 6209.82 \text{ kJ/kmol}$$

Interpolating from the tables

TABLE A-23

Ideal Gas Properties of Selected Gases

	Carbon Dioxide, CO_2 ($\bar{h}_f^\circ = -393{,}520$ kJ/kmol)		
T(K)	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$
270	8,335	6,091	210.062
280	8,697	6,369	211.376
290	9,063	6,651	212.660
298	9,364	6,885	213.685
300	9,431	6,939	213.915

The escaping CO_2 can be considered at an average temperature of $\dfrac{274.274 + 300}{2} = \mathbf{287.137\ K}$

And its h can be estimated at 287.137 K:

$$\bar{h}_e = 8958.21 \text{ kJ/kmol}$$

Interpolating from the tables

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Finally, the energy balance:

$$m_2 u_2 - m_1 u_1 = Q_{12} - m_e h_e$$

$$0.965\text{kg}\left(6209.82\,\frac{\text{kJ}}{\text{kmol}}\right)\times\frac{1}{44.01}\,\frac{\text{kmol}}{\text{kg}} - 1.764\text{kg}\left(6939\,\frac{\text{kJ}}{\text{kmol}}\right)\times\frac{1}{44.01}\,\frac{\text{kmol}}{\text{kg}} = Q_{12} - (m_1 - m_2)\times 8958.21\,\frac{\text{kJ}}{\text{kmol}}\times\frac{1}{44.01}\,\frac{\text{kmol}}{\text{kg}}$$

1.764 → m_1, 0.965 → m_2

$$\boldsymbol{Q_{12} = 20.67\ \text{kJ}}$$

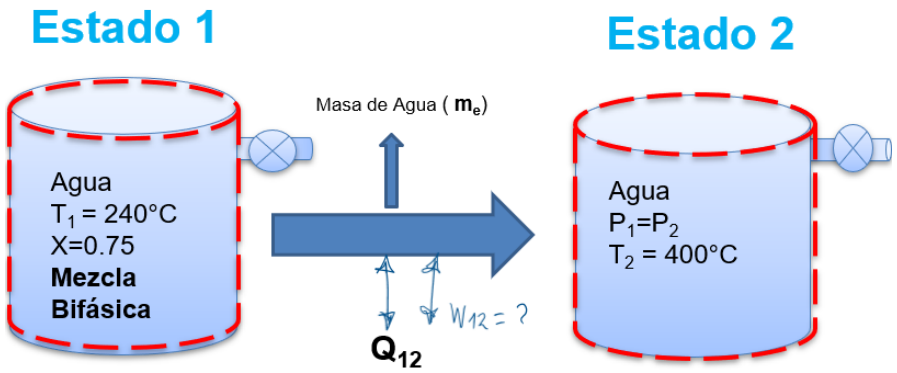
Ejercicio 5: Un tanque cilíndrico de paredes rígidas, de 50 cm de radio y 115 cm de altura contiene agua a 240°C y calidad de 0.75. Por medio de una válvula se extrae masa lentamente, durante este proceso existe transferencia de calor a *presión constante*. El proceso se detiene cuando en el recipiente el agua alcanza los 400°C. Determine:

a) La masa que se extrae del recipiente durante el proceso.

b) El calor transferido durante el proceso.

state 1 $\begin{cases} T_1 \checkmark \\ x_1 \checkmark \end{cases} \Rightarrow P_1$

state 2 $\begin{cases} T_2 \checkmark \\ P_1 = P_2 \end{cases}$



- During the time that the process lasts, the change in mass within the control volume is different from zero, therefore it is not a steady state.
- Also, we will see later the properties of the output stream are not the same at the beginning and at the end.

$m_2 - m_1 = m_i - m_e$?

$m_2 u_2 - m_1 u_1 = Q - W + m_i h_i - m_e h_e$

↓ ?

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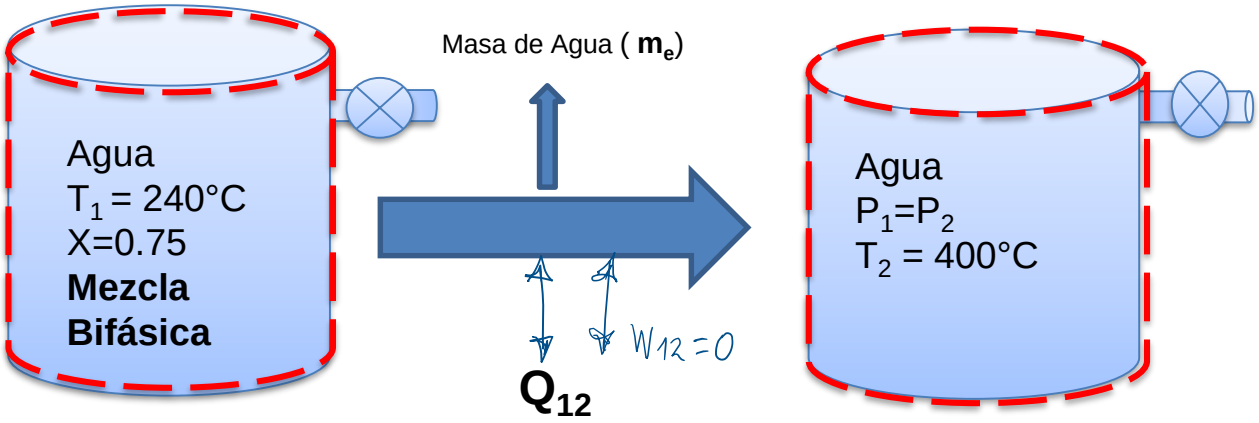
Estado 1

Estado 2



Consideraciones

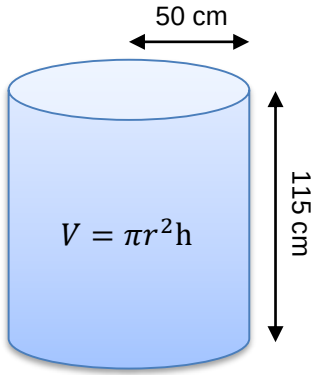
- Proceso isocórico (paredes rígidas)
- Variación de E_p y E_k es despreciable

a) La masa que se extrae del recipiente durante el proceso ⟶ $m_2 - m_1 = mi - m_e$

STATE 1

Paso 1: Hallar m_1

$$m_1 = \frac{V}{v_1}$$



$$V = 903210\ cm^3 = \mathbf{0.9032\ m^3}$$

$$v_1 = v_f + x(v_g - v_f)$$

Tabla A-2 → T = 240 °C…Mixture→ P_{sat} = 33.44 bar

Temp. °C	Press. bar	Specific Volume m³/kg: Sat. Liquid $v_f \times 10^3$	Specific Volume m³/kg: Sat. Vapor v_g	Internal Energy kJ/kg: Sat. Liquid u_f	Internal Energy kJ/kg: Sat. Vapor u_g	Enthalpy kJ/kg: Sat. Liquid h_f	Enthalpy kJ/kg: Evap. h_{fg}	Enthalpy kJ/kg: Sat. Vapor h_g	Entropy kJ/kg · K: Sat. Liquid s_f	Entropy kJ/kg · K: Sat. Vapor s_g	Temp. °C
230	27.95	1.2088	0.07158	986.74	2603.9	990.12	1813.8	2804.0	2.6099	6.2146	230
240	33.44	1.2291	0.05976	1033.2	2604.0	1037.3	1766.5	2803.8	2.7015	6.1437	240

x	0.75
v_f	1.2291 × 10^{-3} m^3/kg
v_g	0.05976 m^3/kg

$$v_1 = 0.0451\ {}^{m^3}/_{kg}$$

$$\boldsymbol{m_1 = \frac{V}{v_1} = 20.0266\ kg}$$

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STATE 2

Paso 2: Hallar m_2

$T_2 = 400\ °C$

$P_2 = 33.44\ bar = P_1$

Fase: ~~vapor~~ sobrecalentado

Tabla A-2 → T = 240 °C

Temp. °C	Press. bar	Specific Volume m³/kg: Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g
230	27.95	1.2088	0.071
240	33.44	1.2291	0.05

Tabla A-4 → T = 400 °C

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
p = 30.0 bar = 3.0 MPa (T_{sat} = 233.90°C)				
Sat.	0.0667	2604.1	2804.2	6.1869
240	0.0682	2619.7	2824.3	6.2265
280	0.0771	2709.9	2941.3	6.4462
320	0.0850	2788.4	3043.4	6.6245
360	0.0923	2861.7	3138.7	6.7801
400	0.0994	2932.8	3230.9	6.9212
440	0.1062	3002.9	3321.5	7.0520
500	0.1162	3108.0	3456.5	7.2338
540	0.1227	3178.4	3546.6	7.3474
600	0.1324	3285.0	3682.3	7.5085
640	0.1388	3357.0	3773.5	7.6106
700	0.1484	3466.5	3911.7	7.7571

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
p = 40 bar = 4.0 MPa (T_{sat} = 250.4°C)				
Sat.	0.04978	2602.3	2801.4	6.0701
280	0.05546	2680.0	2901.8	6.2568
320	0.06199	2767.4	3015.4	6.4553
360	0.06788	2845.7	3117.2	6.6215
400	0.07341	2919.9	3213.6	6.7690
440	0.07872	2992.2	3307.1	6.9041
500	0.08643	3099.5	3445.3	7.0901
540	0.09145	3171.1	3536.9	7.2056
600	0.09885	3279.1	3674.4	7.3688
640	0.1037	3351.8	3766.6	7.4720
700	0.1110	3462.1	3905.9	7.6198
740	0.1157	3536.6	3999.6	7.7141

Interpolación lineal:

P (bar)	v (m³/kg)
30	0.0994
33.44	$v_2 = 0.0905$
40	0.07341

400 °C

$$m_2 = \frac{V}{v_2} = 9.9801\ kg$$

$$m_e = m_1 - m_2 = 10.0465\ kg$$

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b) El calor transferido durante el proceso

$$\Delta U = m_2u_2 - m_1u_1$$

$$\Delta U = Q_{12} - W_{12} + m_i(h_i) - m_e(h_e)$$

Estado 1

$$u_1 = u_f + x(u_g - u_f)$$

Tabla A-2 → T = 240 °C ... Mixture .. $x_1 = 0.75$

Temp. °C	Press. bar	Specific Volume m³/kg: Sat. Liquid $v_f \times 10^3$	Specific Volume m³/kg: Sat. Vapor v_g	Internal Energy kJ/kg: Sat. Liquid u_f	Internal Energy kJ/kg: Sat. Vapor u_g	Enthalpy kJ/kg: Sat. Liquid h_f	Enthalpy kJ/kg: Evap. h_{fg}	Enthalpy kJ/kg: Sat. Vapor h_g	Entropy kJ/kg · K: Sat. Liquid s_f	Entropy kJ/kg · K: Sat. Vapor s_g	Temp. °C
230	27.95	1.2088	0.07158	986.74	2603.9	990.12	1813.8	2804.0	2.6099	6.2146	230
240	33.44	1.2291	0.05976	1033.2	2604.0	1037.3	1766.5	2803.8	2.7015	6.1437	240

x	0.75
u_f	1033.2 kJ/kg
u_g	2604.0 kJ/kg

$$\boldsymbol{u_1 = 2211.3\ kJ/kg}$$

Estado 2

Tabla A-4 → T = 400 °C

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 30.0 bar = 3.0 MPa (T_{sat} = 233.90°C)			
Sat.	0.0667	2604.1	2804.2	6.1869
240	0.0682	2619.7	2824.3	6.2265
280	0.0771	2709.9	2941.3	6.4462
320	0.0850	2788.4	3043.4	6.6245
360	0.0923	2861.7	3138.7	6.7801
400	0.0994	2932.8	3230.9	6.9212
440	0.1062	3002.9	3321.5	7.0520
500	0.1162	3108.0	3456.5	7.2338
540	0.1227	3178.4	3546.6	7.3474
600	0.1324	3285.0	3682.3	7.5085
640	0.1388	3357.0	3773.5	7.6106
700	0.1484	3466.5	3911.7	7.7571

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 40 bar = 4.0 MPa (T_{sat} = 250.4°C)			
Sat.	0.04978	2602.3	2801.4	6.0701
280	0.05546	2680.0	2901.8	6.2568
320	0.06199	2767.4	3015.4	6.4553
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400	0.07341	2919.9	3213.6	6.7690
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500	0.08643	3099.5	3445.3	7.0901
540	0.09145	3171.1	3536.9	7.2056
600	0.09885	3279.1	3674.4	7.3688
640	0.1037	3351.8	3766.6	7.4720
700	0.1110	3462.1	3905.9	7.6198
740	0.1157	3536.6	3999.6	7.7141

Interpolación lineal:

400 °C

P (bar)	u (kJ/kg)
30	2932.8
33.44	u_2 = 2928.3624
40	2919.9

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Ya que se trata de un sistema transitorio, las propiedades varían con el tiempo en cualquier punto del sistema. Por ende, para hallar $\mathbf{h_e}$, se toma el promedio de las entalpías de los estados 1 y 2.

$$h_1 = h_f + x h_{fg}$$

Tabla A-2 → T = 240 °C

Temp. °C	Press. bar	Specific Volume m³/kg: Sat. Liquid $v_f \times 10^3$	Specific Volume m³/kg: Sat. Vapor v_g	Internal Energy kJ/kg: Sat. Liquid u_f	Internal Energy kJ/kg: Sat. Vapor u_g	Enthalpy kJ/kg: Sat. Liquid h_f	Enthalpy kJ/kg: Evap. h_{fg}	Enthalpy kJ/kg: Sat. Vapor h_g	Entropy kJ/kg · K: Sat. Liquid s_f	Entropy kJ/kg · K: Sat. Vapor s_g	Temp. °C
230	27.95	1.2088	0.07158	986.74	2603.9	990.12	1813.8	2804.0	2.6099	6.2146	230
240	33.44	1.2291	0.05976	1033.2	2604.0	1037.3	1766.5	2803.8	2.7015	6.1437	240

x	0.75
h_f	1037.3 kJ/kg
h_{fg}	1766.5 kJ/kg

$$\boldsymbol{h_1 = 2362.175\ kJ/kg}$$

Tabla A-4 → T = 400 °C

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 30.0 bar = 3.0 MPa (T_{sat} = 233.90°C)			
Sat.	0.0667	2604.1	2804.2	6.1869
240	0.0682	2619.7	2824.3	6.2265
280	0.0771	2709.9	2941.3	6.4462
320	0.0850	2788.4	3043.4	6.6245
360	0.0923	2861.7	3138.7	6.7801
400	0.0994	2932.8	3230.9	6.9212
440	0.1062	3002.9	3321.5	7.0520
500	0.1162	3108.0	3456.5	7.2338
540	0.1227	3178.4	3546.6	7.3474
600	0.1324	3285.0	3682.3	7.5085
640	0.1388	3357.0	3773.5	7.6106
700	0.1484	3466.5	3911.7	7.7571

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 40 bar = 4.0 MPa (T_{sat} = 250.4°C)			
Sat.	0.04978	2602.3	2801.4	6.0701
280	0.05546	2680.0	2901.8	6.2568
320	0.06199	2767.4	3015.4	6.4553
360	0.06788	2845.7	3117.2	6.6215
400	0.07341	2919.9	3213.6	6.7690
440	0.07872	2992.2	3307.1	6.9041
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540	0.09145	3171.1	3536.9	7.2056
600	0.09885	3279.1	3674.4	7.3688
640	0.1037	3351.8	3766.6	7.4720
700	0.1110	3462.1	3905.9	7.6198
740	0.1157	3536.6	3999.6	7.7141

Interpolación lineal:

400 kJ/kg

P (bar)	h (kJ/kg)
30	3230.9
33.44	h_2 = 3224.95
40	3213.6

$$\boldsymbol{h_e = \frac{h_1 + h_2}{2} = 2793.56\ kJ/kg}$$

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Finalmente, se reemplazan los datos en el balance de energía y se halla Q_{12}.

$$m_2u_2 - m_1u_1 = m_ih_i - m_eh_e + Q_{12} - W$$

$$Q_{12} = m_2u_2 - m_1u_1 + m_e(h_e)$$

$$Q_{12} = (9.9801)(2928.3624) - (20.0266)(2211.3) + (10.0465)(2793.56)$$

$$\boldsymbol{Q_{12} = 13006.029\ kJ}$$

Thanks!

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$$P_1 V_1^n = P_2 V_2^n$$

$$\frac{P_1}{P_2} = \frac{V_2^n}{V_1^n}$$

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n$$

$$\left(\frac{P_1}{P_2}\right) = \ln\left[\left(\frac{V_2}{V_1}\right)^n\right]$$

$$\ln\left(\frac{P_1}{P_2}\right) = n \ln\left(\frac{V_2}{V_1}\right)$$

$$\boxed{n = \frac{\ln\left(\frac{P_1}{P_2}\right)}{\ln\left(\frac{V_2}{V_1}\right)}}$$

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