Understanding High-Altitude Balloon Flight Fundamentals

Hank D. Voss[1], Natalie A. Ramm[2] and Jeff Dailey[1]
Taylor University, Upland, IN, 46989

For effective research and teaching it is vital to understand the physics of balloon flight. Starting with the basic equations of motion in a viscous fluid a relationship is obtained relating the ascent velocity to the balloon size and gas parameters, to the atmospheric parameters, and to the fluid flow viscosity parameters (coefficient of drag and Reynolds number). In addition, the differential thermal heat transfer is important for understanding lift particularly around the tropopause region where the ascending balloon gas is expanding (and cooling) while the external stratospheric temperature is increasing. The detailed equations of motion are fundamentally based on the more complex thermodynamic and fluid dynamic equations with aerodynamic forces and balloon shape changes from a sphere. Theoretical data are compared with several balloon flights where a special internal probe within the balloon is used to measure heat transfer. A dynamic Excel database is available based on these equations and available constants to help predict and understand the balloon flight and the atmospheric environment. From the physical understanding of the balloon physics the ascent rates, fluid properties, and heat transfer can be used for making new measurements and improving STEM teaching.

Nomenclature

A_b	=	Surface area of the balloon (m^2)
A_c	=	Cross sectional area (m^2)
C_d	=	Coefficient of drag
F_d	=	Force due to atmospheric drag
F_{lift}	=	Lifting force of the gaseous fill in the balloon (N, lb_f)
FL	=	Free lift (kg)
g	=	Gravity
h_c	=	Convective heat transfer coefficient
k	=	Thermal conductivity
M_a	=	Molar mass of air. (28.96 g/mol)
M_g	=	Molar mass of gas. Helium: 4.0026 g/mol, Hydrogen gas (H_2): 2.0158 g/mol
m_g	=	Mass of gas (kg)
m_{tot}	=	Total mass: Includes payload, balloon, and ballast masses
n	=	Moles = mass/Molar mass
P	=	Pressure
P_a	=	Atmospheric pressure. (atm, Psi)
P_g	=	Pressure of gas. (atm, Psi)
ρ_a	=	Mass density of air (kg/m^3)
ρ_g	=	Mass density of gas (kg/m^3)
Q	=	Heat
R	=	Gas constant. $8.206 \times 10^{-5} \frac{\text{m}^3\text{atm}}{\text{mol K}}$
T	=	Temperature
t	=	Time
T_a	=	Temperature of atmosphere. Kelvin (K) and Celsius (°C)
T_g	=	Temperature of gas. Kelvin (K) and Celsius (°C)
V	=	Volume
V_b	=	Volume of balloon (m^3)
v_b	=	Velocity of balloon (m/s)

[1] Professor, Department of Physics and Engineering, 236 W. Reade Ave, . [2] Student Physics, 236 Reade Ave.

I. Introduction

To improve education and understanding of high-altitude balloon flight it is important to consider the interrelated and fundamental balloon flight physics. Understanding flight physics combines classical dynamics, thermodynamics, electromagnetic (EM) radiation balance, fluid dynamics, and stability to optimize experiments and improve learning in the study of this relatively unexplored troposheric and stratospheric regions. Researches and students have the opportunity to learn much as they relate this environment and technology to the disciplines of physics, engineering, chemistry, astronomy, aeronomy, meteorology, biology, ecology, environmental science, and education.

Reviews of scientific ballooning are presented by Morris (1975)[1], Brock and Richardson (2001)[2], Yajima et al. (2009)[3]. Remarkable benefits of Ballooning include: Atmospheric *insitu* research, Space Weather sensing, testing spaceflight hardware above 99% of atmosphere, develop new researches with inspiring education with investment the future [4], remote sensing instruments for earth and space, cargo transportation, communication links, energy platforms, and other benefits. Furthermore scientific ballooning is low cost with short preparation times, has a fast turnaround with reuse capability, is now expanding with the miniaturization of technology, has flexible launch sites, high data rates, heavy payloads, and long flight times compared to rockets.

II. Balloon Data and Standard Atmosphere Data

To better understand the atmosphere and balloon flight there are a number of very useful software programs for available the include the Atmospheric Properties Calculator, The Totex balloon calculator, and a new Data Base Program being developed at Taylor University.

A. Atmospheric Properties Calculator

The Atmospheric Properties Calculator (by Aerospaceweb.org , Version 2.1.4, released August 2005)[5] is based on US Standard Atmosphere[6] 1976. The Table 1 below is mainly based on the data from this calculator.

Table 1 Representative Atmospheric Properties

						Atmosphere and Balloon Properties												v= 5.1 m/s				
Altitude	Altitude	Temp a	Temp	Density	Pressur	Pressure	Speed	Dynamic	Kinematic	Air	Collision	Mean Free	Mole	Thermal	Pressur	Density	Number	Reynolds #	Balloon	Reynold	Lamina	Turbulent
							Sound	Viscosity	Viscosity	Speed	Frequenc	Path	Volumn	Conducti	Scal He	Scale H	Density	/Unit Leng	Diamete	Number	Bounda	Boundary
(km)	(ft)	(°C)	K	kg/m^3	(atm)	(Pa)	(m/s)	(Ns/m^2)	(m^2/s)	(m/s)	Hz (1/s)	(m)	$m^3/kmol$	J/(m s K)	km	km	$1/m^3$	1/m	m		cm	cm
0	0	15	288.2	1.225	1	101,325	340	1.79E-05	1.46E-05	459	6.92E+09	6.63E-08	23.64	0.025	8.43	10.42	2.55E+25	3.49E+05	1.879	6.6E+05	1.206	4.833
2	6,562	2	275.2	1.0066	0.785	79,540	333	1.73E-05	1.71E-05	448	5.56E+09	8.07E-08	28.78	0.024	8.06	9.95	2.09E+25	3.49E+05	2.006	7.0E+05	1.351	5.259
4	13,123	-10.98	262.2	0.8194	0.609	61,707	325	1.66E-05	2.03E-05	438	4.41E+09	9.92E-08	35.35	0.023	7.68	9.49	1.70E+25	3.49E+05	2.148	7.5E+05	1.520	5.744
6	19,685	-23.96	249.2	0.6601	0.466	47,217	316	1.59E-05	2.42E-05	427	3.47E+09	1.23E-07	43.88	0.022	7.31	9.02	1.37E+25	3.49E+05	2.305	8.0E+05	1.718	6.294
8	26,247	-36.93	236.2	0.5258	0.352	35,666	308	1.53E-05	2.90E-05	416	2.69E+09	1.55E-07	55.09	0.021	6.93	8.56	1.09E+25	3.49E+05	2.479	8.7E+05	1.954	6.922
10	32,808	-49.9	223.3	0.4135	0.262	26,547	300	1.46E-05	3.53E-05	404	2.06E+09	1.97E-07	70.05	0.020	6.56	8.10	8.60E+24	3.49E+05	2.677	9.3E+05	2.237	7.651
12	39,370	-56.5	216.7	0.3119	0.191	19,353	295	1.42E-05	4.56E-05	398	1.53E+09	2.60E-07	92.85	0.020	6.37	6.37	6.49E+24	3.49E+05	2.930	1.0E+06	2.661	8.658
14	45,932	-56.5	216.7	0.2279	0.14	14,186	295	1.42E-05	6.24E-05	398	1.12E+09	3.57E-07	127.12	0.020	6.37	6.37	4.74E+24	3.49E+05	3.243	1.1E+06	3.275	9.999
16	52,493	-56.5	216.7	0.1665	0.102	10,335	295	1.42E-05	8.54E-05	398	8.15E+08	4.88E-07	173.99	0.020	6.37	6.37	3.46E+24	3.49E+05	3.595	1.3E+06	4.035	11.562
18	59,055	-56.5	216.7	0.1217	0.075	7,599	295	1.42E-05	1.17E-04	398	5.96E+08	6.68E-07	238.10	0.020	6.38	6.38	2.53E+24	3.49E+05	3.991	1.4E+06	4.973	13.384
20	65,617	-56.5	216.7	0.0889	0.055	5,573	295	1.42E-05	1.60E-04	398	4.35E+08	9.14E-07	325.77	0.020	6.38	6.38	1.85E+24	3.49E+05	4.431	1.5E+06	6.129	15.493
22	72,178	-54.58	218.6	0.0645	0.04	4,053	296	1.43E-05	2.22E-04	400	3.17E+08	1.26E-06	448.99	0.020	6.44	6.26	1.34E+24	3.49E+05	4.932	1.7E+06	7.619	18.024
24	78,740	-52.59	220.6	0.0469	0.029	2,938	298	1.44E-05	3.07E-04	402	2.32E+08	1.73E-06	617.08	0.020	6.50	6.32	9.76E+23	3.48E+05	5.484	1.9E+06	9.455	20.941
26	85,302	-50.61	222.5	0.0343	0.022	2,229	299	1.45E-05	4.24E-04	403	1.70E+08	2.37E-06	845.51	0.020	6.57	6.38	7.12E+23	3.48E+05	6.092	2.1E+06	11.708	24.296
28	91,864	-48.62	224.5	0.0251	0.016	1,621	300	1.46E-05	5.84E-04	405	1.25E+08	3.24E-06	1,155.10	0.020	6.63	6.44	5.21E+23	3.48E+05	6.761	2.4E+06	14.469	28.149
30	98,425	-46.64	226.5	0.0184	0.012	1,216	302	1.48E-05	8.01E-04	407	9.22E+07	4.41E-06	1,573.30	0.020	6.69	6.50	3.83E+23	3.48E+05	7.495	2.6E+06	17.845	32.565
32	104,987	-44.66	228.5	0.0136	0.009	912	303	1.49E-05	1.10E-03	409	6.82E+07	5.99E-06	2,136.80	0.020	6.76	6.56	2.82E+23	3.48E+05	8.302	2.9E+06	21.966	37.627
34	111,549	-39.41	233.7	0.0099	0.007	709	306	1.51E-05	1.53E-03	413	5.03E+07	8.22E-06	2,929.40	0.021	6.92	6.39	2.06E+23	3.48E+05	9.227	3.2E+06	27.370	43.775
36	118,110	-33.87	239.3	0.0073	0.005	507	310	1.54E-05	2.13E-03	418	3.74E+07	1.12E-05	3,990.70	0.021	7.08	7.08	1.51E+23	3.48E+05	10.233	3.6E+06	33.966	50.781
38	124,672	-28.33	244.8	0.0054	0.004	405	314	1.57E-05	2.93E-03	423	2.79E+07	1.51E-05	5,397.20	0.022	7.25	6.70	1.12E+23	3.48E+05	11.320	3.9E+06	41.933	58.697
40	131,234	-22.8	250.4	0.004	0.003	304	317	1.60E-05	4.01E-03	428	2.10E+07	2.03E-05	7,248.90	0.022	7.42	6.86	8.31E+22	3.48E+05	12.495	4.3E+06	51.520	67.626
			Most columns based on Atmospheric Properties Calculator (U.S. Standard Atmosphere 1976), Not for commercial use																			
			Last three columns based on balloon velocity of 5.1 m/s																			

B. Totex Balloon Data[7]

Table 2 Reference Totex Balloon Data

Balloon Weight (gr)	200	300	350	450	500	600	700	800	1000	1200	1500	2000	3000
Diameter at Release (cm)	117	123	125	130	133	142	146	150	157	179	185	195	212
Volume at Release (cu.m)	0.83	0.97	1.03	1.1	1.22	1.5	1.63	1.76	2.01	2.99	3.33	3.89	4.97
Gross Lift (gr)	960	1110	1185	1335	1405	1720	1870	2020	2310	3440	3830	4470	5720
Nozzle Lift (gr)	760	810	835	885	905	1120	1170	1220	1310	2240	2330	2470	2720
Payload (gr)	250	250	250	250	250	250	250	250	250	1050	1050	1050	1050
Recommended Free Lift (gr)	510	560	585	635	655	870	920	970	1060	1190	1280	1420	1670
Rate of Ascent (m/min)	320	320	320	320	320	320	320	320	320	320	320	320	320
Diameter at Burst (cm)	300	378	412	472	499	602	653	700	786	863	944	1054	1300
Volume at Burst (cu m)	14.1	28.3	36.6	55.1	65.1	114.2	145.8	179.6	254.3	336.5	440.5	613.1	1150.3
Bursting Altitude (km)	21.2	24.7	25.9	27.7	28.4	30.8	31.8	32.6	33.9	33.2	34.2	35.4	37.9

(http://ukhas.org.uk/guides:balloon_data)

"Its worth noting that the data above is based on the use of Hydrogen rather than Helium. The Balloon **Gross Lift** is the lift generated by the volume of Gas. Hydrogen has a density of about 0.09 kg/cu m and air about 1.2 kg/cu m at normal atmospheric pressure - generating a lift of a bit over 1.1kg/cu m. Helium has a density of about 0.17Kg/cu m - generating a lift of a bit over 1.0Kg/cu m. Subtract the **Balloon Weight** plus the **Payload** weight form the **Gross Lift** to give the *free lift*. The **Recommended Free Lift** gives a **Rate of Ascent** of 320m/min (a bit over 1000ft per minute). Heavier payloads can be carried than the values above - this will either reduce ascent rate, burst altitude (if the balloon is further inflated to compensate) or both. The following spreadsheet allows you to calculate the affect on burst altitude and ascent rates of various levels of fill and payload. To use: choose the balloon size and fill in the payload weight - then adjust the launch diameter until you get the desired ascent rate (normally about 320m/min) - the volume at launch will tell you how much gas you will need." guides:burst3.xls by Steve Randall

B. Balloon Launch and Burst Estimator[7]

Table 3 Modified Balloon Fill and Burst Estimator

Totex Balloon Burst Estimator – by Steve Randall- Modified Voss June 2012

Gas		Chosen gas density(Kg/m3)	Air density at 0C,101 kPa		Air Density Model		Gas	density
hydrogen		0.0899	1.205		7238.3		Hydrogen	0.09 at 0C,101 kPa
							Helium	0.179 at 0C,101 kPa
Dia.= 2.4 m	7.8 ft					Dia.= 9.4 m	31.0 ft	
Laun Vol (cu m	Launch Dia (m)	Area (sq m)	Balloon (g)	Payload (g)	Burst Dia (m)	Burst Volume (cu m)	Burst Volume Rat	Burst height (m)
7	2.3734	4.42408	1500	3000	9.44	440.46825	62.924	29981
247 ft^3	7.79 ft	47.63 ft^2	3.31 Lbs	6.62 Lbs	30.97 ft	15552.9 ft^3		
Gross Lift(Kg)	Free Lift (Kg)	Free Lift (N)	Balloon Cd	Ascent Rate (m/sec	Ascent rate (ft/min)	Neutral Lift Kg	Time burst (min)	Burst Height (ft)
7.81	3.3057	32.4289	0.25	6.975997	1372.876	6.3057	71.6278	98336
17.2 (lbs)	7.29 (lbs)	7.29 Lbsf				13.90 Lbs		

Notes:

Fill in the green cells - results in yellow cells (Pink cells are intermediate calculations, Tan cells are constants)
Based on Kaymont Totex Sounding Balloon Data
Model tends to under estimate balloon burst for small balloons by upto 3.5% - and over estimate for big balloons by upto 3.5%
Air density model based on NRLMSISE Standard Atmosphere Model - good to 80Km

Totex Balloon Data:

Balloon (g)	200	300	350	450	500	600	700	800	1000	1200	1500	2000	3000
Burst dia (m)	3.00	3.78	4.12	4.72	4.99	6.02	6.53	7.00	7.86	8.63	9.44	10.54	13.00
Cd	0.25	0.25	0.25	0.25	0.25	0.3	0.3	0.3	0.3	0.25	0.25	0.25	0.25

C. Taylor Balloon Flight Spreadsheet[8]

The final Balloon Calculator is the Data Base Spreadsheet under development at Taylor University (Ramm and Voss, This publication, 2012). It includes many of the gas filling requirements and flight related equations of motion as described.

III. Balloon Experiment for Understanding Balloon Fundamentals

It is very difficult to measure temperature in a changing radiation environment (UV, Visible, IR) as the pressure and density vary by 99% and the IR and UV radiations change by orders of magnitude. Special care must be taken to increase convective flow for heat transfer to the sensor while keeping the sensor thermal mass and energy dissipation low. In addition, low emissivity and absorptivity coatings must be used on the sensor to minimize energy transfer to and from the environment.

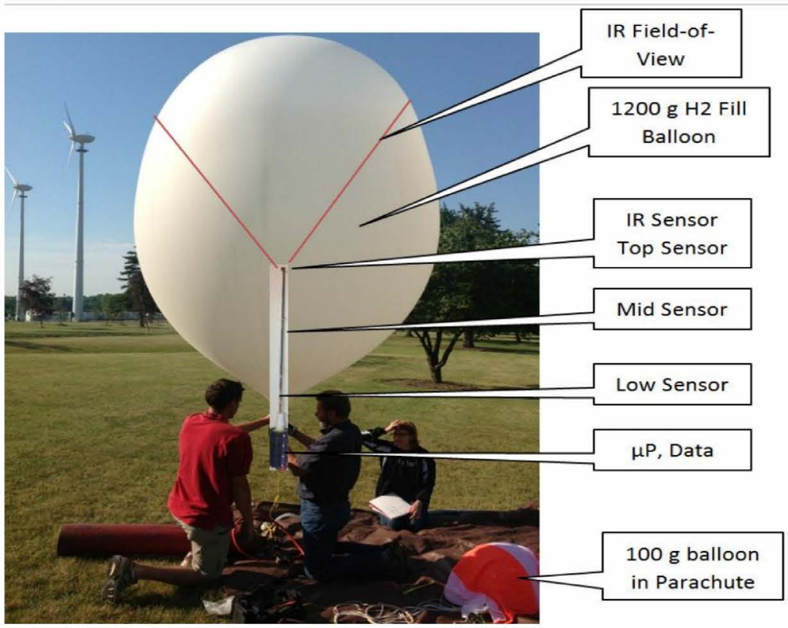


Fig. 3-1 Test HARP Balloon Flight 282 to study the Temperature profile inside of the balloon using a series of internal temperature sensors on a boom. Boom is overlaid on Balloon for illustration.

Balloon Flight 282 was launched on June 9, 2012 at 9:00 AM to investigate the internal and external temperatures of the flight. The external temperatures where monitored using a calibrated and certified Met unit using an exposed thermistor. Another external temperature sensor based on a diode junction was floated about 3 cm from the POD for verification inter-calibration.

On the internal 70 cm boom three diode temperatures were located as indicated in Fig. 3-1. Near the Top sensor an additional IR sensor was positioned to measure the balloon thin film temperature. The IR sensor field-of-view was 80 degrees and faced the top of the balloon. The boom POD is shown in Fig. 3-2 and collected all of the internal data at four samples per second for wireless transfer and internally stored in a memory stick.

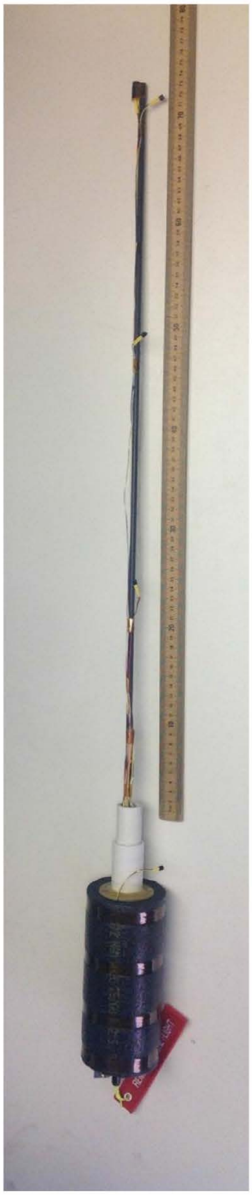


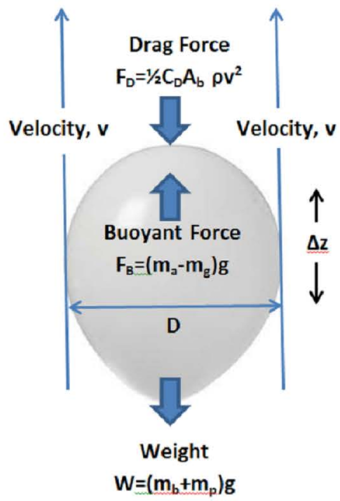
Fig. 3-2 internal temperature boom for insertion into nozzle.

Fig. 3-3 Temperature POD with calibrated MET unit (with plastic protective cover) and diode temperature sensor in white plastic hollow ball with holes for convection.

Fig. 3-4 Flight 282 at beginning of launch showing four PODS and the parachute with a enclosed 100g balloon. The internal probe boom is not visible but is located inside the balloon.

Over the past year three balloon flights have now been flown with the internal temperature boom to better understand the heat transfer and temperature variations within the balloon. These data are then used to check the model simulations to see if the physics is properly accounted for to explain the observed rate of assent and radiation balance.

IV. Balloon Fundamental Motion



A. Basic forces and Lift

A diagram of the vertical forces on a balloon is shown in Figure 4-1 assuming a stationary atmosphere (no vertical winds). The upward buoyant force or Gross Lift is $F_B = (m_a - m_g)*g$ where m_a is the balloon fill equivalent atmospheric mass that is displaced by the balloon gas mass, m_g, and g=9.8 m/s^2 is the acceleration of gravity. Hydrogen gas at STP has a density of 0.09 kg/cu m and air a density of about 1.2 kg/cu m which generates a lift of about 1.1kg/cu m. The balloon gross mass, m_G, includes the mass of the rubber balloon, m_b, plus the mass of the payload, m_p.so that $m_G=m_b + m_p$.

The Nozzle Lift is F_B - m_b g. The Free Lift is the net lift with the payload attached, $F_L = F_B - W = F_b - m_G$. g.

B. Drag Force

When the Balloon system is first launched it quickly accelerates to a constant upward speed based on force balance between the Free Lift force and the drag force, $F_L=F_D$.

$$\text{The Drag Force, } F_D=\tfrac{1}{2}C_D A_b\, \rho_a v^2, \quad (1)$$

where A_b is the cross sectional area of the balloon = π $D^2/4$, ρ is the atmospheric density, v is the balloon upward velocity, and C_D is the Drag constant of proportionality and is usually about 0.3 as indicated in Table 2. To understand this relationship you can use conservation of energy.

Drag force on the balloon surface = $F_D*\Delta z$ proportional to the Kinetic Energy imparted to air =½ m_a v^2 where Δz is a vertcal increment of height. If we multiply and divide the KE side by V/V, where V is the Volume of the displaced air, V=(A)(Δz), we get that $F_D*\Delta z \propto \tfrac{1}{2}(V/V)\, m_a v^2 = \tfrac{1}{2}\Delta z\, A\, \rho_a v^2$. Therefore, $F_D=\tfrac{1}{2}C_D A_b \rho v^2$.

This formula can also find the velocity during parachute descent by taking A as the area of the parachute, A_p (ref). The descent terminal velocity can be found by the requirement that the drag force must equal the total parachute and payload weight: $m_G\, g= F_D=\tfrac{1}{2}C_D A_b\, \rho_a v^2$. Solving for v gives the falling terminal velocity, v_T,

$$v_T = (2mg/(C_D\rho A))^{1/2} \quad (2)$$

Where the Drag Coefficient, C_D, is between 0.5 to 0.8 (Seifert and McIntosh, 2011)[9] for the parachute.

The Drag constant, C_D, is a function of the Reynolds number, Re = v D ρ_a / μ, where μ = dynamic viscosity. From Fig. 4-2[10] the Coefficient of Drag for a balloon (see Table 1) is in the region of interest shown was the flow can change from laminar to turbulent. Understanding the flight dynamics and atmospheric parameters during a flight can help to indirectly measure C_D. The two dimensional flow past a cylinder is easier to visualize as shown in fig. 4-3 and is claimed to be very similar to the three dimensional flow around a sphere.

Coming up with clever ways to video capture the aerodynamic flow in the in-flight high-altitude balloon laboratory at high altitudes would greatly help to understand the flow behavior and drag coefficient. Evaluation of the Aerodynamic Differences of a Balloon and a Sphere Using Computational Fluid Dynamic Modeling in Fluent software has been demonstrated by Scholes (2011)[11] and the MS thesis is available as a PDF. The results of this study show that the drag on a realistic balloon shape is not statistically different from a sphere although only small balloons at low altitudes were investigated with diameters less than 1m and Reynolds numbers about 10^4-10^5.

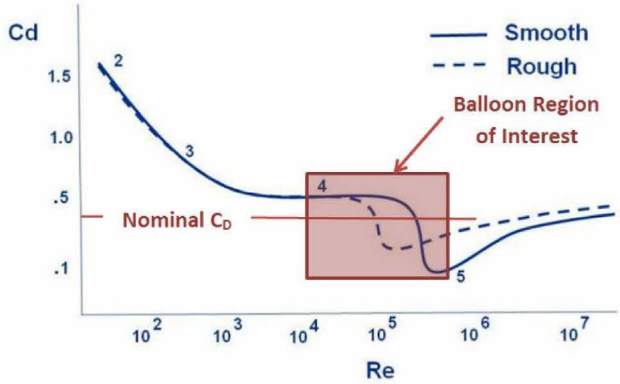


Fig. 4-2 The Coefficient of Drag, C_D, is primarily dependent on the Remolds Number, Re, and the condition of the balloon surface. The balloon region of interest is shown in red. The dip between points 4 and 5 indicate the transition from a Laminar to a turbulent change in flow regime. Blue data taken from NASA.gov in reference.

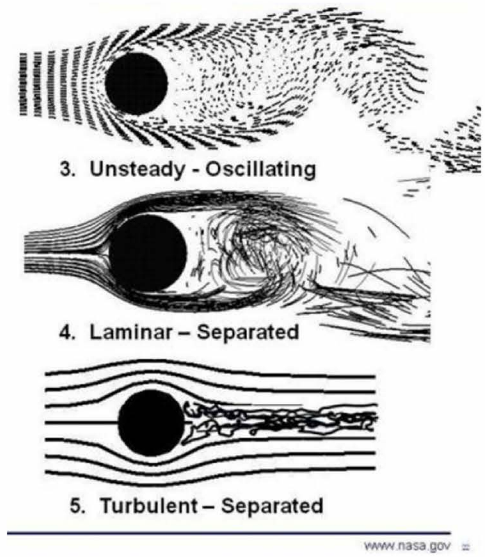


Fig. 4-3 Example of Laminar (region 4) and Turbulent (region 5) of the flow regime shown in Fig. 4-2 for a cylinder. Data from NASA.gov**.**

C. Gas Law equations

For an ideal gas, PV = nRT, where P is the pressure, V is the balloon volume, n are the number of moles of lifting gas, R is the Gas constant (R= 8.31 joules/(mole °K)), and T is the internal balloon temperature. If we multiply both sides this equation by the average molecular mass of air (M_a=28.97 kg/mole) we can solve for the density of air as, $\rho_a = M_a P_a/(R\ T_a)$. We can also solve for the volume of the balloon if we use the fill gas parameters designated by the subscript g: $V_b = m_g\ R\ T_g /(M_g\ p_g)$. V_b is a function of the balloon radius when approximated to the volume of a sphere, $4/3\ \pi\ r^3$.

D. Equations of motion

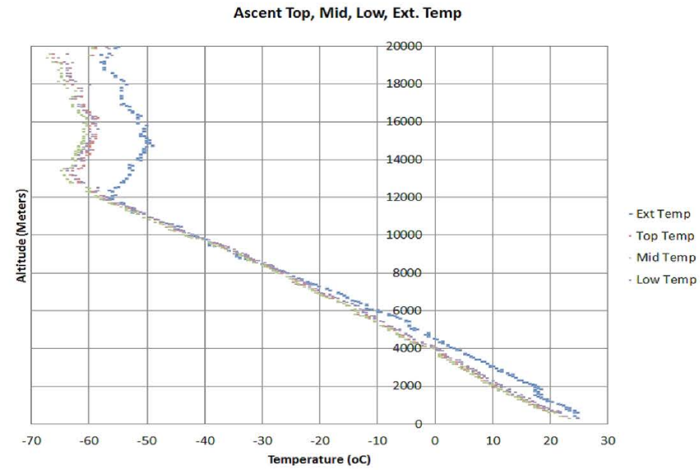
By applying Newton's law, F=ma, the dynamic motion of the balloon can be nicely solved using a second order differential equation with certain approximations (Bachman). For steady state, a=0, the sum of forces are zero with the drag force equaled by the lifting force (F_L=F_D). In this case the steady state ascent rate can be solved as

$$\mathbf{V_b} = \sqrt{\frac{\pi D^3(\rho - \rho_B)g/6 - (m_B + m_P)g}{C_D \rho \pi D^2/8}} \quad . \qquad (3)$$

Using Table 1 to plug in realistic values (see Bachman[12]) the vertical speed of the balloon is on the order of 5 m/s. For many flights the balloon continues to rise over 30 km at nearly a constant rate of 5 m/s (about 1000 ft.min) even though many parameters are changing (density, balloon size, drag, temperature) and we will look at this next with regard to energy balance.

V. Balloon Heat Transfer

Fig. 5-1 1 Previous Balloon Flight 280 with internal temperature boom. The three boom internal temperature monitors are near each other while the external temperature is somewhat warmer in the troposphere below 6km. A striking temperature difference id observed above 12 km when the external temperature stops falling at the Lapse rate. The balloon is likely cooler because of continued adiabatic expansion.



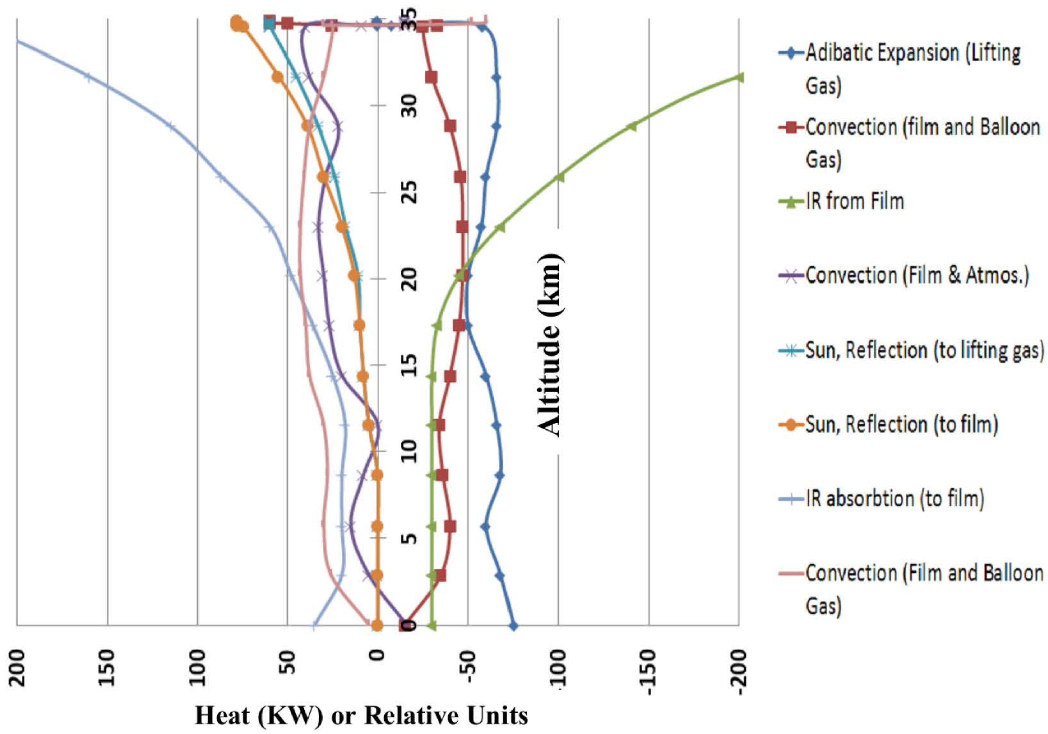


Fig. 5-2 Heat going into and out of Balloon film and lifting gas. Adapted from Yajima et al. 2004, Fig 2.35.

In Fig. 5.2 adapted from Yajima [3] the component heat transfer is shown as function of altitude. Note that the blue line is the adiabatic expansion of the lift gas and that it is nearly constant as the balloon ascends. Also note the solar energy inputs and the large increase if IR radiation and absorption as the balloon ascends.

VI. Ascending Motion

The assent profiles depends strongly on the temperature reversal at the tropopause (about 15 km) when the temperature changes from falling in the troposphere to increasing in the stratosphere. The rate of ascent equation (3) shows that when the adiabatic expansion continues in the stratosphere while the external temperature increases with altitude. Depending on the solar angle the solar heating can also accelerate the balloon with increasing altitude.

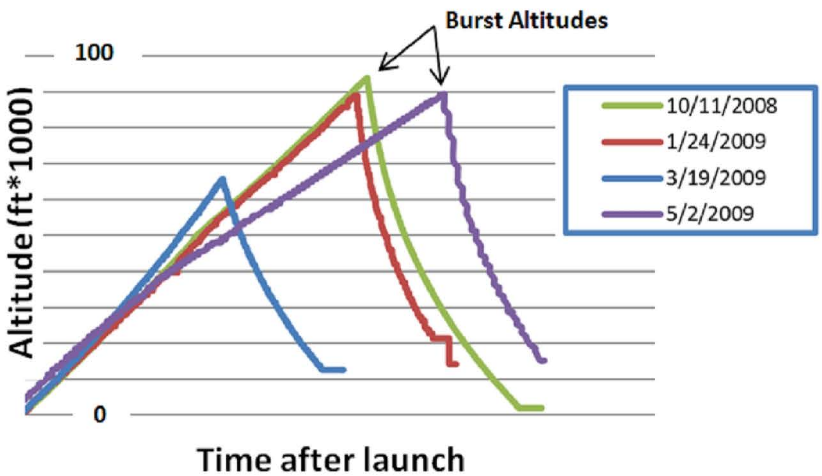


Fig. 6-1 Plot shows four balloon assent rates for different times. Note the pronounced "knee" observed on the 5/2/2009 launch at 40,000 ft.

VII. Future Work and Education

Additional work is planned for making more measurements of the internal temperature variations within the balloon and the balloon film surface. More accurate emissivity's and absorptivity's are required with a better understanding of the IR, visible and UV heating radiation. Student education is greatly enhanced with a good understanding of the balloon physics and when ascent data profiles, fluid flow behavior, and radiation heat transfer can be quantitatively compared with models.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No.107557. We would like to thank NSF for their support. Also, we would like to thank Dr. Don Takehara and Ms. Sue Gavin for their encouragement and support.

References

(1) Morris, A. L., BT-1777 Scientific Ballooning Handbook, Access Number BT-1777, Scientific Ballooning Handbook, National Center for Atmospheric Research, Report NCAR-TN/IA-99, May 1975

(2) Brock, Fred and Scott J. Richardson, Meteorological Measurement Systems, Oxford University Press, USA, ISBN-10: 0195134516, 304 pages, (2001)

(3) Yajima, N., Izutsu, N., Imamura, T., and Abe, T., Scientific Ballooning, Springer, ISBN 978-0-387-0972715, 2009, pages 213

(4) Voss, H. D., Jeff Dailey, and Steve J. Snyder, High-Altitude Balloon Launches and Hands-On Sensors for Effective Student Learning in Astronomy and STEM, *Voss*, Earth and Space Science: Making Connections in Education and Public Outreach, ASP Conference Series, Vol. CS-443, p340, ©2011, Editor Jenson: ISBN 978-1-58381-766-7.

(5) Aerospaceweb.org, Atmospheric calculator, http://www.aerospaceweb.org/design/scripts/atmosphere/, Based on US Standard Atmosphere 1976, Version 2.1.4, released August 2005

(6) US Standard Atmosphere, 1976, NASA, N77-16482, PDF, 241 pages, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770009539_1977009539

(7) Steve Randall Spreadsheet http://ukhas.org.uk/guides:balloon_data

(8) Ramm, Natalie and Hank Voss, High-Altitude Balloon Data Base, Published in this conference, June, 2012

(9) Seifert, P. and G. C. McIntosh, Terminal Velocity of High-Altitude Ballooning: Experiment Versus Theory, Academic High Altitude Balloon Conference, June 22-24, 2011, Ames, Iowa, p140-145

(10) NASA Drag on a Sphere, http://www.grc.nasa.gov/WWW/K-12/airplane/dragsphere.html,

(11) Scholes, Daniel B., Evaluation of the Aerodynamic Differences of a Balloon Shape and a Sphere Using Computational Fluid Dynamic Modeling in Fluent, Master Thesis, Mechanical Engineering, Utah State University, Logan, Utah, 2011, (Available PDF on Web at http://digitalcommons.usu.edu)

(12) Bachman, R. A., Idealized dynamics of balloon flight, American Association of Physics Teachers, Am. J. Phys. 52 (4), April 1984