Atmospheric Work Production and Dissipation

- There is a potential to do work when heat is carried upwards by convection in the atmosphere.

- Producing this work is not trivial; the expansion must be carried out at mechanical equilibrium.

Work Production

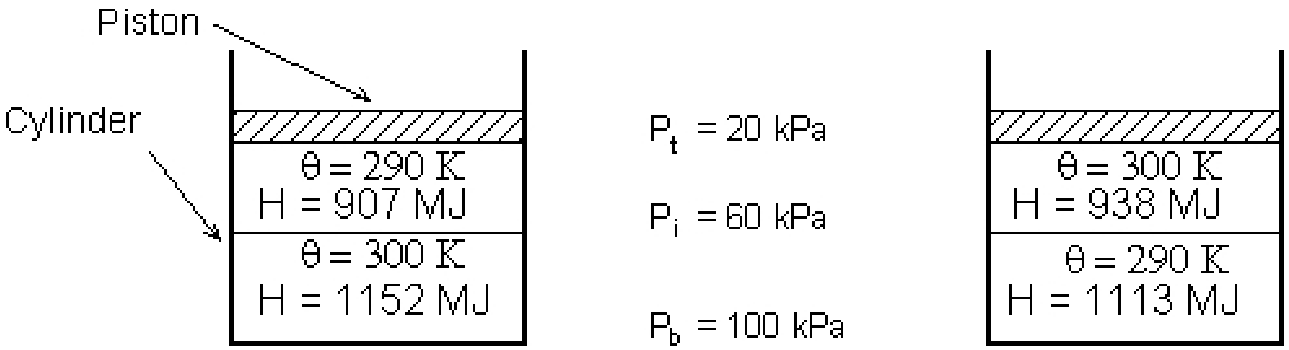
In 1905, Austrian thermodynamist Max Margules used closed thermodynamic systems to calculate the mechanical energy produced as a result of isentropic re-arrangement of air masses.

Margules calculated the work produced when air masses of uniform entropy initially side by side are re-arranged so that they are on top of one another

He also calculated the work produced when air masses of uniform entropy initially on top of one another exchange position.

The next slides give examples of a Margules re-arrangement.

Margules re-arrangement of large air masses initially on top of one another.



Initial Conditon
(high entropy
on bottom)

Final condition
(high entropy
on top)

H = 2059 MJ

ΔH = 7115 kJ

H = 2052 MJ

W = Δh = 872 J/kg

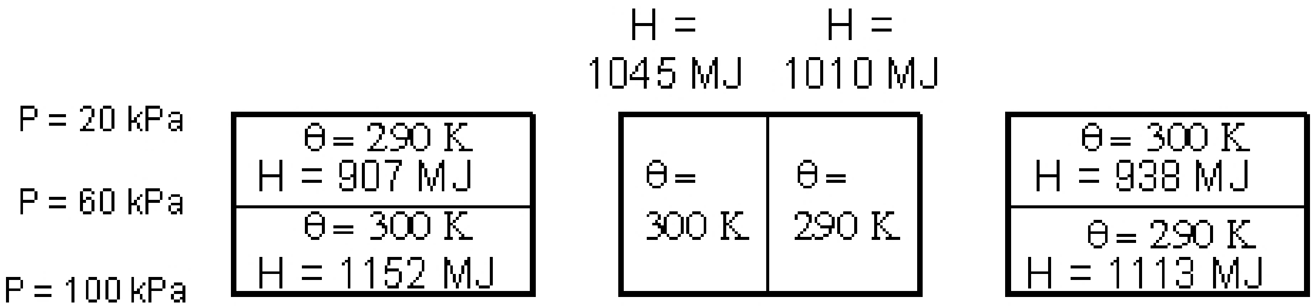
The work corresponds to a velocity of 42 m/s

$$m = (P_b - P_t)/g = 8163 \text{ kg}$$

Notes:

Closed piston covered isolated thermodynamics system
Mass based on column area of one square meter

Margules re-arrangement of large air masses


H = 1045 MJ

H = 1010 MJ

P = 20 kPa

P = 60 kPa

P = 100 kPa

θ = 290 K
H = 907 MJ

θ = 300 K
H = 1152 MJ

θ = 300 K

θ = 290 K

θ = 300 K
H = 938 MJ

θ = 290 K
H = 1113 MJ

State 1	State 2	State 3
(high entropy on bottom)	(side by side)	(high entropy on top)
H = 2059 MJ	H = 2055 MJ	H = 2052 MJ

ΔH = 3558 kJ

Δh = 436 J/kg

ΔH = 3558 kJ

Δh = 436 J/kg

ΔH = 7115 kJ

Δh = 872 J/kg

The work in going from state 2 to state 3 is is half as much as in going from state 1 to state 3 because state 2 is an intermediate state.

Equations

Enthalpy per unit mass

$$h = C_p T$$

Enthalpy of a large air mass

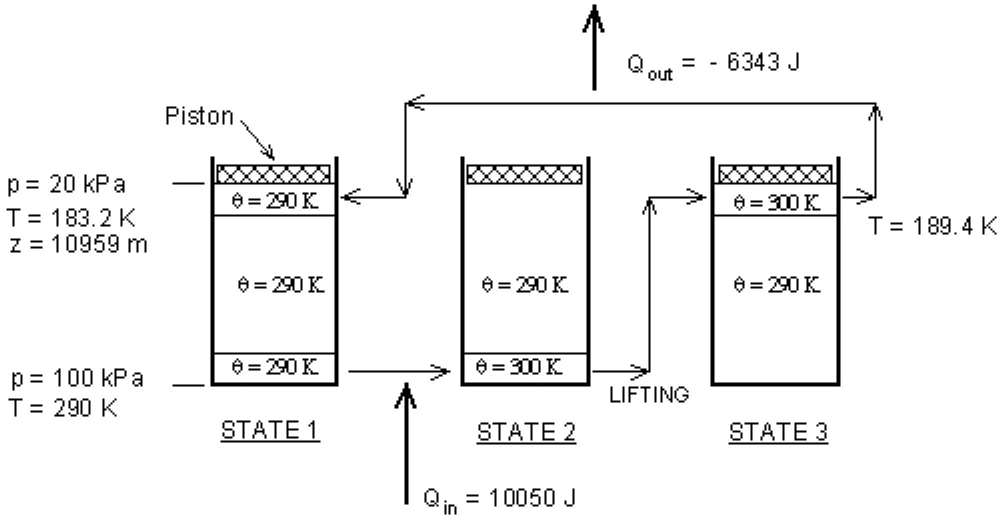
$$H = f(P_1 , P_2 , \theta) = \frac{C_p \, \theta \, [(P_1)^{(k+1)} - (P_2)^{(k+1)}]}{g \, (k+1) \, (P_0)^{k}}$$

where $k = R / C_p = 2/7$

Entropy per unit mass

$$s = C_p \ln (\theta) + \text{constant}$$

Work production when a thin layer is raised



The work per unit mass can be calculated using four methods giving the same result.

1. Heat received minus heat given up

$$W = Q_{in} + Q_{out} = 3703 \text{ J}$$

2. Heat received multiplied by the Carnot efficiency based on the temperatures at which the heat is received and given up.

$$W = Q_{in} (1 - T_{out}/T_{in}) = 10050 (1 - 183.2/290) = 10050 * \mathbf{0.368} = 3703 \text{ J}$$

Corresponds to a velocity of 86 m/s.

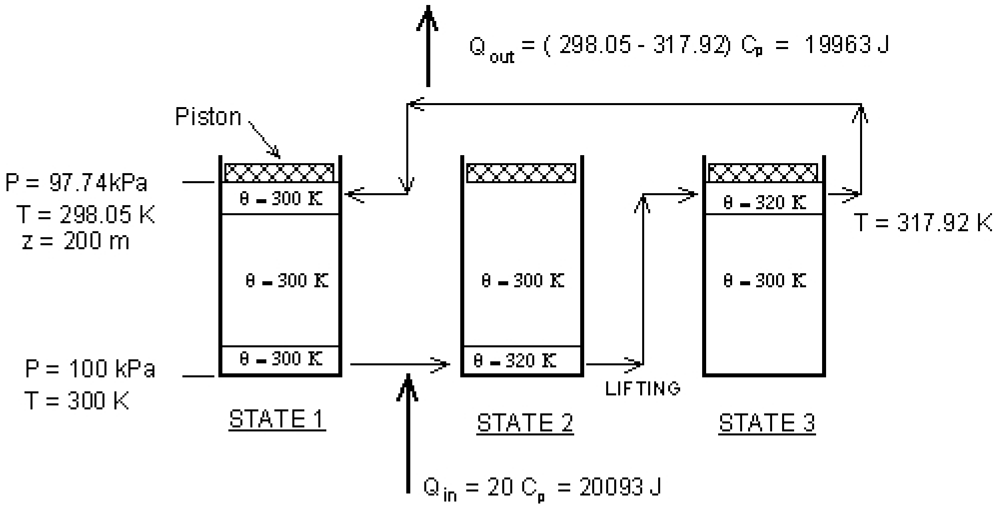
3. Previous Margules' equation for the enthalpy of large air mass.

4. Standard meteorological Convective Available Potential Enegy (CAPE) equation.

The work per unit mass raised is approximately four times higher than in the Margules mass on top of one other case because the air is raised approximately twice as high and because the work is allocated to the raised air only.

The work is related to the heat received and to the temperature at which heat is received by the Carnot efficiency, which is not evident when using large air masses.

Manzanares Ideal Process Work Calculation



The work per unit mass can be calculated using five methods giving the same result.

1. Base delta-P from density difference (standard engineering method)
   Delta-P = (P/R) (delta-T) g z = (100000/287)(320-300)*9.8*200= 142 Pa
   Work = C_p (Turbine delta-T) = C_p (320 - 319.87) = 131 J

2. Heat received minus heat given up
   $W = Q_{in} + Q_{out} = 20093 - 19963 = 131$ J

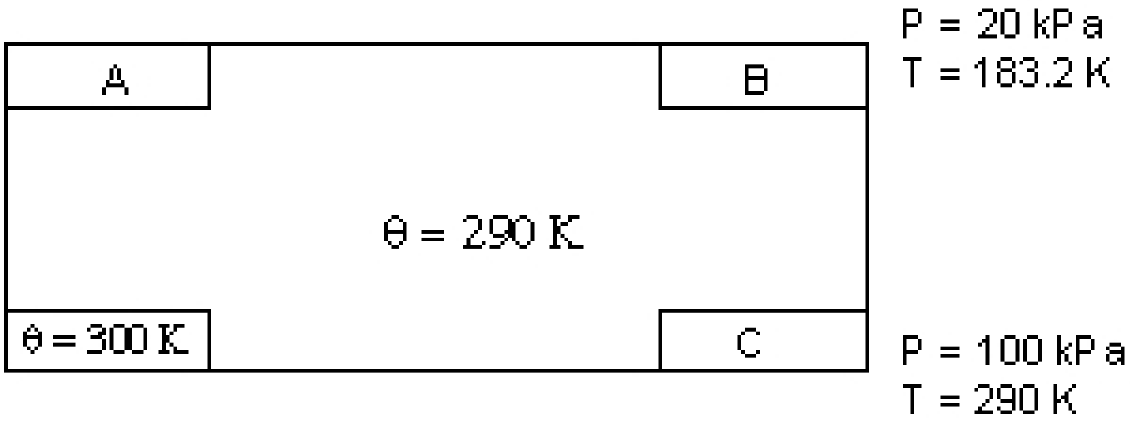
3. Heat received multiplied by the Carnot efficiency based on the temperatures at which the heat is received and given up.
   $W = Q_{in}\ (1 - T_{out}/T_{in}) = 20093\ (1 - 298.05/300) = 20093 * \mathbf{0.0065} = 131$ J

4. Previous Margules' equation for the enthalpy of large air mass.

5. Standard meteorological Convective Available Potential Enegy (CAPE) equation.

The work is related to the heat received and to the temperature at which heat is received by the Carnot efficiency - not evident from base pressure reduction method.

The work corresponds to a velocity of 16 m/s.



The work is the same whether the 300 K potential temperature parcel is moved to A or B.

The work produced when the parcel is moved to C is zero.

Work is produced during upward heat transport, work is not produced as a result of horizontal heat transport.

Horizontal versus Vertical

What does it mean? (1)

The fact that the work calculated using the Carnot efficiency method is the same as the work calculated from the reduction in enthalpy provides **absolute validation** of Margules' approach.

The work produced when large air masses change positions can be calculated using Carnot efficiency by calculating the average temperatures at which heat has to be supplied and removed to restore the initial condition.

Work in the air masses initially side by side case is half as much as work in the air masses initially on top of one another case because half as much air is raised, and not because of horizontal distance.

In order to see the relation between temperature and work the system must be simple

- One dimensional,
- Isolated,
- Close, Uniform entropies,
- Simple change of condition.

Once the significance of Carnot efficiency is realized, reduction in enthalpy results can be verified in more complex situations by calculating the average temperature at which heat has to be supplied and removed to restore the initial condition.
See Michaud: Thermodynamic Cycle…

What does it mean? (2)

Margules' **closed thermodynamic system (CTS)** method is based on conservation of energy.

Other methods of explaining the energy of the wind include:

1. Isentropic **rearrangement to a reference state** that minimizes total enthalpy,
    - System with a horizontal gradient – Arakawa and Schubert
    - One dimensional column – Randall
2. **Carnot Engine** without the explicit use of close system – Emanuel, Renno.
3. **Equation of Motion (EOM)** dynamic models.
4. **Convective Available Potential energy (CAPE)** – Acceleration of buoyant rising air mass.

Without rigorously defined thermodynamic system, results of rearrangements and of the Carnot Engine method can not be independently verified.

Equation of Motion models are verified by their ability to match observation, But a small change in initial conditions of a model parameter can have major Effect on development making validation difficult.

CAPE does not consider work of expansion and compression.

What does it mean? (3)

Margules' closed thermodynamic system method (CTS) and the equation of motion (EOM) method are both based on constant entropy processes. The CTS method is able to answer many questions that are difficult to answer with EOM method.

The CTS method unequivocally shows work production results from upward heat transport and not from horizontal heat transport, but the fact that work is produced in the case where air masses initially side by side are re-arranged was used to justify that theory that horizontal heating gradients are responsible for producing energy .

What does it mean? (4)

The Margules method yields efficiencies of approximately 15% because the atmosphere receives and gives heat at average temperatures of 290 K and 250 K respectively.

Margules obtained lower results because his layers only extended up a few kilometers.

The heat transported upward by convection averages 150 W/m^2 therefore the work is approximately 25 W/m^2.

Estimates of the efficiency of the atmosphere range from 0.01% to 15%!

Where does the mechanical energy go?

The Margules method is silent about what happens to the mechanical energy.
The mechanical is presumed to somehow increase the kinetic energy of the air.

In order to understand what happens to the mechanical energy it is necessary to examine at specific reversible processes.

The specific reversible process does not have to correspond to the real world because all reversible processes produce the same quantity of work.

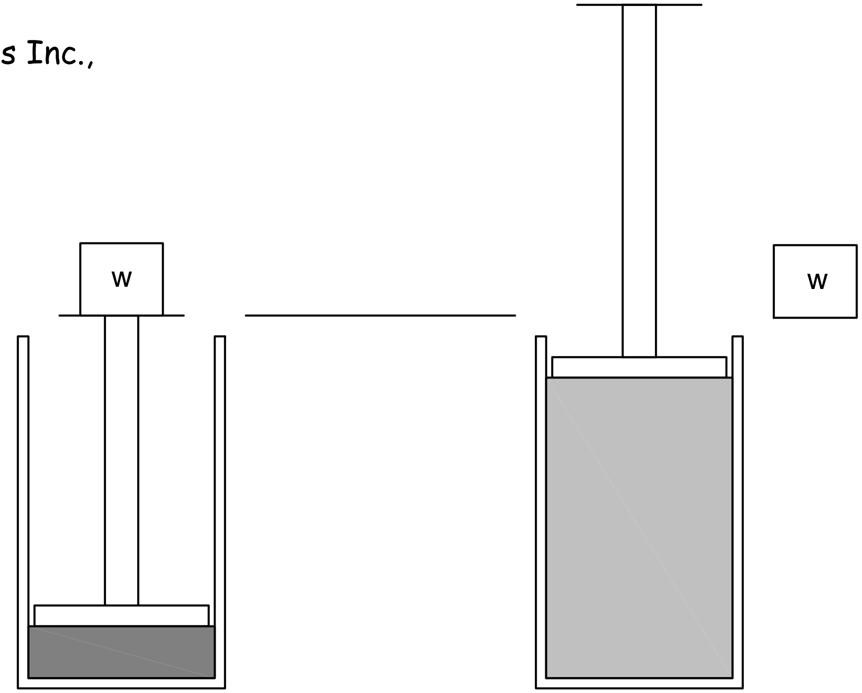
The Margules only works for reversivble processes; there is no way of analyzing irreversible processes.

With specific processes, the effect of irreversibility can easily be investigated
By replacing reversible operations (turbines) with irreversible operations (restrictions).

The next section examines what happens to the mechanical energy.

Van Ness: "Understanding Thermodynamic"
Concept of reversibility chapter

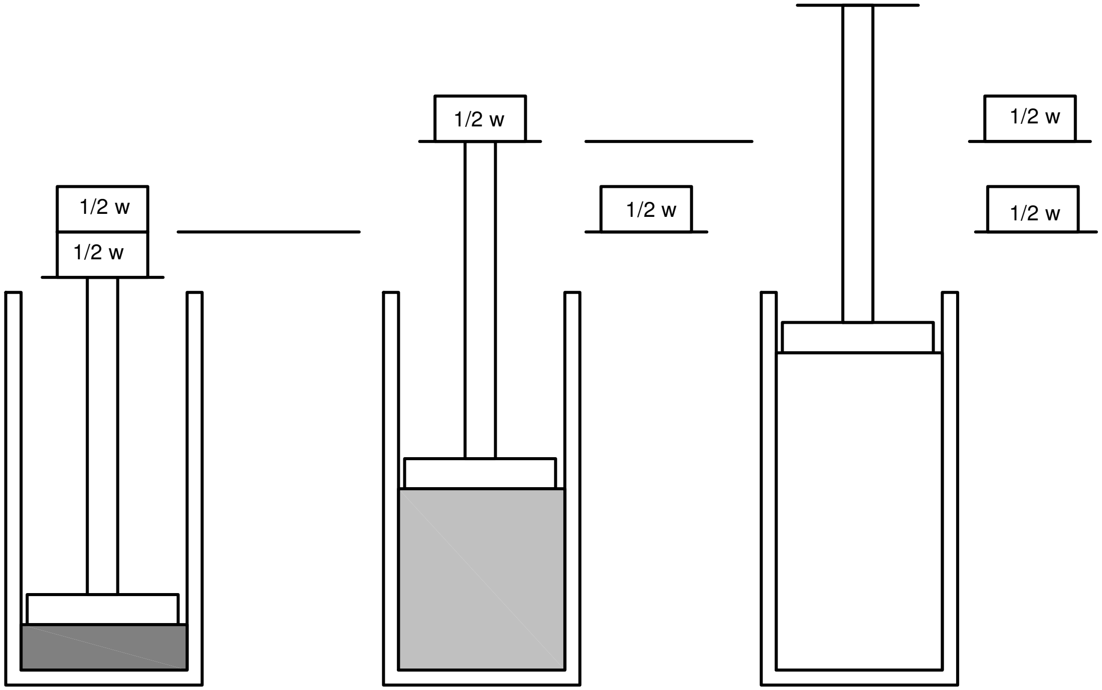
Reference: Van Ness, H.C., 1969:
Understanding Thermodynamics. Dover Publications Inc.,
New York, Pages 17-25.
http://vortexengine.ca/misc/Van_Ness.pdf



Initial condition   Final condition

Van Ness Figure 1
The whole weight is slid off the piston at once.
No work is done.
None of the weight is lifted.

Van Ness Figure 2



Initial condition Intermediate condition Final condition

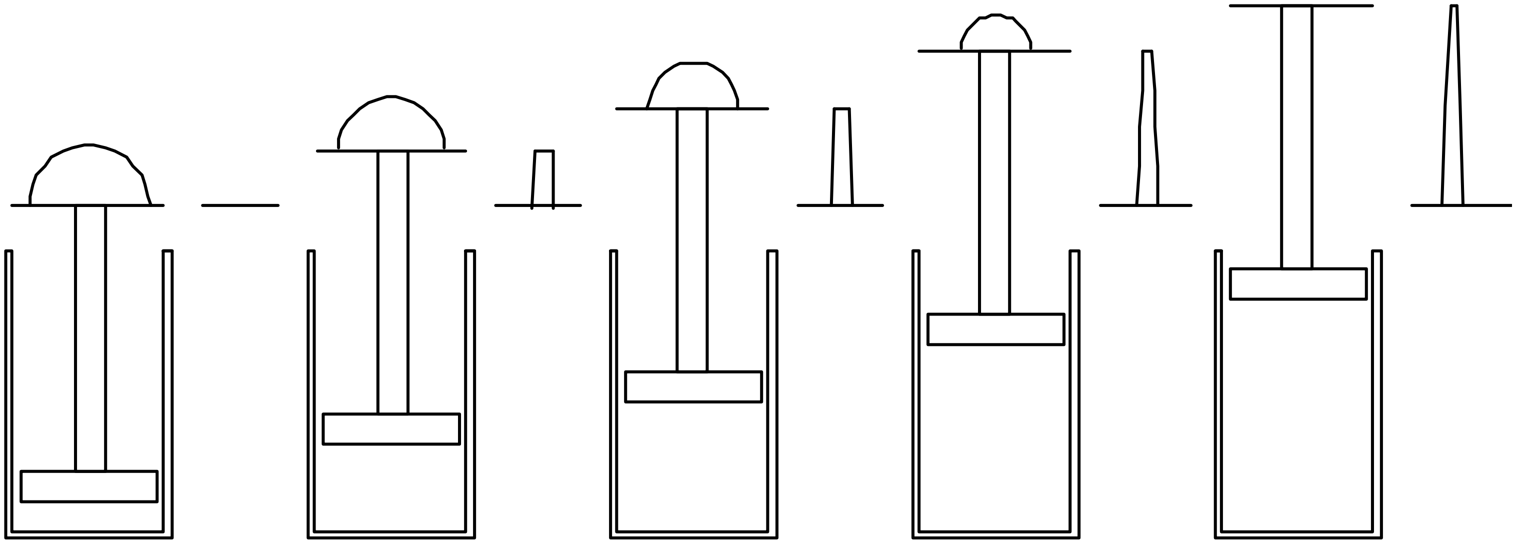
Van Ness Figure 2

Weight is slid off half at a time.

Work is done.

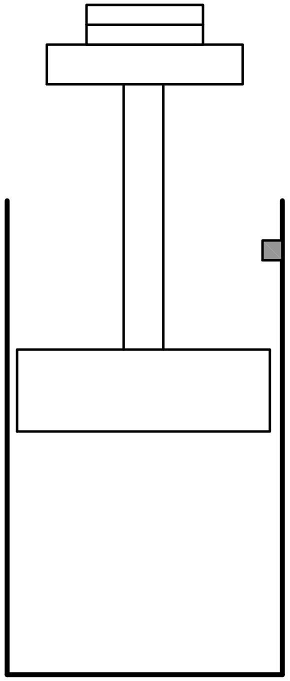
Approximately half of the weight is raised half the height.

Van Ness Figure 3



Van Ness Figure 3
Sand is slid off one gain at a time.
The maximum work possible is done.
All the sand is raised approximately half the height.
The process is at mechanical equilibrium and is reversible.

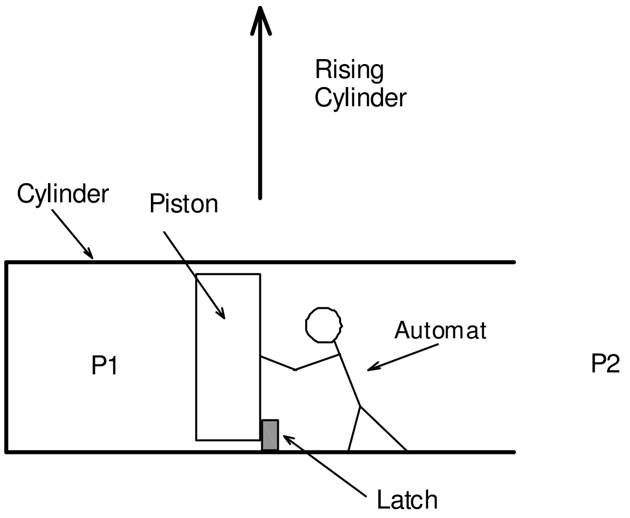
Van Ness Isentropic/Isenthalpic Expander



- Maximizing work production requires that the force acting on the piston be gradually reduced. The process is reversible.

- Suddenly sliding the weight off the piston and letting the piston slam against the latch, lift no weight and produces no work. The process is irreversible.

Reversible Expansion and the Automat



Rising Horizontal cylinder

Air rises in a weightless cylinder with a latched piston.

When the latch is let go, the work required to push away the ambient air is less than the work that could be produced by isentropic expansion, therefore the excess work becomes heat.

Capturing the work requires that the expansion take place in mechanical equilibrium.

Without the automat to capture the work any work beyond the work required to push the ambient air away is lost.

Rising cylinder expansion can be of three kinds

Expansion of pure air initially at 100 kPa and 30 C to 95 kPa.

A. Isentropic expansion: T2=25.6 C, W=4431 J/kg
B. Unlatch against 95 kPa: T2=26.63 C, W=3384, Wloss=1047 J/kg
C. Unlatch against 0 kPa: T2=30 C, W=0, Wloss=4431 J/kg

B is equivalent to popping a balloon. No organized velocity is produced; the POP sound provides indication of the work dissipation.

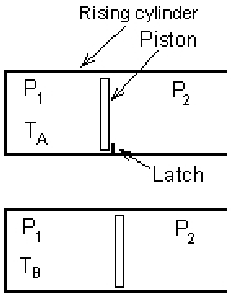
B is what happens to a rising air mass. If there is no mean for capturing the work while the air expands, the work reverts to heat.

Approximately 20% of the work that would produced with isentropic expansion is lost irrespective of the change in pressure.
I.e. 20% of the work would be lost if the pressure change had been from 100 to 99.9 kPa.

Work loss form lack of mechanical equilibrium calculation

Initial Condition

Final Condition



Reversible Expansion

$T_{BR} = T_A (P_2 / P_1)^k$ where $k = R / C_p = 2/7$

$W_R = c_p(T_A - T_{BR})$

Irreversible Expansion

$T_{BI} = T_A (k (P_2 / P_1) + 1) / (k + 1)$ from $\Delta h = P_2 (\Delta V)$

$W_I = c_p(T_A - T_{BI})$

Loss Work

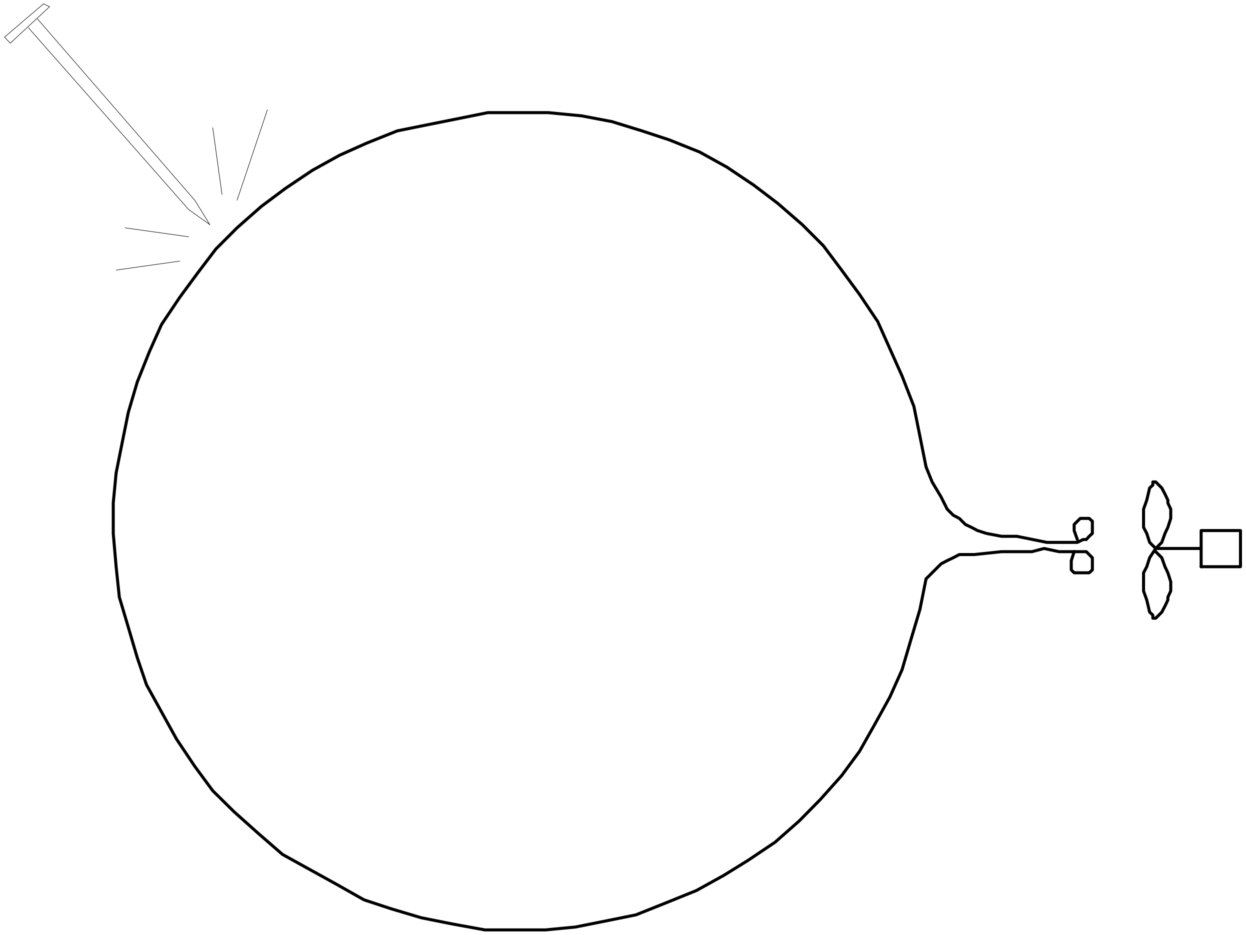
$W_{loss\%} = 100 (W_R - W_I) / W_R$

$W_{loss\%} = 100 ((k R + 1)/(k + 1) - (R)^k) / (1 - (R)^k)$ where $R = P_2 / P_1$

Limit $W_{loss\%}$ as R approaches 1 is 22.2%

Therefore 22.2 % of the work that would be produced if the expansion were carried out at mechanical equilibrium is lost as the cylinder is raised irrespective of how small the friction between the cylinder and piston.

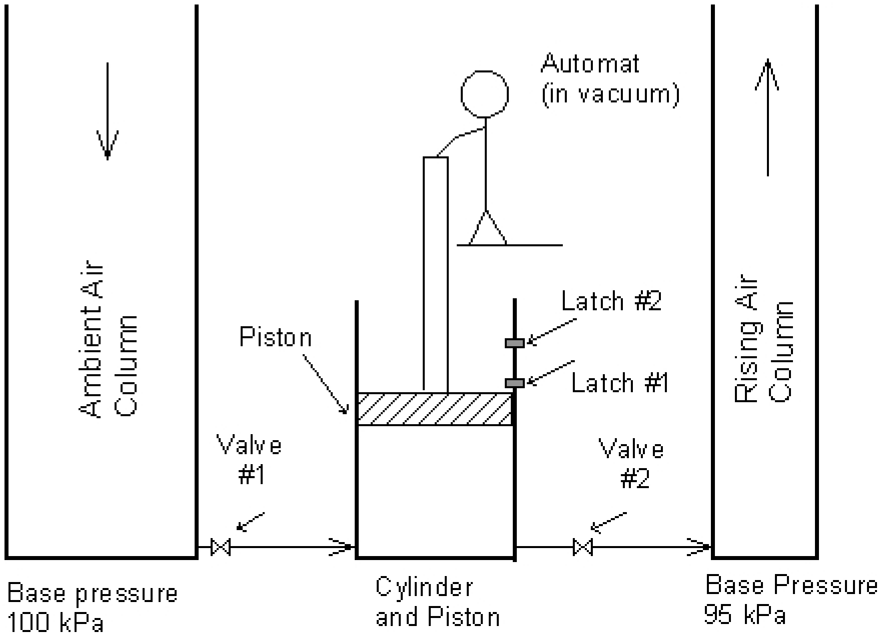
Energy dissipation when the balloon is punctured – Poption?



POP

What happens to the kinetic energy of the jet which could be captured by the turbine if the balloon is punctured?

Mechanism permitting Constrained or Unconstrained air transfer



Constrained reversible transfer - Efficiency 10 to 30% (no latch)

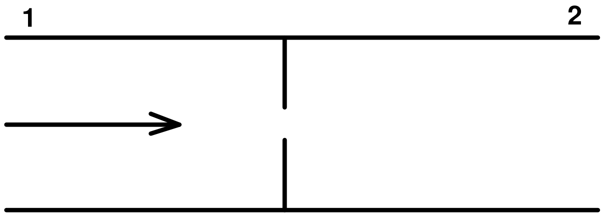
1. Start with piston at bottom of the cylinder, open valve #1,
2. Automat raises piston and let 1 kg of air at 100 kPa in cylinder,
3. Close valve #1,
4. Automat raises piston until cylinder pressure decreases to 95 kPa,
5. Open valve #2,
6. Automat pushes piston to the bottom of the cylinder.

Note: air temperature decreases - work is produced.

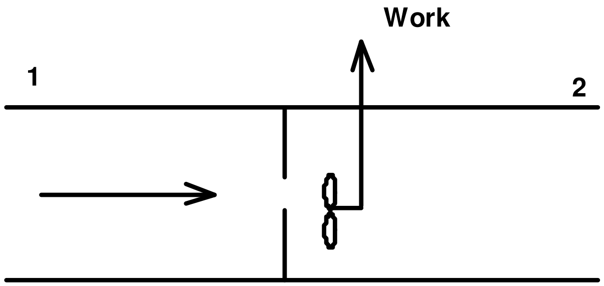
Unconstrained irreversible transfer- Efficiency 0% (2 latches)

As above except after step 3. set latch #1 and #2.
Automat lets go of the piston, release latch #1, piston snaps against latch #2 without doing any work.
Note: Position latch #1 to hold piston in place; position latch #2 so that the final pressure is 95 kPa by trial and error.
Note: Air temperature does not decrease - no work is produced.

Expander Types



Isenthalpic Expander $h2 = h1$, $T2 = T1$



Isentropic Expander $s2 = s1$

Results of not using reversible process

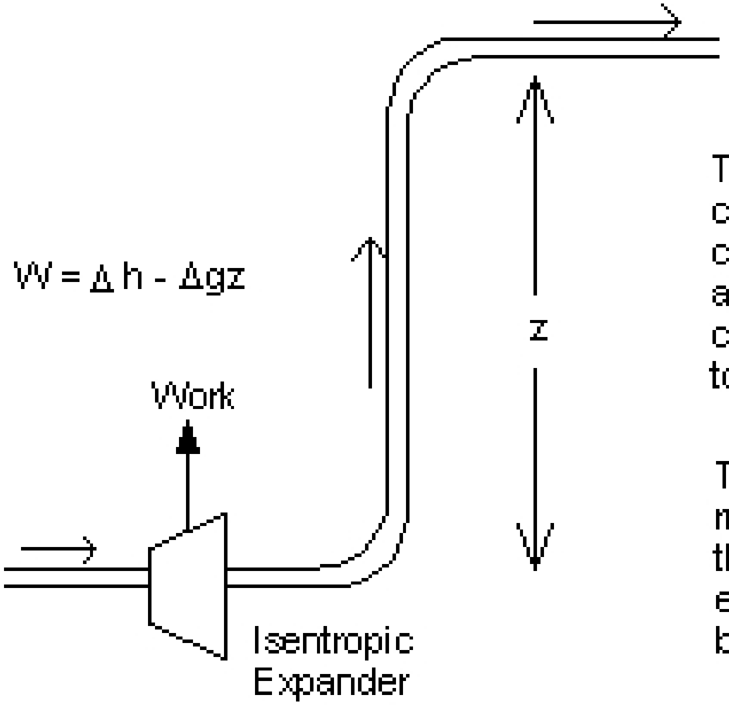
- Unrestrained expansion is less well recognized as a source of energy dissipation than frictional dissipation.

- Reversible systems are the only one for which energy calculations can be done. The alternative is likely to be no calculation at all. (H. Van Ness)

- Atmospheric science is generally unwilling to consider ideal machines or closed system.

- Unrestrained expansion agitates the molecules to the point where any work which would be produced dissipates (irrespective of gas viscosity!).

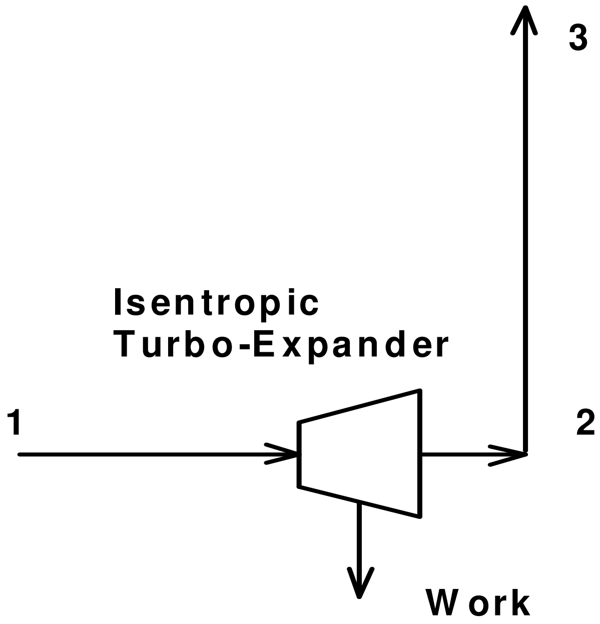
Work Tester



The Margules method confirms that the work that could be produced when air is lifted isentropically can be calculated using the total energy equation.

The total energy equation method does not require that the air masses have uniform entropy or that the system be closed.

Isentropic Lifting



Isentropic Lifting

$s3 = s2 = s1$

$T3 < T2 < T1$

$Work = h1 - h2$

$h3 = h2 - gz$

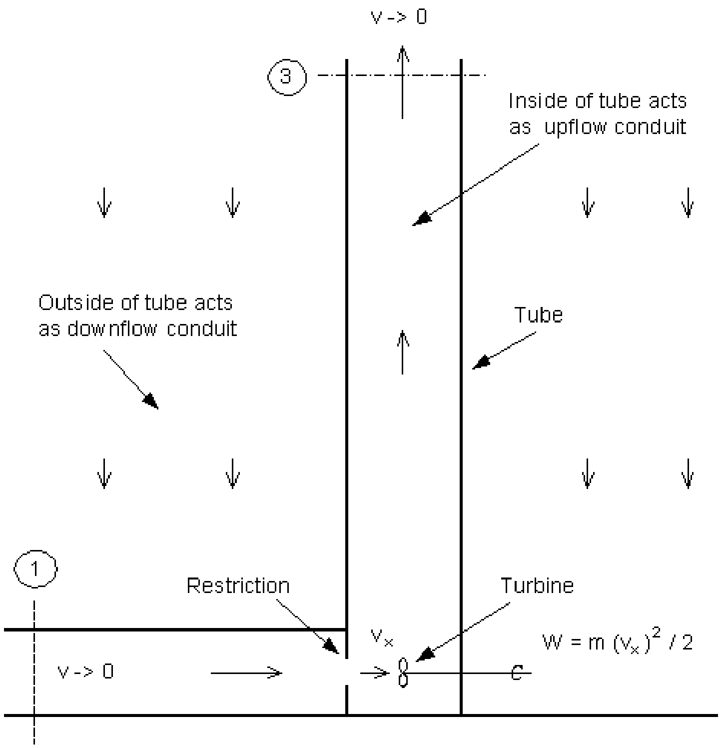
- Isentropic lifting requires an isentropic expander (except in the special case where W=gz).

- Isentropic expansion is widely used in meteorology.

- Isentropic expansion implies that work has been produced and taken out of the system.

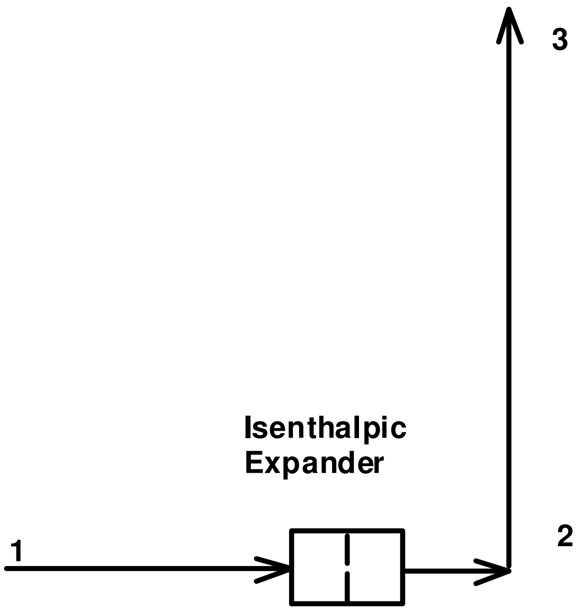
- No shaft, no isentropic expansion.

Single Tube System



Single tube gravity cycle.
The inside of the tube acts as the upflow conduit.
The outside of the tube acts as the downflow conduit.
The cross sectional area of the conduit has no effect on ideal cycles because the velocity is assumed to approach zero except at the turbine.

Isenthalpic Lifting



Isenthalpic Lifting

$\text{Work} = 0 = h1 - h2$

$s2 > s1, \ s3 = s2$

$T2 = T1, \ T3 < T1$

$h3 = h2 - gz$

If there is no work taken from the system (no shaft), entropy must increase.

Static energy (h+gz) is what is conserved.

The isenthalpic expander is not esential. A plain tube without an isentropic expander is all that is necessary for the expansion to be constant a constant static energy one.

(Adiabatic lifting with no mixing assumed in both cases)

Atmospheric consequences (1)

The kinetic energy of the wind is a only fraction of the work that would be produced if the expansion occurred at mechanical equilibrium.

Most of the potential work is dissipated because the expansion is not carried out at mechanical equilibrium.

Significant horizontal winds is only produced:

- when equilibrium requires that heat be carried horizontally as well as vertically.
- or when the expansion work is transmitted downward by the chimney effect of a convective vortex.

Atmospheric consequence (2)

If the work is not captured during the expansion, it is inexorably lost.

The motion produced as a result of density differences represents a small fraction of the mechanical energy that could be produced.

Calculating wind using equation of motion models can never find the work lost as a result of unrestrained expansion.

The work loss as a result of unrestrained expansion is lost irrespective of whether the expansion is considered to be reversible (isentropic) or irreversible (constant static energy).

Atmospheric consequences (3)

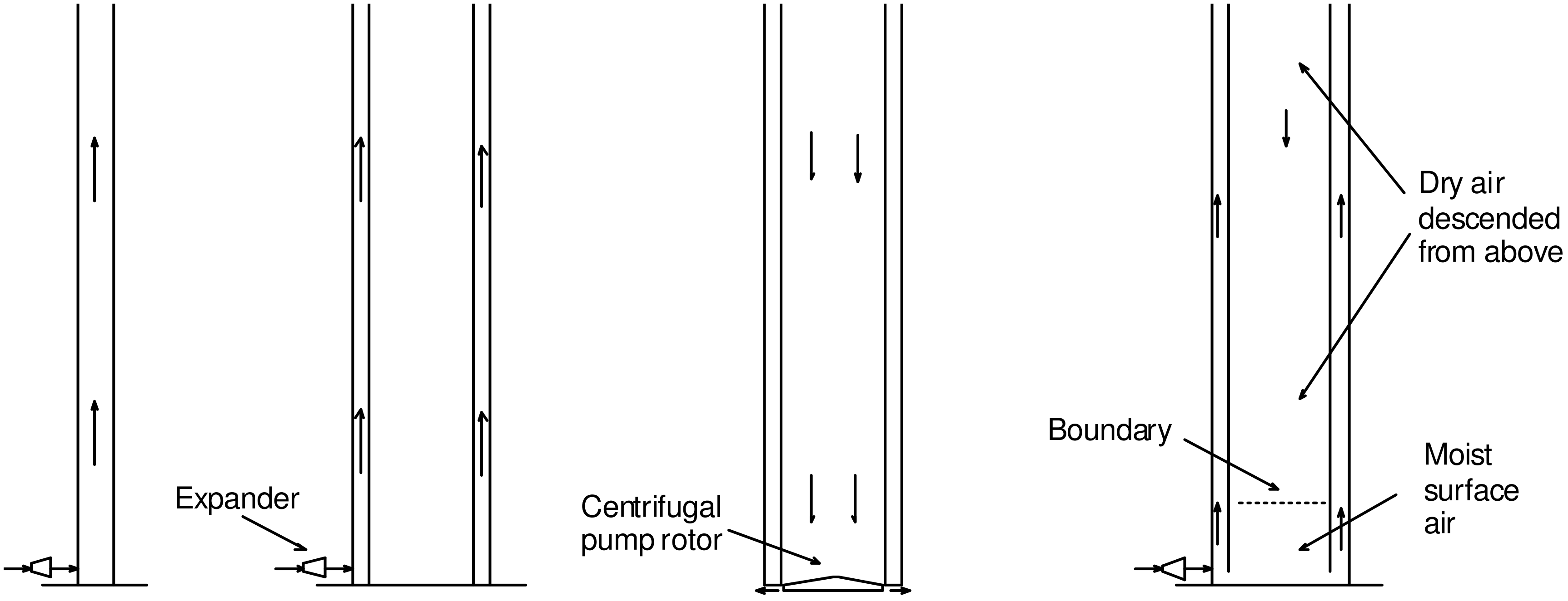
The usual meteorological isentropic expansion implies that work leaves the system which it does not.

The expansion cannot be isentropic when there is no shaft to take the work out of the system.

If there is no shaft the expansion has to be at constant static energy, $h + gz = \text{constant}$.

The fact that atmospheric flow can occasionally be sufficiently organized to approach mechanical equilibrium makes atmospheric motion difficult to predict.

Annular Tube



Circular upflow tube

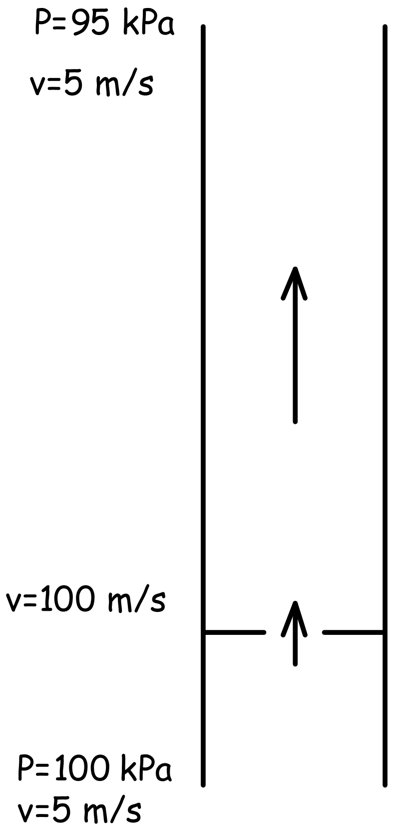
Annular outer upflow tube

Circular inner downflow tube

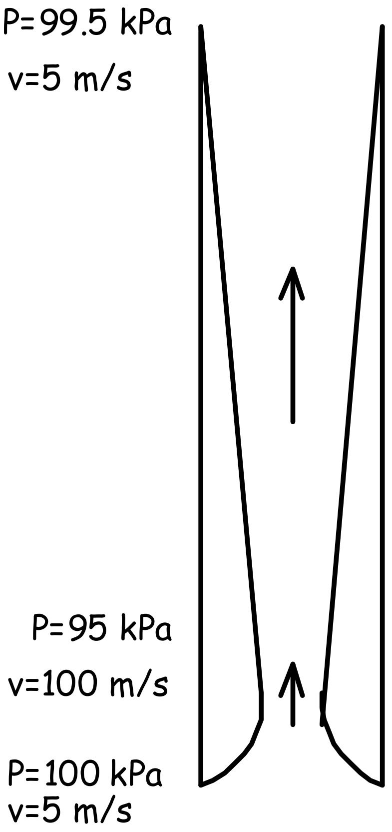
Dual tubes outer upflow inner static

A vortex as a dual annular tube

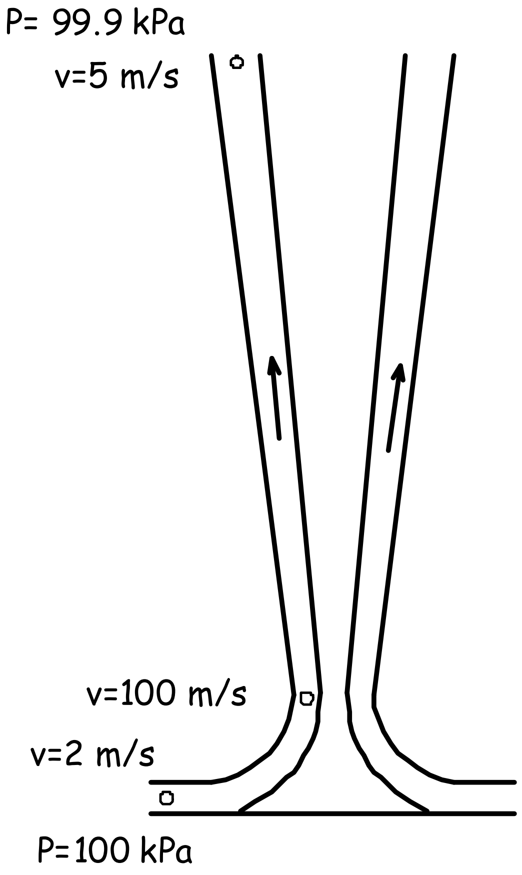
Recovery



Orifice

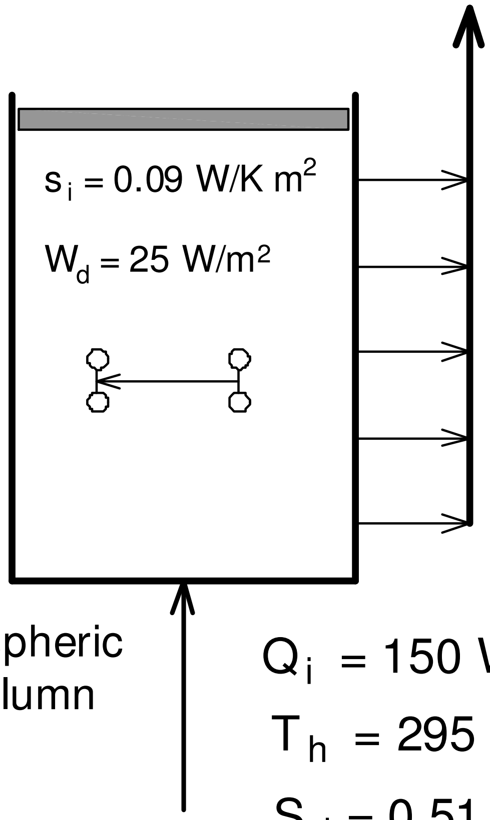


Venturi



Annular Tube

Internally Generated Entropy



$s_i = 0.09$ W/K m^2

$W_d = 25$ W/m^2

$Q_o = -150$ W/m^2

$T_c = 250$ K

$S_{eo} = -0.60$ W/K/m^2

Heat out
1.5 C/d

Atmospheric
Air Column

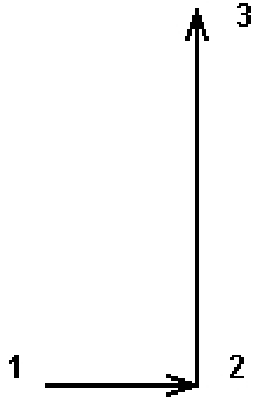
$Q_i = 150$ W/m^2

$T_h = 295$ K

$S_{ei} = 0.51$ W/K m^2

Heat in

Three types of continuous lifting processes

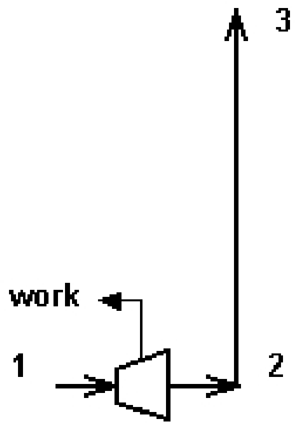


USUAL

Isenthalpic Lifting

h3 = h2 - gz
s3 > s1

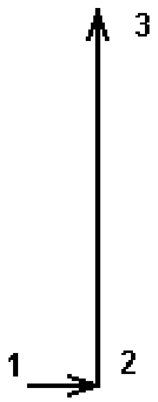
Irrespective of where dissipation occurs. Irrespective of whether of whether dissipation is due to resistance to flow or unrestrained expansion.



APPROCHABLE

Isentropic Lifting
s3 = s2 = s1
w = h1 - h2

Requires an isentropic expander. Requires a shaft to get the work out of the system.



IMPOSSIBLE

Isentropic Lifting
s3 = s2 = s1
w = 0

Isentropic expansion without device for taking work out of the system is impossible except in one case (w=0).
It is the basis of most atmospheric models.

Water Analogy

- Dissipation of energy in the atmosphere is analogous to dissipation of the potential energy of water.

- The potential energy of water on a high plateau gets dissipated irrespective of whether the water returns to the sea in a long meander or in a short single drop.

- The only way that the potential can be captured is to provide a dam and a turbine to make the descent take place at mechanical equilibrium.

- Without the turbine, the static energy of the water is constant and the enthalpy and the entropy of the water increases.
- With the turbine, the enthalpy and the entropy of the water are constant, the static and potential energy of the water decrease .

(assumes an adiabatic process and an ideal liquid with no vapor pressure)

Rock Analogy

- A rock at the top of a high mountain has potential energy.
- Tossing the rock off the mountain is not sufficient to capture this potential energy.
- Capturing the potential energy requires that there be a "mean" for carrying out the descent at mechanical equilibrium.
- Without the "mean" there is no mechanical equilibrium which leads to agitation and eventually frictional dissipation.
- Without a "mean" to at least approach mechanical equilibrium, potential energy reverts to heat somehow or other.

- Without a "mean" the potential energy of a rock dropped in the sea is lost.

- Without a "mean" the potential energy of a buoyant air mass or of an air having the potential of becoming buoyant is lost.

Intelligible Simplification

- The rise of a helium filled balloon demonstrates that the balloon had potential energy.
- Releasing the balloon is not sufficient to capture this potential energy.
- Capturing the energy requires a mechanism such as:
  - attaching a weight to the balloon,
  - or having the helium rise in a continuous conduit with an expander at its base.

- Solar heating or humidification produces buoyant air or air that has the potential of becoming buoyant.
- With natural convection, the potential energy is lost.
- Capturing the potential energy requires a mechanism for carrying out the process at mechanical equilibrium,

i.e.: <u>a conduit with an expander</u>.

Giant with a Straw simplification

Suppose that there is a giant with a 15 km straw and that the giant puts the lower end of the straw close to the earth's surface.

The giant sucks on the straw and fills with warm humid air from the boundary layer, the air in the straw becomes warmer than the ambient air.

When the giant takes his mouth off the end of the straw the upward flow continues. It is like starting a siphon.

The upward flow can be stopped by either lifting the bottom of the straw out of the boundary layer or by making holes in the straw above the boundary layer.

Rather than trying to calculate the upward velocity, close the bottom of the straw and calculate the differential pressure at the bottom of the straw. Provide a small opening at the bottom of the straw with an isentropic expander, keeping the velocity in the straw low so that friction and exit losses remain negligible.

This ideal process makes the energy produced per unit mass of air raised easy to calculate.

Review

There is a potential to do work when heat is carried up by convection in the atmosphere.

The extent to which this potential is realized is proportional to the extent that the expansion is constrained, to the expansion taking place at mechanical equilibrium.

There is potential to produce 25 MW/km^2. The work produced as a result of heat received over a long period can be produced in a short time.

The work resulting from heat received over a large area over a long period of time can be produced in a much shorter period of time.