Physical Meteorology 1

Lecture 7

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Thermodynamics

SOME DEFINITIONS:

THERMO – related to heat

DYNAMICS - the study of motion

SYSTEM – an object or set of objects ENVIRONMENT – the rest of the universe

MICROSCOPIC – at an atomic or molecular level

MACROSCOPIC - at a level detectable by our senses





THERMODYNAMICS

➤ is the study of the relationship between heat and motion.

✓ is a macroscopic description of the properties of a system using state variables (e.g. volume, temperature, pressure)

Atoms are in constant motion, which increases with **temperature**.

Dry Air Thermodynamics

Thermodynamics is a branch of physics that deals with the energy and work of a system

The primary focus is on the relation between internal and mechanical energy.

Expansion of the gas at constant pressure



Specific volume, *a*, is the volume occupied by 1.0 g of air.

dW = PdV $\alpha = V/m = 1/\rho$ $dw = Pd\alpha$



Internal energy of an ideal gas

Two conditions are necessary for a perfect gas:

1) $P\alpha = RT$

2) U = f(T)

Internal Energy

The temperature of an object reflects an internal energy of the object. This is opposed to the external energy of an object (such as kinetic energy).

Different objects may be at the same temperature but have vastly different amounts of internal energy. To move between temperature and energy, we must know the heat capacity of the object.

Internal Energy = Heat Capacity × Temperature

$$du = c_V dT$$

Heat Capacity

- Internal energy change, du, is usually seen as a change in temperature.
- The temperature change is proportional to the amount of heat added.

dT = dh/c

Where c is the specific heat capacity.

$$c_p = c_v + R$$

Specific heat of dry air

The amount of heat required to raise the temperature of a unit mass of gas equals one degree.

$$c_{pd} = 1005 \ Jkg^{-1}K^{-1} \qquad c_{vd} = 718 \ Jkg^{-1}K^{-1}$$
$$R_d = c_{pd} - c_{vd} = 287.05 Jkg^{-1}K^{-1}$$
$$R_d = \frac{R^*}{M_d} = \frac{8314}{28.964} = 287.05 Jkg^{-1}K^{-1}$$

 $p \alpha = R_d T$ Equation of state for dry air

The First Law of Thermodynamics $\mathcal{AH} = \mathcal{AU} + \mathcal{AW}$ heatchange inworkaddedchange inworkenergyenergy

dh = du + dw

 $dh = du + pd\alpha$ The Energy Equation $dh = c_V dT + pd\alpha$

Definitions

• ADIABATIC - A process in which heat is neither added nor subtracted from the system.

• **DIABATIC** - A process in which heat is added or subtracted from the system, e.g., solar heating, radiation cooling.

Adiabatic Processes

 Heat can be added to parcel by many processes (radiation, friction, condensation of water vapor, turbulent transfer of heat), however...



$dh = du + Pd\alpha$

Processes in which no heat (dh) is added or withdrawn from a system (Parcel), so that her change in temperature is a result of expansion and compression





Therefore, there is value in applying the First Law of Thermodynamics for *adiabatic processes*

 $du = -Pd\alpha$



Many processes in the atmosphere are dry adiabatic





Volume at t_i

Volume at t_f



1) $dW > 0 \rightarrow du < 0 \rightarrow dT < 0$ 2) $dW < 0 \rightarrow du > 0 \rightarrow dT > 0$

Potential Temperature

$$T = cons. \times P^k \quad k = R / c_p$$

 $\frac{\theta}{1000^k} = \frac{T}{p^k} = cons. \qquad \theta = T(\frac{1000}{p})^k$

Potential temperature, Θ , is a conserved quantity in an adiabatic process.

the temperature a parcel would have if moved to the 1000 hPa level in a dry adiabatic process.

Potential temperature can act as a tag or air tracer



Potential temperature can act as a tag or air tracer



Differentiating

$$d(pa) = pda + adp = Rd$$

pda = RdT - adp

From the First Law of Thermo for an ideal gas:

 $dh = c_v dT + p da *$

$$dh = c_v dT + R dT - a dp$$

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But $c_p = c_v + R$ $dh = c_p dT - \alpha dp^{**}$

Let us consider four special cases

If a process is conducted at constant pressure then dp = 0.

1) For an isobaric process:

$$dh = c_p dT - adp$$
$$dh = c_p dT$$
$$dh = c_p dT + pda$$



If the temperature is held constant, dT =

2) For an isothermal process:

$$\frac{dh = c_p dT - adp}{dh = -adp = pda = dw}$$





Volume and pressure change

If a process is conducted at constant density then

$$d\rho = d\alpha = 0.$$

3) For an isosteric process:





Temperature changes

If the process proceeds without exchange of heat with the surroundings dh = 0.

4) For an adiabatic process:

$$c_{\nu}dT = -pda$$
 $c_{p}dT = adp$

• Adiabatic (isolated - no heat input)

p V V V V V V V

Volume, pressure and temperature change





Most atmospheric temperature changes are adiabatic. For an adiabatic process:

$$c_{v}dT = -pda \qquad c_{p}dT = adp$$
$$du = dw$$

Remember a = RT/p thus

 $c_p dT = RT/p dp$ Separating the variables and integrating $c_p/R \int dT/T = \int dp/p$

 $c_p/R \int dT/T = \int dp/p$

If we define a reference pressure of 1000 hPa (mb) then

$$\ln\frac{\theta}{T} = \frac{R}{c_p} \ln\frac{1000}{p}$$

P, T are initial pressure and temperature.

 $\theta = T (1000/p)^{0.286}$

Entropy

- Some processes that do not violate the first law of thermodynamics (conservation of energy) will neveroccur spontaneously.
- Entropy (S) is a measure of the disorder in a system, and is a state variable (like P,V,T) that does not depend on the path taken.



Entropy and Reversible Processes

For any **reversible process** (e.g. Carnot cycle):

$$\oint \frac{dQ}{T} = 0$$

$$\int_{Ia}^{b} \frac{dQ}{T} + \int_{IIb}^{a} \frac{dQ}{T} = 0$$

$$\int_{I}^{b} \frac{dQ}{T} = -\int_{II}^{a} \frac{dQ}{T} = \int_{II}^{b} \frac{dQ}{T}$$



The entropy of a system in a given state is independent of the path taken to get there, and is thus a **state variable**.

Entropy and Disorder

• Entropy is a measure of the disorder of a system.

 All real systems tend to disorder - i.e. the entropy of the universe always increases in irreversible processes.

The Second Law of Thermodynamics

 $ds \equiv dh/T$

Where s is defined as entropy.

$$dh = c_p dT - adp$$

 $ds=dh/T=c_p dT/T - (R/p)dp$

$$\oint dh/T = \oint c_p/TdT - \oint (R/P)dp$$

$\oint dh/T = \oint c_p dT/T - \oint R dp/p$ But $\oint c_p dT/T = 0$ and $\oint Rdp/p = 0$

Because T and p are state variables; Thus:

 $\oint ds = 0$ Entropy is a state variable.

Dry adiabatic process $\frac{ds}{T} = \frac{dh}{T}$ $\theta = T(\frac{1000}{\ldots})^k$ $k = R / c_n$ $\ln \theta = \ln T + k \ln 1000 - k \ln p$

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Thanks for your attention



Any Question?