January 2013

Air Circulation Under Reduced Atmospheric Pressures

Lendell E. Hillhouse

AIR CIRCULATION UNDER REDUCED ATMOSPHERIC PRESSURES

by

Lendell E. Hillhouse
Bachelor of Science, University of Nebraska-Omaha, 2008
Master of Science University of North Dakota, 2013

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

In partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

December
2013

This thesis, submitted by Lendell Hillhouse in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done, and is hereby approved.

Dr. Vadim Rygalov
Chairperson

Dr. David Whalen

Dr. Michael Gaffey

This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the Graduate School at the University of North Dakota and is hereby approved.

Dr. Wayne Swisher
Dean of the Graduate School

December 5, 2013
Date

Title: Air Circulation under Reduced Pressures

Department: Space Studies

Degree: Master of Science

In presenting this thesis in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the library of this University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by the professor who supervised my thesis work or, in his absence, by the Chairperson of the department or the dean of the Graduate School. It is understood that any copying or publication or other use of this thesis or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota in any scholarly use which may be made of any material in my thesis.

Lendell Hillhouse
December 4, 2013

TABLE OF CONTENTS

LIST OF FIGURES

ACKNOWLEDGMENTS

I wish to express my sincere appreciation to Dr. Vadim Rygalov for both his invaluable math modeling expertise, and for giving me the idea to do this research in the first place. Without his guidance, advice, and boundless patience this project would not have been possible.

I am also grateful for the participation of Dr. David Whalen and Dr. Michael Gaffey on my thesis committee.

Also, I must thank Dr. Glenn Sowell, Dr. Daniel Wilkins, and Professor David Kriegler of the University of Nebraska-Omaha Physics Department. Their lessons in Physics and in life have been invaluable.

Finally, I want to thank my fellow students and all the faculty and staff of the Space Studies department for being a part of my experience here at UND JDOSAS.

All involved, at any level, have made me a better scientist and a better person.

ABSTRACT

The control of heat exchange is vital for plant life in off-world, low pressure, greenhouses. The ability to control this process was limited by methodology and technology. Mathematical models, based on classical mechanics are created to enhance our control capabilities. Data is collected using various sensors placed inside the Low Pressure Test Bed (LPTB) Chamber at Kennedy Space Center. Data from those sensors became non-linear at various pressures below 25 kPa. We introduced mathematical calibration corrections and found that sensor data linearity could be extended to a greater range of pressures. These calibration corrections allow for sensor calibration corrections in operational environments that differ from the environment of calibration (normal Earth atmospheric pressure).

CHAPTER I

INTRODUCTION

Biospherics and Closed Ecological Systems

Humans are a part of a large integrated system of life here on Earth. Our survival as a species is often at the mercy of unseen forces and events. For example, our chances for survival would be greatly reduced if an event destroyed the plankton in the world's oceans. Such would be a major disruption in the food chain, and a virtual shock wave would radiate out from this event affecting all life on Earth. Many species that humans depend on for food, gas exchange, and other needs would be wiped out. Humanity would be put under great biological stress and face extinction.

Life is predicated upon a series of complex reactions, exchanges of information and materials, and energy procurement. The energy for life can be found in the environment. For example, the Sun provides energy for plant life. Plant life uses this energy to produce structures and regulate physiological processes. Some of the energy is held in reserve for later use. Plants have the ability to produce energy when specialized cells are struck by photons. Most animals on Earth are incapable of drawing large amounts of energy from their environment passively. Instead, they rely on a series of actions to secure energy and material resources. For animals, they must locate, move to, and consume other life forms that contain stored energy and materials. This can be either other animals, in the case of carnivores or omnivores, or plants. Based on such dependency, we can argue that plant forms are the base of any mega food structure.

However, if we expand our analysis even further, we see a large community of microorganisms (some capable of photosynthesis, and others not) that make up the base of the whole environmental structure. Any disturbance to this microscopic community can have consequences for the communities of mega flora and fauna. In sum, we are studying a large nebulous web of interconnections between several species and their environment.

The "food web" is only a part of a larger web that must be studied in great detail if we are going to be able to create reliable and stable ecosystems off-world. This new science requires knowledge in the fields of biology, chemistry, physics, and engineering. When all of the above disciplines are mixed together we have a new science, Biospherics.

The science of biospherics grew out of the study of closed ecological systems. The name was coined in 1987 at workshop held by the United Kingdom's Royal Academy (Pechurkin, 1994). Biospherics is about relationships between several sciences all trying to achieve the same goal: a closed ecological system. Dr Pechurkin lists the four main goals of this new science when he writes:

> 1. [T]o create working models of the Earth's biosphere and its ecosystems and thus to understand better the regularities and laws that control its life. This is especially important because the Earth's biosphere is presently under ecological stress on a global scale.
> 2. [T]o create biospheres for human life support beyond the limits of Earth's biosphere. These are essential for permanent human presence in space.
> 3. [T]o create ground-based life support systems that provide a high quality of life in the extreme conditions of the Earth's biosphere, as at polar latitudes, deserts, mountains, under water, etc.
> 4. [T]o use closed ecological systems to develop technologies for the solution of pollution problems in urban areas and for developing high yield sustainable agriculture. (1994, 85)

The main focus of Biospherics is on experimental results (Pechurkin, 1994). The goal is to test equipment and procedures that will allow some human control over the closed ecological system. This is the most important part of any work in man-made ecosystems. The technology is only viable if conditions can be maintained in a stable supportive capacity. As previously explained, any change in the conditions can ripple out and affect the entire system. If such change happens too quickly or drastically human life could be lost.

Furthermore, Biosphereics is not limited to experiment alone. Much of the work done is theoretical modeling of ecosystems here on Earth (Pechurkin, 1994). Much of the work is mathematical modeling. There are many paths of interconnection in any ecological system (Grace, 2006). For a system to be as stable as possible, many of these connections must be explored and experiments created. However, the main focus in Biospherics is not strictly the relationship between the system's participants. Rather the dynamic exchanges of energy and materials are given a higher priority (Pechurkin, 1994). The use of certain mathematical procedures can make these studies easier to conduct with little loss of relevant information. For years ecologists and biologists used these procedures to do their work (Grace, 2006). Biospherics absorbed these methods when it incorporated biologists and ecologists (Pechurkin, 1994). In summation, a biosphericist focuses not on relationships of the components of the ecosystem, but on the dynamics of those relationships.

The largest biospheric experiment on record is the Russian Bios series of programs. Started in the 1960s, the Bios series placed a small crew of individuals in a self-contained habitat structure. As the program progressed, the Russians improved the performance of the habitat and the living conditions for the crew (Gitelson, Lisovsky, & MacElroy, 2003).

In the Bios program, the Russians conducted several tests of various system components (humans, plant, and microbes are components of this system). The system had a relatively high closure index materially, but the closure index of information dropped due to the need for outside support for medical and technical assistance. In addition, the system operated at the very limits of stability. Therefore, any change within a system of this type would most likely lead to full system failure and death for the living components (Rygalov, 2008).

The Bios system also experienced mass loss. In any closed ecological system we want to keep as much material in the system as possible. This becomes a problem with excess biomass. Excess biomass is composed of portions of dead biological material that cannot be used to supply the rest of the system. For example, humans do not consume every part of a plant. In fact, doing so could prove fatal in the case of some plant species. In the Bios program scientists saw that dead plant material would accumulate and not decay fast enough. The proposed solution was burning of the plant material in a special incinerator. The incinerator would reduce the amount of excess biomass; it would also add instability. This instability is created by the technical needs of the incinerator and the loss of mass from the system. Furthermore, the health of the system would be at risk if the waste gases from the process built up in the system (Gitelson, Lisovsky & MacElory, 2003: Rygalov, 2008).

Bios 3, the last of the experiments, showed that these kinds of habitats were possible. Humans proved adequate as the regulators of the system. The system could operate for five to seven years and with stored minerals the system has a closure index of 93% (Rygalov, 2008).

The Russian Bios facility is a good laboratory for the study of Biospherics. However, no work goes on at that facility today as funding from the Russian government was withdrawn (Rygalov, 2008). Furthermore, the Russians seem to be turning away from closed ecological systems and looking for other solutions to life support issues. For example, for a future flight to Mars the Russians are relying on a Vitacycle device to provide fresh vegetables for the crew. However, the plants grown in this device will not be used to provide much of the mission's oxygen supply. The plants are to be used strictly for food (Berkovich et al., 2009).

Other nations have closed biospheric facilities as well. The United States has the failed Bioshere 2 facility in Arizona. The Japanese have a rather successful facility that incorporates animals into the system (Rygalov, 2008). What do we really know about Biospherics from these experiments?

First, as we should expect system monitoring and stability is a key factor. Second, these systems, while relatively successful, are too large for space flight. The Bios facility occupies a large area with a mass that is prohibitive for use in space. If we wish to use these systems for space flight and off-world settlement, they must be smaller and lighter.

Another issue to consider is stability. The Bios experiments showed that these closed systems can work; it also showed us that any small change could destroy the whole system. The question becomes: can we make these systems smaller and maintain the same level of stability? The problem is that when we reduce a system's size, we may also reduce its ability to continue to operate within our needs. If this is the case, smaller changes perhaps indictable by current technologies, would lead to failure and death. If we wish to make use of closed ecological systems in relation to space, we must look to the science of Biospherics for the answer to our question as well as other questions. This will be the direction of future research in this area.

This paper will focus on the ability to regulate temperature and mass transport (air) in the conceptual off-world greenhouse. It is hoped that this closed system will provide some of the life support needs for long duration off-world missions. However, we shall see that the stability problem is present. We shall discuss the low pressure experiments, detail the theoretical models, and provide an overall picture of the most likely conditions inside the structure. Our results will allow us to explore the instabilities and provide methods that allow us to monitor and control heat exchange data to maximize optimal conditions for plant growth.

Low Pressure Greenhouses for Open Space Applications

When manned space flight became a reality, serious research into sustainable life support systems began. These systems required the use of plants for food and gas exchange.

Much of the modern ground work for the greenhouse design and concept is laid in the 1990s. Schwartzkopf, working for Lockheed, introduced early designs that are still in development today. The Schwartzkopf greenhouses are designed to be deployed on orbital facilities or on planets. In orbit, the greenhouse concept provides a 100 square meter growing area with a mass of 12,322 kg. For the lunar surface, (any planetary surface with sufficient light and low atmospheric pressure can be considered analogous) two options are available. The first is inflatable with a growing area of 528 square meters and total mass of 43,480 kg. The second is also an inflated structure with the addition of a rigid “skeleton” for support. The supported system provides a growing area of 224 square meters and total mass of 17,999 kg (Schwartzkopf et al,1991).

All three concepts are examples of the early work done in this area. The large masses for each system make them costly to deploy. Therefore, the cost to deploy the systems in great numbers is overly-burdensome. With this in mind, for the rest of the decade and up to the current era, we would see these same structures considered but with reduced growing space and lower mass. However, as noted previously, this solution produced instabilities that are not (as of this date) fully understood.

Another issue to consider is human participation. In practice, these early greenhouse designs require a large amount of human interaction to function (Koelle, 2000). This fact raises serious issues with employment of these systems.

Astronauts or settlers would be required to spend much of the mission deploying and maintaining the greenhouse structures to achieve their function. This time would require the use of supplementary life support resources which would increase overall mission mass and present a significant risk of an accident occurring during the deployment stage. On Mars for example, in the case of failure in the deployment phase, mission designers would be forced to either increase mission mass to provide extra supplies or take the risk of crew loss until the in-situ supply system can be established. Resupply from Earth could take more than two years.

Furthermore, the Schwartzkopf systems are not fully operational upon planetary deployment (Kolle). It will take time for the plants to reach the level of activity needed for sustained operations.

The main effort of research into off-world greenhouses can be found in NASA Technical Memorandum 2000-208577 (NTM 2000). NTM 2000, is the culmination of a workshop that took place over several days in December 1999. Greenhouses for Martian missions and potential settlement are the focus of the memorandum. In fact, the research discussed in this work is generated from the research presented at the workshop (NASA).

At the time of the 1999 workshop, several small systems were in use or development. J.M. Clawson gave detailed descriptions and operational parameters for seven growing chambers (2000). However, the deployment and operation of these systems provided special challenges.

Clawson (2000) found that as system volume, and hence mass, decreased, the efficiency of the system decreased as well. However, inside spacecraft, or an orbital facility, volume is at a premium and needs to be kept as low as possible for operations. Clawson found that an inflatable modular system operating at low pressure (outside the pressurized crew areas) could increase the volume requirement but reduce the impact of mass (Clawson). In addition, low pressure is shown to increase the biological activity of some species (Corey, Barta et al. 1997). None of the systems Clawson listed as operational at this time were of this variety (2000).

For the reasons mentioned above, low pressure operations became the standard. In addition operating at low pressure prevents engineering faults that could decrease closure or lead to total system failure (NASA, 2000).

By the end of the 1999 workshop it became clear that the future for deployable off-world greenhouses would focus on low pressure experiments (with or without plants), and all of the special challenges that a low pressure environment offered (NASA).

The reduction of total pressure significantly impacts many environmental characteristics. Under the reduced pressure regime, plant health is compromised by the environmental changes. For example, we find that at pressures below 25 kPa free convection ceases as a method of heat exchange. Lettuce wilting and decreased reproduction in other plants is seen at greenhouse operational levels. It is believed that both impairments arise out of the inability to exchange heat, and to maintain adequate water balances in the low pressure environment (Corey et.al, 2000)(Kitaya & Hirai, 2007).

From 1999-2013, research into low pressure thermodynamics and fluid mechanics is taking place at SLSLab KSC NASA. Plant Physiology Facility for the University of Guelph provided support for various low pressure experimental designs and activities. Early experiments included chambers similar in design and concept to the “Thermotron" chamber (“TC”) (Fig 1.) (Fowler et.al. 2000).

The TC is one of the earlier designs used for the study of low pressure environments. It is extremely large with an internal (empty) volume of slightly over three and a half cubic meters. Humidity, pressure, temperature, and wind velocity can all be regulated and measured. Illumination sources are water cooled and their intensity is adjustable. The pressure can be lowered to a minimum of .133kPa. Cooling is provided by water coils. Experimental control interfaces and data collection are all run from a central computer (Fowler et al. 2000).

The early incarnations of the TC proved to be problematic. The lamps originally produced too much heat which caused instabilities leading to a loss of control over experimental humidity levels. In addition, the original system was prone to leaks and structural failures. It took three re-fittings before the system became both safe and operational. The system is not automated and, hence, could not be operated for long periods without human interaction. This is a significant problem as time is a major factor in allowing gases to reach equilibrium (Fowler et al. 2000).

Fig. 1. Thermotron Chamber

A smaller, less sophisticated low pressure chamber (Fig 2.) was also in use around the same period. In 2002, this smaller chamber was modified to study the water cycle under reduced atmospheric pressures. The small chamber is actually a vacuum oven modified with copper coils and measurement devices. Sensors are placed in the chamber and read through a small window located at the top. The chamber’s low volume and high interaction requirements are offset by its experimental adaptability. (Rygalov et al., 2002).

Figure 2: Small Chamber

Around 2008, Dr. Raymond Wheeler placed NASA'S Life Sciences latest low pressure research device into operation. The Low Pressure Test Bed ("LPTB") is NASA'S most recent "moderate" sized low pressure research tool. Originally designed as a device to test and calibrate equipment operating in low pressure environments, it is now equally utilized as a test chamber for studying those low pressure environments (NASA, 2008).

With an overall volume of one cubic meter the LPTB is a middle ground between the TC and the smaller chamber used in 2002 (NASA, 2008). Like the TC, it can measure and control several environmental conditions. Unlike the TC, it is fully automated and can be used for long periods without human interaction (NASA, 2008).

The LPTB has a usable volume of .56 cubic meters of instrumentation space and comes equipped with fans as well as the more sensitive humidity and temperature sensors. It can operate with an internal pressure of less than 1 kPa, and internal operating temperatures 283 K to 313 K. The LPBT is cylindrical which makes some of the fluid mechanics analysis easier (NASA, 2008). We chose to use the LPTB for our experiments because of its state of the art sensors and ability to operate and record data without constant intervention. More details will be provided in the “Methods” chapter.

Experiments designed to measure wind velocity proved problematic. We will show that at low pressure wind velocity (created by forced convection) is difficult to create and measure due to the environment itself and the inability of experimental equipment to provide useful data. When the air reaches mechanical and thermal equilibrium, circulation must be created by agitation. However, standard techniques broke down at low pressures and data became difficult to mate sufficiently to established physical principles (Fig. 3) (Rygalov & Wheeler, Air Circulation Under Reduced Pressures, 2008).

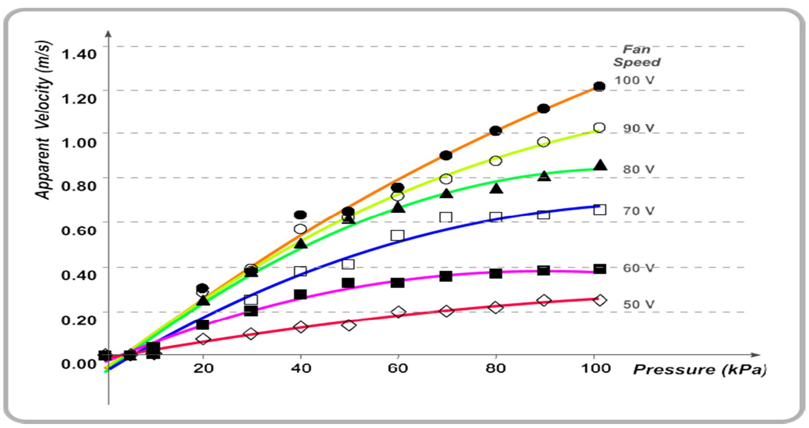

Fig. 3. Wind Speed vs. Pressure (Rygalov & Wheeler, Air Circulation Under Reduced Pressures, 2008).

Our first goal is to restate and apply physical laws and theories in forms that describe the low pressure environment. Next, we will discuss data collection methods, equipment, and results for both forced and natural convection and the implications of those results (reduced heat and mass exchange) for plants in this environment. Finally, we will present our results and the implications for future research into low pressure environmental control.

CHAPTER II

THEORY

Mathematical Modeling of Anemometer Function and Calibration

There are several methods of heat transfer modeling. We shall confine our discussions to the forms that yield simple and predictable results. We do so with the understanding that, in future works on this subject, a more in-depth treatment is required.

The phenomenon of heat transfer is a consequence of physical laws. That being said, we see that heat transfer is difficult to model precisely in certain conditions and numerous assumptions are required. For example, the Navier-Stokes partial differential equations ("N-S PDEs") form the basis of many of these laws. The N-S PDEs are complicated. Some of the equations have no solutions at this time (Fefferman, 2013). However, some solutions are approximated by analytical and numerical methods (Schnider, 1973).

For the purpose of completeness we state the following laws of Thermodynamics:

(0) When two objects or mediums of the same temperature are in thermal contact with a third all eventually have the same temperature.

(1) Work done by a system is equal to the sum of heat added to a system and heat taken from that system.

(2) In any isolated system, useful energy decreases as time increases (entropy tends to increase).

(3) At 0 Kelvin, entropy becomes constant.

There are three methods of heat exchange. All three of them can be drawn out of the four laws of Thermodynamics stated above. Radiation is heat exchange by the action of photons interacting with an object. The heat exchanged by this process is a function of the difference of the temperature of an object, the temperature of its surroundings, and the area of the object. It is stated mathematically as:

$$\frac{dQ}{dt} = \alpha\sigma A(T_S^4 - T_o^4)$$

$\frac{dQ}{dt} = Heat\ flow$

α = emissivity

σ = Stefan-Boltzmann Constant

A = Surface area

T_S = Temperature of surroundings

T_0 = Temperature of object

Looking at the equation, it is clear to see that heat exchanged by radiation is completely independent of pressure. Therefore, we predict that as pressure drops below 25 kPa radiation heat exchange will remain constant.

Heat can be exchanged by objects (or mediums) placed in thermal contact with each other. For example, suppose we have two (ideal) air masses of different temperatures separated by a partition that allows heat to flow across it. Over some time (t) the temperature of both air masses will reach thermal equilibrium (0th law of

Thermodynamics). In addition, the pressure is below 25 kPa. Heat exchanged in this manner is called conduction and is mathematically represented by (Kennard, 1938):

$$\frac{dQ}{dT} = \frac{a}{4}\frac{\gamma + 1}{y - 1}\sqrt{\frac{2R}{\pi M}}\ P(\frac{T_2 - T_1}{\sqrt{T}})$$

$\frac{dQ}{dt} = Heat\ flow$

a = Temperature accommodation coefficients

γ = ratio of specific heats

R = Gas Constant

M = Molecular weight

P = Pressure

T_1 and T_2 = Temperatures of two parallel surfaces

T = An experimental temperature roughly = T_1

It is evident from the equation that conduction is impacted by pressure. It is clear that the rate of conduction decreases as the pressure approaches zero.

Convection is the transfer of heat between fluid layers of varying temperatures. Convection is present in almost every environment on Earth. Convection drives the weather, the oceans, and plate tectonics. It is an extremely efficient process, but difficult to model.

Convection is not a true form of heat transfer. It is a combination of two physical processes. The heat transfer is a side effect of these processes. Advection is one component and is the transport of a material and heat via currents in large streams of matter. The other component is supplied by the random motion of the particles in the stream (Cess, 1973).

Convection can take place in several ways. However, only natural and forced convection are relevant to the topic at hand. Lord Rayleigh defined the ability of a fluid to achieve natural convection. The following equation is called the Rayleigh number (Rayleigh, 1916):

$$R_a = \frac{\alpha g d^3}{\kappa \nu} \Delta T \quad (1)$$

R_a =Rayleigh number

α = Thermal expansion coefficient

g = acceleration of gravity

d = distance between two surfaces

κ = thermal diffusivity

ν = Kinematic viscosity

ΔT = Temperature differences between the surfaces

We can make the following substitution and relate the Rayleigh number to air density (Turcotte & Schubert, 2002).

Let $\alpha = \Delta\rho = \rho_0 \alpha \Delta T$. Substitution yields:

$$R_a = \frac{\rho_0 \alpha g d^3}{\kappa \nu} \Delta T \qquad (2)$$

When the Rayleigh number is large enough natural convection begins. For non-rigid plates of material (low density gas layers) this critical value is roughly 657 (Turner, 1973). In our experiment we do not expect this condition to be met. The air density decreases as the pressure decreases making R_a values drop accordingly.

In addition, the illumination for the greenhouse design is provided from above. Because of the illumination configuration, we can have two thermal environments that impact free convection. If the canopy is not dense enough, photons will reach the ground (presumably a lower albedo than the leaves) and we will have a warmer air mass near the surface. However, if the canopy absorbs or deflects most of the photons, the ground will not be heated sufficiently. The warmer surface will be above the cooler surface. The second thermal configuration does not allow for free convection (Monteith & Unsworth, 1990).

It is useful to introduce another quantity at this time - the Grashof number. Once the existence of flow is established by the Rayleigh number, we can define that flow's nature by the Grashof number (G_r). Low G_r values indicate a flow that is laminar in character. Conversely, high G_r values indicate a turbulent flow. The Grashof number is calculated in the following manner (Hoy & Roos, 2005):

$$G_r = \frac{\beta g L^3 \rho^3}{\mu^2} \Delta T \qquad (3)$$

β = Thermal expansion coefficient (1/K)

L = the characteristic dimension (A/P → m)

ΔT = Temperature difference between an object and the medium (K)

We need one more quantity to complete our examination. The Prandtl number (P_r) is calculated by dividing the dynamic viscosity of air by its thermal conductivity. For air its value is around 0.71 and is quite stable in the greenhouse operational (pressure and temperature) range (Monteith & Unsworth, 1990).

If we multiply G_r and P_r, the result is equal to R_a (Monteith & Unsworth, 1990). When entering the values for air at 25 kPa and 288k we find that $R_a = 6.86\Delta T$. Free convection in the greenhouse will be laminar and its effects limited. These conclusions are in agreement with earlier experiments that show reduced convective heat transfer in a low pressure environment (Mehrabian, 2003).

The free energy in the environment is not conducive to the establishment of large streams of matter and the lower pressure negatively impacts particle motion from collision. The solution is to add energy to the system. This is easily done by agitating the air with fans. Fan use is an example of forced convection.

One of the solutions to the Navier-Stokes equation yields a dimensionless number for forced convection that is analogous to the Rayleigh number for free convection: Unlike the Rayleigh number, the Reynolds number tells of the condition of the fluid flow itself. The flow can be both straight and predictable, or it can be turbulent and chaotic (Reynolds, 1883). There are many forms of the Reynolds number (varying by physical layout, material composition, and other parameters). We shall restrict our discussion to the simplest case relevant to our experiments. The Reynolds number for a plate is (Engineering Tool Box):

$$Re = \frac{\rho \mathbf{u}}{\mu} \mathrm{L} \qquad (4)$$

Where

Re = Reynolds number

ρ = Air density (kg/m^3)

μ = Dynamic Viscosity (kg/ms) ~1.8 E-5 for air

L = Distance from the leading edge of the flow (m)

u = Velocity of the flow (m/s)

A turbulent flow will allow the atmosphere of the greenhouse to mix by the addition of energy. This mixing allows heat to be transferred from objects in the medium. For example, leaves under illumination carry a large amount of heat that is dissipated by transpiration (Wheeler, 2000). Cooler air must be placed in thermal contact with the leaf so the heat can be transferred. The only way to get the cooler air near the “ground” of the greenhouse (to leaf height) is to agitate it. To achieve this leaf contact, we must be able to accurately measure and adjust the flow velocity of air in the greenhouse.

For turbulent flow, the Reynolds number must be above a specific finite value. The flow is laminar up to $R_e = 5x10^5$. At greater values the flow becomes turbulent. In between these two values there is a transitional zone (Holman, 2002). Clearly to attain and maintain the necessary conditions for forced convection we must be able to regulate and monitor wind velocity.

We continue our analysis of mass and heat transfer at low pressure and invoke the ideal gas law. We know that the environment will be one of low atmospheric pressure and temperature. Consequently, the deviations from the ideal gas law formulated by Van der Waals and the coefficients of the Virial expansion are negligible. This being the case we state the following:

$$PV = nRT \tag{5}$$

P = Pressure

V = Volume

n = Number of moles

R = The Gas constant (8.315 J/mol*K)

T = Temperature (K)

We can modify this form of the ideal gas law to determine the behavior of several moles of gas.

First we take the number of molecules and multiply by Advogadro’s number. This yields the total number of molecules in the gas (N)

$$N = n \times N_A \tag{6}$$

$$n = \frac{N}{N_A} \tag{7}$$

Placing (7) into (5) we get

$$PV = \frac{N}{N_A} RT \qquad (8)$$

Where $\frac{R}{N_A} = k$ Therefore

The ideal gas law becomes

$$PV = NkT \qquad (9)$$

Where k is the Boltzmann constant.

The chamber is assumed to be fully functional. No loss of material is expected. If any material losses should occur, they will be negligible. Therefore, this experiment will be isochoric (constant N and V).

Referring to Equation 5, we expect that as pressure drops inside the chamber the temperature will decrease. We can estimate the final temperature of any gas that has constant volume in the following manner.

$$P_1 = \frac{NkT_1}{V} \text{ and } P_2 = \frac{NkT_2}{V}$$

Taking the ratio of the final pressure versus the initial pressure yields

$$\frac{P_2}{P_1} = \frac{NkT_2}{NkT_1}$$

Now we eliminate the constants and solve for T_2

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right) \qquad (10)$$

Furthermore, we know that as the pressure declines the density of the gas will decline as well. Using equation 1, we can write the following:

$$P = \frac{m}{v}RT \rightarrow P = \rho RT$$

Where rho is density.

Therefore

$$\frac{P}{RT} = \rho \qquad (11)$$

With the ideal gas law and the various convection conditions and forms defined, we now turn our attention to the modeling and performance of anemometers. This study requires two more physical formulas. The first is the well-known Bernoulli's equation; the second is the adiabatic Boyle-Marriot Gas Law. We will not explicitly state them here, but will indicate their function in determining anemometer function and calibration when needed.

Dynamic Pressure Anemometer (Pitot –Tube Anemometer)

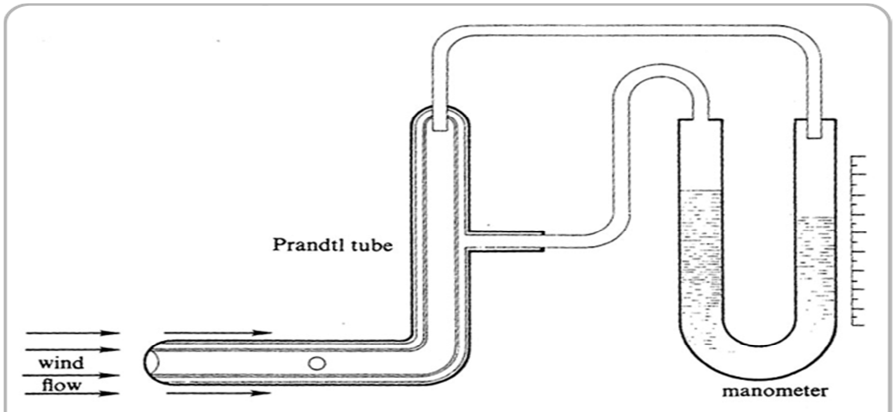

Figure 7.1. Pressure tube anemometer.

Fig. 4. Pitot Tube Diagram (Fritschen & Gay, 1979, p. 165)

A Pitot tube measures stagnation pressure of an internal fluid utilizing Bernoulli's equation. Stagnation pressure is the sum of two other pressures (Clancy, 1975). If one can measure both the dynamic and static pressure, then the stagnation pressure can be found using Bernoulli's equation. However, in this case, we are interested in the dynamic pressure as we can derive the wind speed from it. Therefore, we must be able to measure both the stagnation pressure and the static pressure. The Pitot tube Anemometer, whose functioning can be easily understood from the picture on Fig. 4 (extracted from Fritschen & Gay., 1979), allows us to measure the relevant pressures.

We want to measure the pressure on the intake port. The dynamic pressure is equal to $P + 1/2\rho\mathbf{U}^2$ (Clancy, 1975) (Fritschen & Gay, 1979). We also have a side port. The pressure on the side port is equal to $P - 1/2C\rho\mathbf{U}^2$ (Fritschen & Gay, 1979) where P = atmospheric pressure (static);

$\mathbf{U}$ = wind velocity

ρ = air density;

C = constant, which is less than unity.

Subtracting the side port pressure from the intake port pressure yields

$\Delta P = (\rho(1 + C)*\mathbf{U}^2)/2$,

Where ΔP = the differential pressure measured with a manometer or differential pressure transducer. Solving for wind velocity yields:

$\mathbf{U} = [2*\Delta P/\rho(1 + C)]^{1/2}$, and provides basis for Pitot tube calibration for wind speed measurements.

We can now invoke the idea gas law and declare the following:

$\rho = P/RT \rightarrow \rho \approx P$

Hence we can write,

$$\rho_c \mathbf{U}_c^2/2 = \rho \mathbf{U}^2/2$$

Here c indicates air density and velocity for sensor calibration conditions. Finally we solve for velocity and get:

$$\mathbf{U}_c = \mathbf{U}(\rho/\rho_c)^{1/2} = \mathbf{U}(P/P_c)^{1/2}$$

Dynamic Pressure Anemometer (Vane Anemometer)

While the Pitot tube provides operators with the best velocity data, it does have one drawback. It cannot measure the velocity of a flow of significant size. It only gives an estimate for the average velocity of the entire flow by measuring a small portion of it. This means that we would have to place several Pitot tubes in the greenhouse. Therefore, we would see an increase in mass and a decrease in usable volume. Increasing the size of one unit would have the same effect. The Pitot tube's best use is to evaluate data gathered from other sensors and aid in determining the accuracy of the data obtained from other sensors (Fritschen & Gay, 1979).

The solution is to gather data from a vane anemometer, one of the oldest tools in meteorology. The vane anemometer works by generating the rotation of a central shaft when wind flows over blades connected to the shaft. The fan revolutions are measured and used to calculate wind velocity (Fritschen & Gay, 1979). However, this system is not always accurate. Even in a standard pressure environment, friction and drag would play a role. Furthermore, in a low pressure environment we find that generated wind speed, for our limited velocity fans, do not have sufficient pressure to cause detectable rotation.

There are many complex formulas regarding the relationship between wind velocity and fan rotation rate. Fortunately, approximations exist that make the calculations less tedious and still give us a good view of the instrument's behavior at low pressures. For example, the American Society of Mechanical Engineers (ASME) states that wind velocity is approximated by fan rotation rate (American Society of Mechanical Engineers, 1971).

Vane or cap anemometers function on the basis of balance between drag forces from exerted air flow and friction forces generated by interaction between rotating propeller and air as well as propeller axel and gear (Fritschen & Gay, 1979). In principle, this device is easy to use. However, data analysis becomes problematic when the anemometer is placed in a low pressure environment. Mathematical corrections are made to bridge the gap between mechanical and statistical behavior.

For an anemometer operating at standard pressures and densities, mechanics dictates that we sum the mechanical behavior of the forces on the axle and propeller. This yields the dynamic force of the wind acting on the anemometer. Expressed quantitatively this yields (Rygalov, et. al., 2007):

$$f\omega r + C\nu\rho R^2\left(\frac{\omega R}{R}\right) = 0.5(C_+ - C_-)\rho G\mathbf{U}^2 \quad , \qquad (12)$$

Where

f = coefficient of proportionality for friction in propeller axel

ω = circular frequency of propeller rotation (1/s)

r = radius of propeller axel (m)

R = radius of propeller (m)

ρ = air density (Kg/m^3)

ν = Kinematic viscosity of air (m^2/s)

C = coefficient proportionality for friction force of propeller rotating in the air

C_{+-} = drag coefficients for drag forces exerted on the propeller

G= area of propeller vane (m^2)

From this equality we solve for wind velocity in terms of ω:

$\omega = 0.5(C_+ - C_-)G\mathbf{U}^2 * \{\rho/C\nu R^2(f*r/C\nu R^2 + \rho)\}$.

Air density ρ = P/RT, by (11)

Taking obtained relations into account, adjustment for modified pressures could be presented as:

$\omega/\omega_o = P/\{[R*T/M]*[f*r/C\nu R^2] + P\}$, which is the inverse hyperbolic function of total pressure P (Ryalov, 2008).

Hot - Wire Anemometer.

The hot wire anemometer measures air velocity by the removal of heat from the hot wire by the surrounding air. At normal pressures, all three modes of heat transfer are operating. At lower pressure, however, the heat flow becomes increasingly reliant on radiation. Conduction is still a factor, but the average number of molecule collisions with the hot wire decrease dramatically and convection stops below 25 kPa.

Mathematically we can express the response of this sensor using the following thermodynamic equation:

$$\Delta T = \varepsilon(Q_i - Q_a)$$

Where

ΔT = change in temperature (Kelvin).

ε = A physical constant (Kelvin/Joule).

Q_i = Heat generated by the hot wire (Joule).

Q_a = Heat gained by a cooler mass of fluid (Joule).

We state, as a reminder, that the right-hand side of this equation is completely dependent on the pressure of the surrounding medium. We can easily substitute any of the equations for heat exchange for the heat exchange quantity.

We now make the following statement by invoking energy conservation: The heat energy created by the wire is equal to the heat removed by the air over time t. Stated symbolically as:

$Q = C_P \rho G K_L (T - T_a)$,

Where:

Q = amount of heat per unit of time provided for hot wire;

C_P = specific heat capacity for the air circulating around hot wire;

ρ = air density;

G = surface area for heat exchange;

K_L = air circulation rate measured in velocity units (m/s for example);

T = hot wire temperature;

T_a = air temperature.

Solving for K_L yields:

$K_L = Q/[C_P \rho G(T - T_a)]$

We invoke the ideal gas law for pressure and substitute yielding:

$K_L = Q/[C_P MPG(T - T_a)/RT_a]$.

We have determined the response algorithm for the hot wire anemometer at one standard atmosphere. We calibrated our sensor at this specific pressure and need to make the following adjustment to provide a correction for different pressures.

We make this correction by selecting the independent variable (pressure in this case) and divide it by 101.3 kPa. We then multiply that quotient by the calibrated wind speed. This correction will generate a linear function for the sensor response.

With working equations for the function, and calibration corrections, for the three anemometers, we have a good basis for monitoring and controlling wind speed and convection.

At this time, let us pause and consider the following question: why do these sensors need special calibrations? The answer is that this environment is rarified in terms of atmosphere which changes the physical nature of the environment. Our sensors are designed to operate on the basis of classical mechanics. However, as the pressure decreases, molecular behavior becomes statistical.

The Knudsen number (Kn) is a dimensionless number that defines when a problem needs to be treated statistically rather than classically. The Knudsen number is written symbolicly as (Probstein, 1963):

$$\frac{\lambda}{L} = \left(\frac{\pi\gamma}{2}\right)^{\frac{1}{2}} \frac{M}{Re_L} \qquad (13)$$

Where;

λ = Path Length

L = Length

γ = Ratio of Specific Heats (1.4 for air)

M = Mach Number.

As Kn approaches zero, classical formulations and results become less relevant. Instead, problems must be treated using statistical mechanics and Thermodynamics (Probstein, 1963). Therefore, we believe our calibrations will work within a certain range.

However, there will be a low pressure “tipping point” where the calibrations will no longer produce satisfactory results. Rygalov’s (2002), earlier research locates this “tipping point” near 25 kPa.

We conclude this section by describing the environment of the chamber during the experiment. A small amount of energy is being added to the system from both visible photons (the observation window) and infrared photons (from operating sensors). We predict that these sources will not have a significant impact on our results and we disregard them.

In each experiment the pressure range described above could only be maintained for 137 minutes on average. This will not be enough time for the gas to reach thermal equilibrium. Therefore, we do not expect to see the final low temperature as predicted by Equation 5. If the air in the chamber is allowed to reach thermal equilibrium, we would see temperatures more in line with what is predicted by ideal gas law.

Humidity is also measured for the duration of the tests by the four sensors described in the LPTB section. Humidity plays a vital role in the understanding of free convection as well. While the measurement of humidity is routine, the implication for the overall climate picture is subtle and must be examined carefully. We define it here, modestly, to aid in the description of the environment.

In short, humidity is the amount of water vapor in a particular volume of gas (Wyer, 1906). In fluid dynamics this volume is referred to as a parcel. It can have any dimensions we choose and what is true for a parcel of one size can be said to be, generally, true for a parcel of any size under similar pressure and temperature conditions.

In terms of the ideal gas law, one parcel varies from another in terms volume only (Gill, 1982).

Humidity is related to temperature. Two specialized thermometers are used to measure relative humidity. The first is a “dry bulb” thermometer. This thermometer is insulated from the effects of water vapor. Therefore, it is often the best indicator of the actual temperature of the (dry or unsaturated) air. It measures temperature and we shall refer to this temperature as the “dry bulb temperature” (“DBT”) (Engineering ToolBox).

The other thermometer is the “wet bulb” thermometer. It measures the temperature of the mixture of gases and water molecules (“WBT”). In meteorology, this is the temperature of air that is rapidly expanded and cooled to maximum water content and then rapidly compressed to its original pressure (National Weather Service, 2001).

Rygalov (2002) examined this phenomenon in detail and found that the low pressure environment has little or no impact on the relative humidity. However, he did find that temperature impacts relative humidity. Evaporation did rapidly increase below 25 kPa. In addition, Rygalov theorized that plants in low pressure environments could experience water stress.

Convection plays a minor role in the heat exchange environment. The Rayleigh number is low indicting a great temperature difference is required to have natural convection. Forced convection is laminar and weak. Looking at the Reynolds number we would have to create sustained wind speed of roughly 67m/s to achieve the turbulent flow that we require. Finally, the winds we can generate produce a very low (~1E-2) Mach number. Hence, the Knudsen number is much less than unity and the environment favors statistical behavior.

In summation, we state our expectations. The low pressure environment will effect sensor functioning and data collection. However, we expect simple calibrations to present an accurate data response to improve monitoring and control of wind velocity. We expect no appreciable amount of convection (free or forced) to take place. Temperature will decrease as we lower the pressure as will humidity (water being pulled into the pumps). However, once the system is stabilized we expect no change in relative humidity (Rygalov, 2002).

CHAPTER III

PROCEDURES

Chamber for Reduced Pressure Environments Simulation

The first phase of the forced convection experiment involved the setup of the LPTB, including calibration and testing of the “onboard” sensors. We decided to run three separate tests, with each test lasting approximately seven hours and ten minutes. It is at this time that we concluded that the data gathered during these tests could be informative concerning the expected absence of free convection.

Tests, Arrangement and Implementation

At the beginning of each test, the LPTB is pressurized to 1kPa (1 atm) of natural air. The initial air mass is in thermodynamic and mechanical equilibrium. Air temperature at this point is 288.6 K as measured by the internal dry bulb thermometer. No significant variance is noted between the air temperature in the chamber and the air chamber of the room. This allows us to conclude that the dry bulb thermometer is working properly.

The LPTB is sealed and pressure is maintained for the next hour and 40 minutes. During this time we collect data from each of the relative humidity sensors (HU 1-3). To determine operational parameters of HU1-3, we take an average of the readings and then compare that average to the predicted relative humidity given by the dry and wet bulb measurements.

During each experiment, we notice a spike in internal temperature at roughly 35 minutes after chamber closure. We theorize that the sealing of the chamber created a minor shock as external air entered the chamber as the door closed. This shock heated the air inside temporarily. In addition, ambient photons coming through the observation window and ambient infrared photons from powered equipment contribute to the rise in temperature. The spike lasts for a short time and in a few minutes air temperature returns to values around 289 K.

The closing of the door has a similar effect on the relative humidity. All humidity sensors record a rise in humidity levels after closure. We again attribute this to the propagation of a shock moving through the chamber (we also would expect smaller waves moving horizontally as air bounces off the side of the chamber). The propagation of the shock can be traced by the location of the humidity sensors (HU1 is located closest to the door, HU2 in the middle, HU3 at the rear). It takes roughly an hour for the humidity sensors to stabilize at the original values. We note these values are at about 70% relative humidity. This is confirmed by the difference between the wet and dry bulb readings during this time. We conclude that at one atmosphere, HU 1-3 are operating within their normal range. We begin depressurization at 1 hour 41 minutes after chamber closure.

We proceed to collect data (relative humidity, wet and dry bulb temperatures and pressure) for roughly six more hours. The difference between the wet and dry bulb temperatures confirm that HU1-3 operate within tolerances for the entirety of the calibration procedure. Pressure drops below 25 kPa three hours, 40 minutes after closure (we examine the data during this time in our “results” section). The chamber operates at

25 kPa, or lower, for the next three hours and ten minutes. The test is completed in the stated time and data is uploaded for study.

We conduct three of these tests and examine the data. In the end all equipment is functioning within tolerances. Therefore, we are ready to proceed with a forced convection test.

After analysis of the calibration data the LPTB is readied for the forced convection test. Figures 5-9 show the preparation steps that are described below.

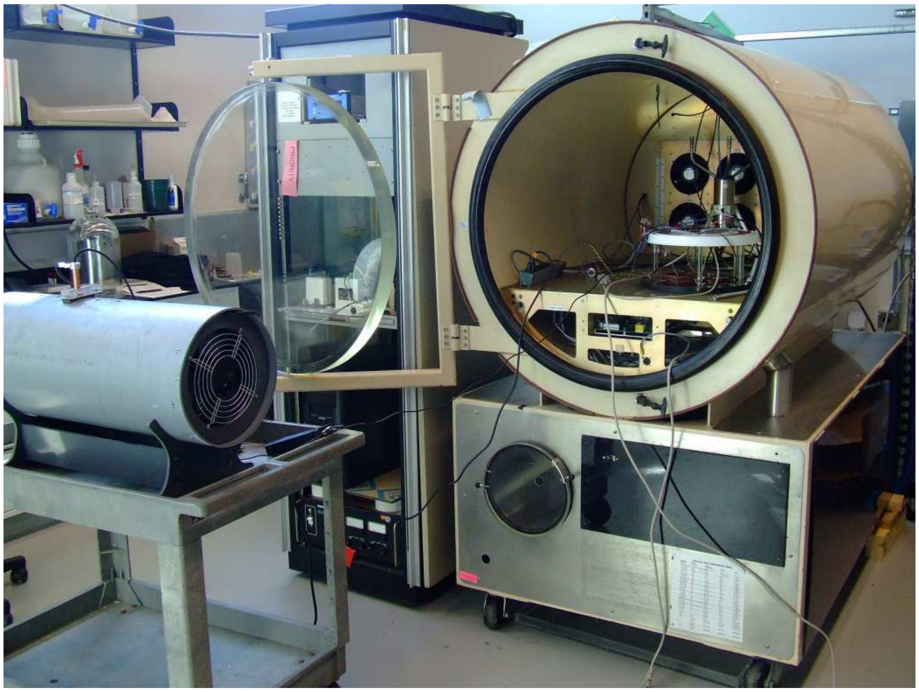

Fig 5. The Low Pressure Test Bed and Wind Tunnel in Preparation Stage for Forced Convection Testing.

Fig 6. Wind Tunnel

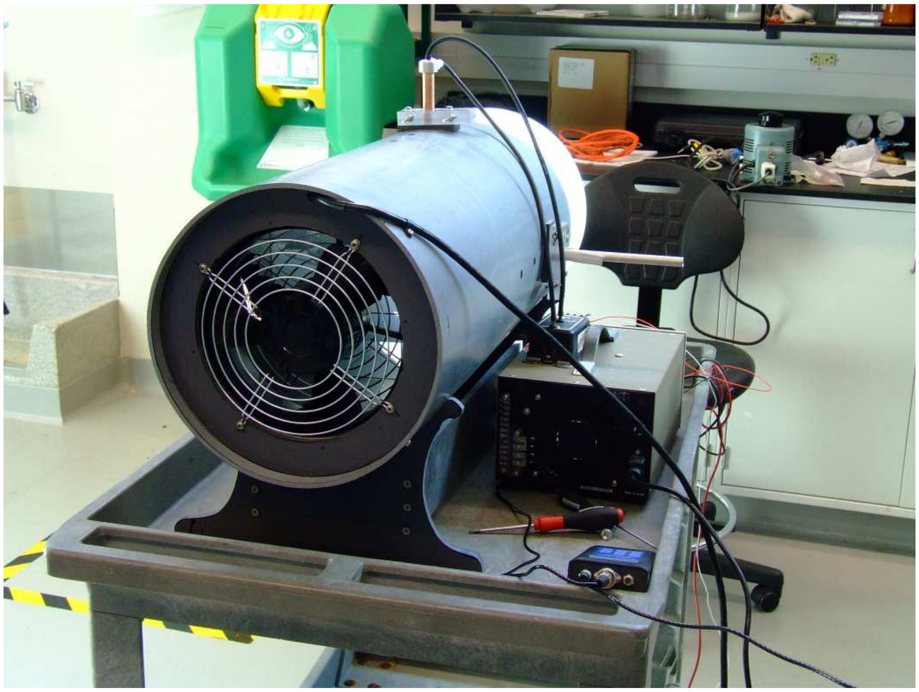

Fig 7. Wind Tunnel Preparations for Data Collection

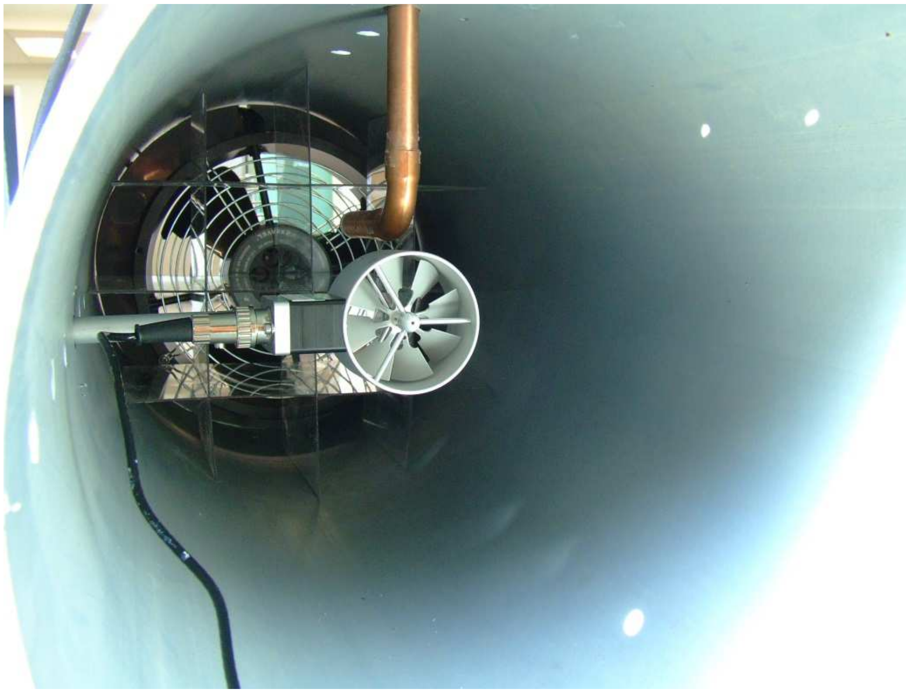

Fig 8. Primary Sensors Placed in the Wind Tunnel in Experimental Configuration.

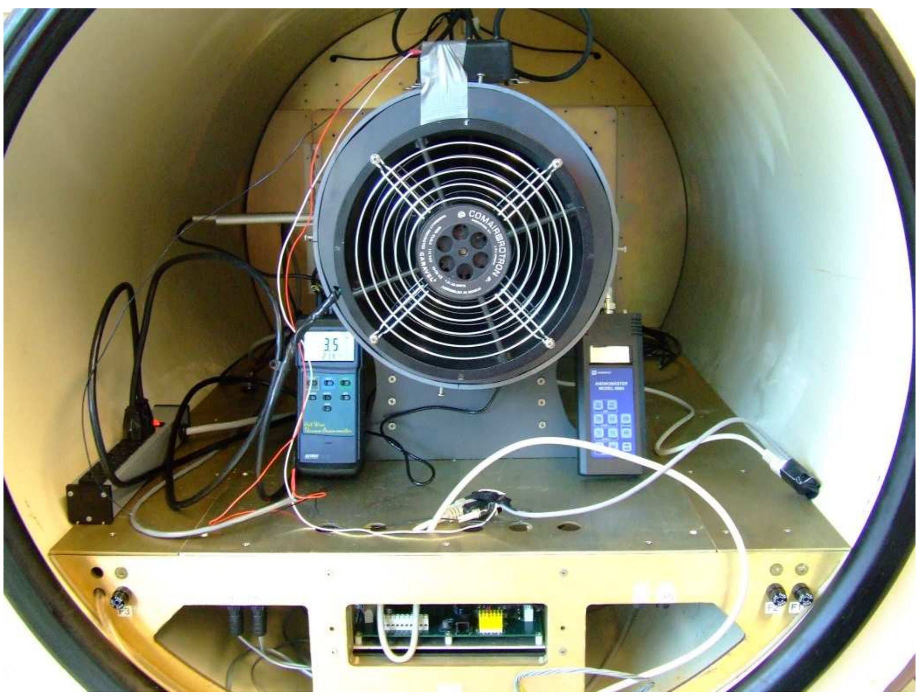

Figure 9. Final Experimental Configuration.

The wind tunnel is inspected and found to be in operational condition. It is at this time that we decided to proceed with the sensor attachment and calibration phase.

A Pitot tube is put into place through a small hole on the ventral side of the wind tunnel. This sensor is used to gather data for the purpose of providing confirmation and comparison of the data collected by similar sensors. We are also testing the Pitot tube's ability to measure wind velocities at low pressure. For this experiment the tube is connected to a SETRA transducer with data measured in volts (SETRA, 2007).

The next sensor added is a Thermo anemometer. This is the sensor that will provide the key data for this experiment. The sensor functions by monitoring the heat exchange environment. Therefore, the data collected will play a major role in our analysis and conclusions. Data is provided in standard metric units for velocity (m/s). This sensor is calibrated as per the instructions and placed in the wind tunnel (EXTECH, 2001).

The final sensor is a vane anemometer provided by KANOMAX. This simple device measures wind velocity using Bernoulli's principle. It provides data in standard metric units for velocity (m/s). It is calibrated as related in the instructions and placed in the wind tunnel (KANOMAX, 2004).

All sensors were calibrated at standard atmospheric pressure. We will make corrections for data gathered in the low pressure environment in the analysis section.

Upon completion of the preparations noted above, the wind tunnel is placed in the LPTB and the door is sealed. The fans are activated and will remain active for the duration of the experiment.

CHAPTER IV

DATA ANALYSIS AND DISCUSSION

Upon conclusion of the experiment, data is collected and analyzed. These tests have been conducted since 2007 at NASA'S Life Sciences Department at Kenedy Space Center. Data and corrections were returned to the Space Studies Department at the University of North Dakota for continuing modelling and research. All of the presented analysis is a recalculation and reevaluation of that data (Rygalov et. al. unpublished data, 2007).

Early results indicate a significant level of non-linear behavior in the response of all sensors and fans (Figs.10-11). Therefore, we concluded that the low pressure environment created an impact on fan rotation rates and sensor responses.

The pressure was returned to normal and this theory was tested. A Hall detector, from the SCWINN company was attached to the rotating vane anemometer and the wall of the wind tunnel (SCWINN, 2007). The LPTB was sealed and the pressure was lowered. The data from this experiment was graphed and displayed in Figure 10 below.

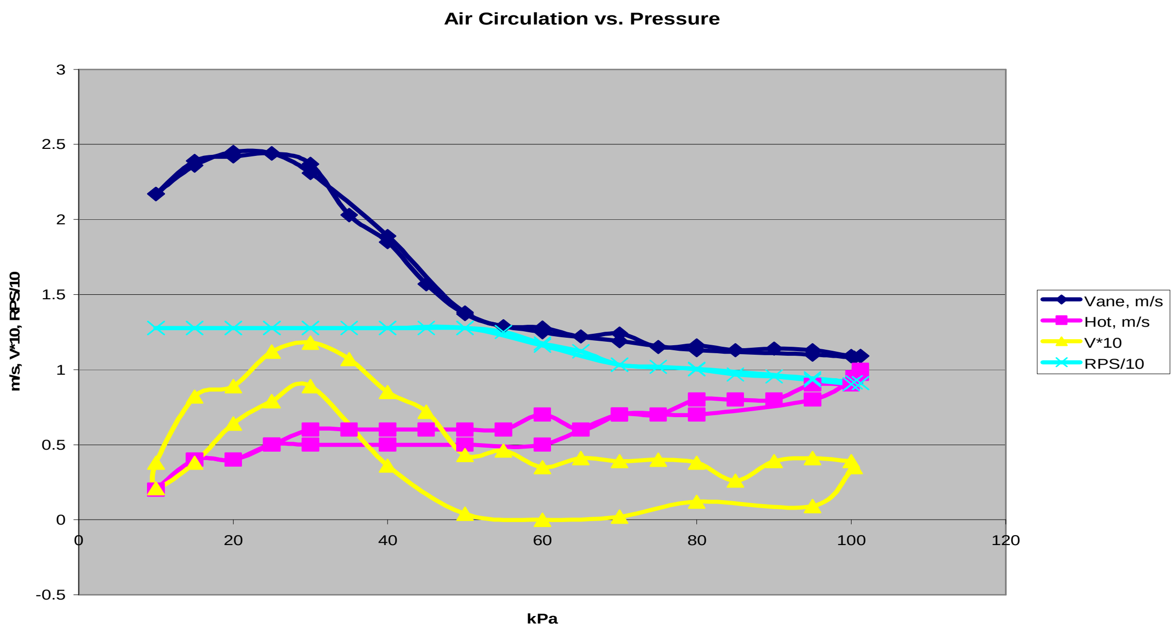

Fig.10 Initial Results for Wind Velocity Measured by Different Sensors and Methods.

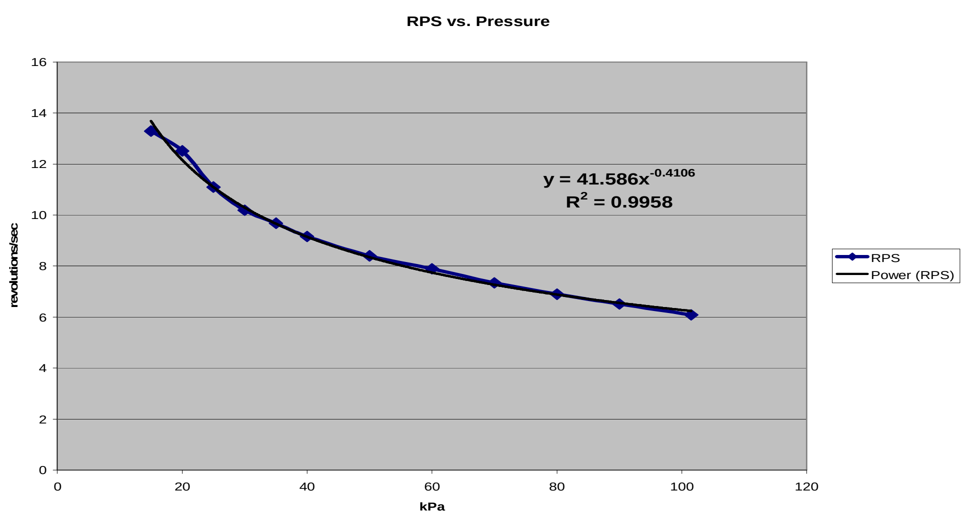

Fig. 11. Fan Revolution vs Pressure

These data provide a good fit to the theoretical model concerning the increase of rotation rate in conjunction with a decrease in pressure (Pontyak Resources Corporation). Specifically stated as:

$$B_S = B_0 \sqrt{\frac{P_1/P_2}{\rho_1/\rho_2}}$$

Where:

B_s = Final blade speed

B_0 = Initial blade speed

P_1 = Initial pressure (101 kpa)

P_2 = Final pressure

ρ_1= Initial air density

ρ_2= Final air density

Additionally, to achieve a better fit to the expectancy curve we modify the previous equation in the following manner (Rygalov & Wheeler, 2008):

$$U = U_0 \left(\frac{T}{T_0}\right)^{\frac{1}{2}} \left(\frac{P}{P_0}\right)^{\frac{1}{2\gamma}-\frac{b}{2}}$$

Where:

U_0= velocity where fan was calibrated

b = compressibility $0<b\leq1$

P = current atmospheric pressure

P_0= normal atmospheric pressure, 101.3 kP

γ = adiabatic correction coefficient for Boyle-Marriott Gas Law

Free Convection Results

We took the opportunity to test our conclusions about the lack of free convection and the effects on temperature and humidity during a test of the temperature and pressure equipment. As expected, both relative humidity and temperature decreased during these tests and we present our findings below.

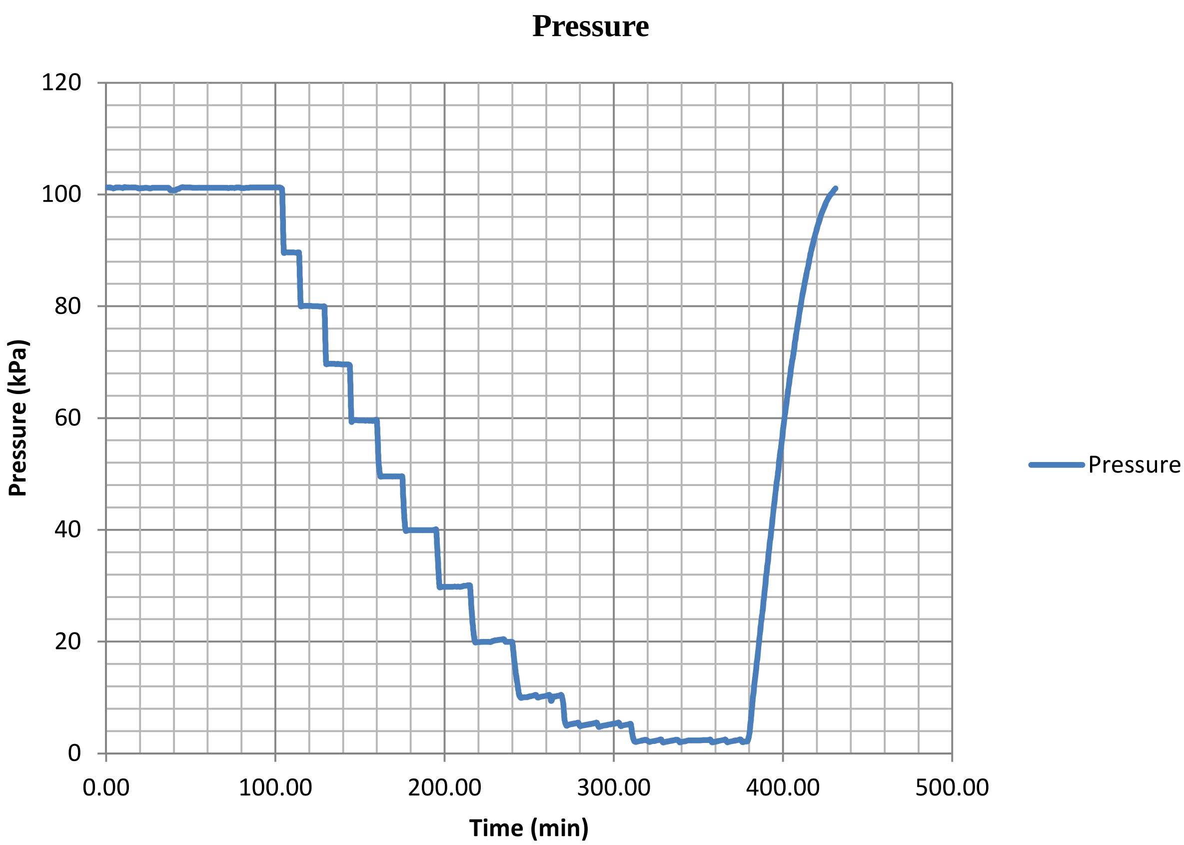

Fig. 12 Measured Air Pressure.

The figure above shows the decrease of the air pressure in the chamber versus time. As stated previously, the total time for this experiment is roughly seven hours and the pressure minimum of 1kPa is maintained for a short period of time.

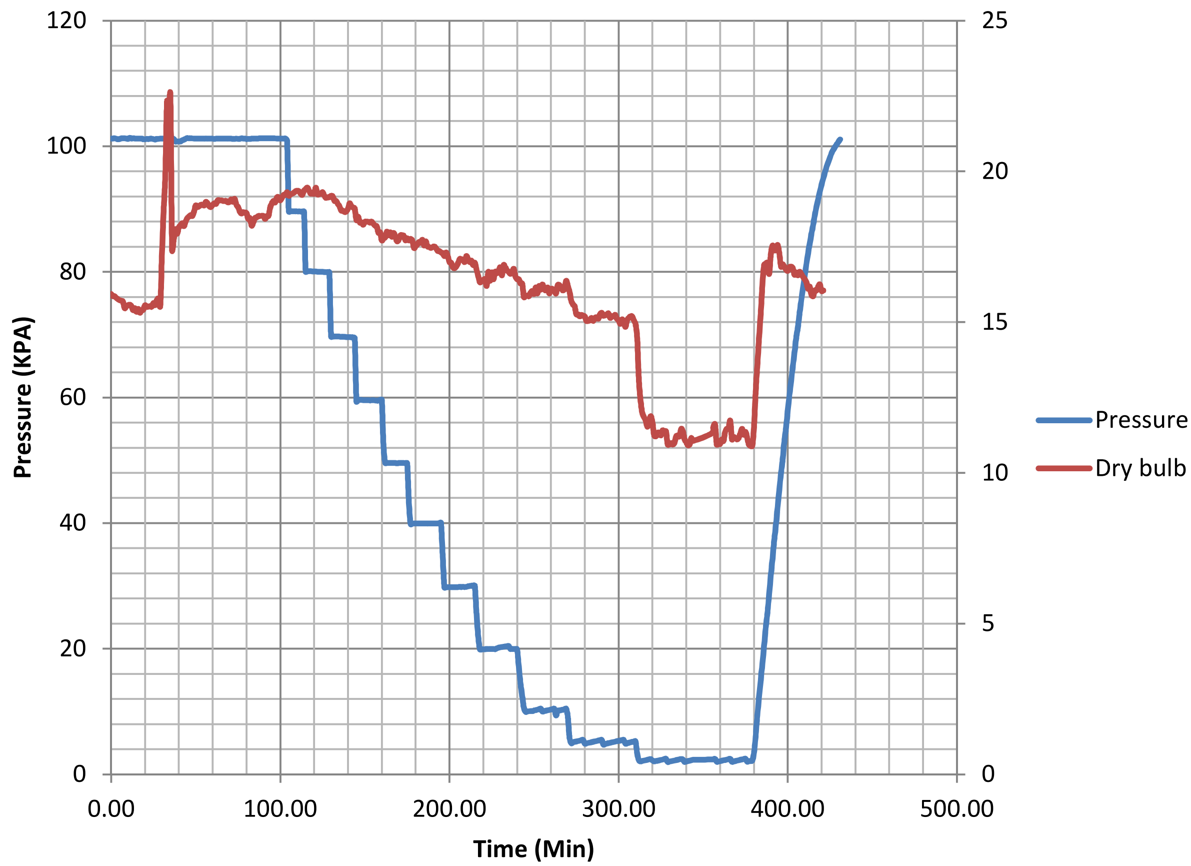

Fig. 13 Dry bulb temperature (c°) vs time and pressure.

The dry bulb temperature (figure above) is treated as the ambient air temperature and is graphed on the right vertical axis. The temperature decreased about 6 K. This is in rough agreement with the ideal gas law. Our measured value is somewhat higher than we expected. We believe that additional heating came from ambient photons coming through the view port and electrical heating from the sensors themselves. In addition, the air in chamber needed more time to reach mechanical equilibrium. We are confident that if more time elapsed we would see much lower temperatures.

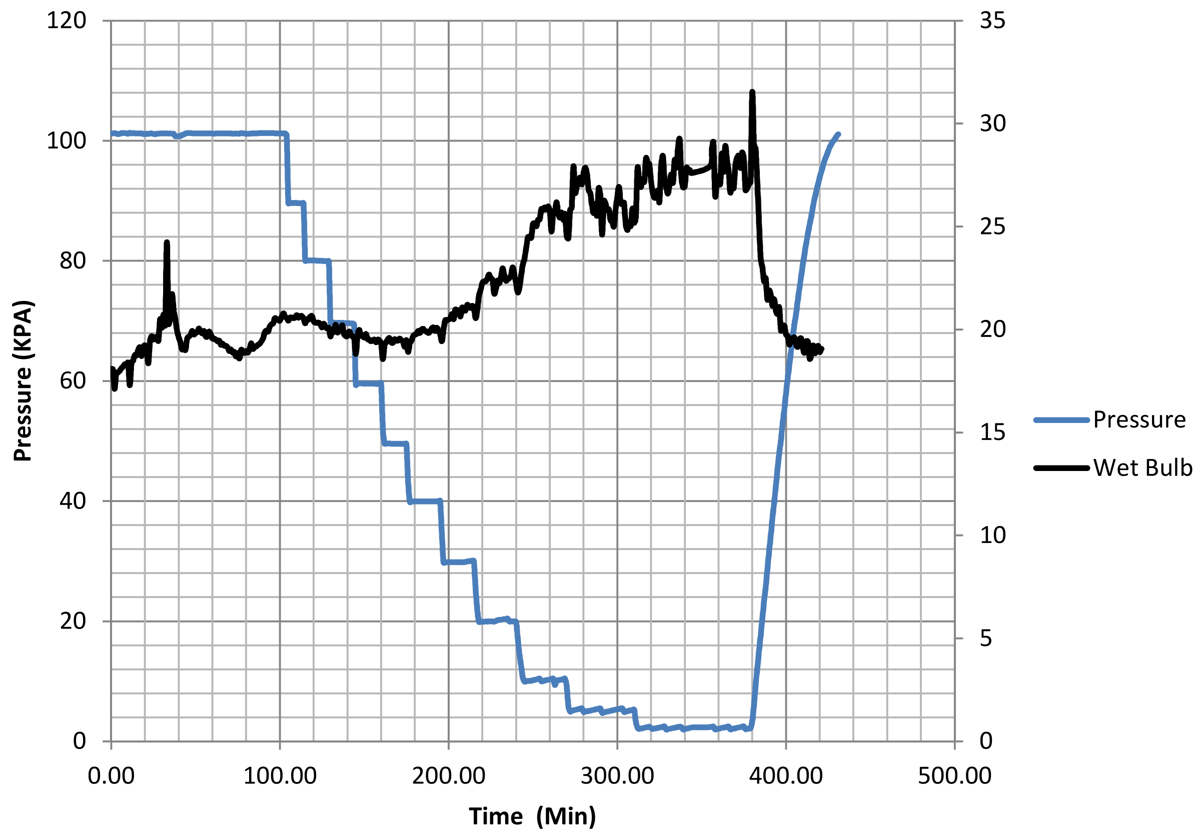

Fig. 14 Wet bulb temperature (c^{o}) vs time and pressure.

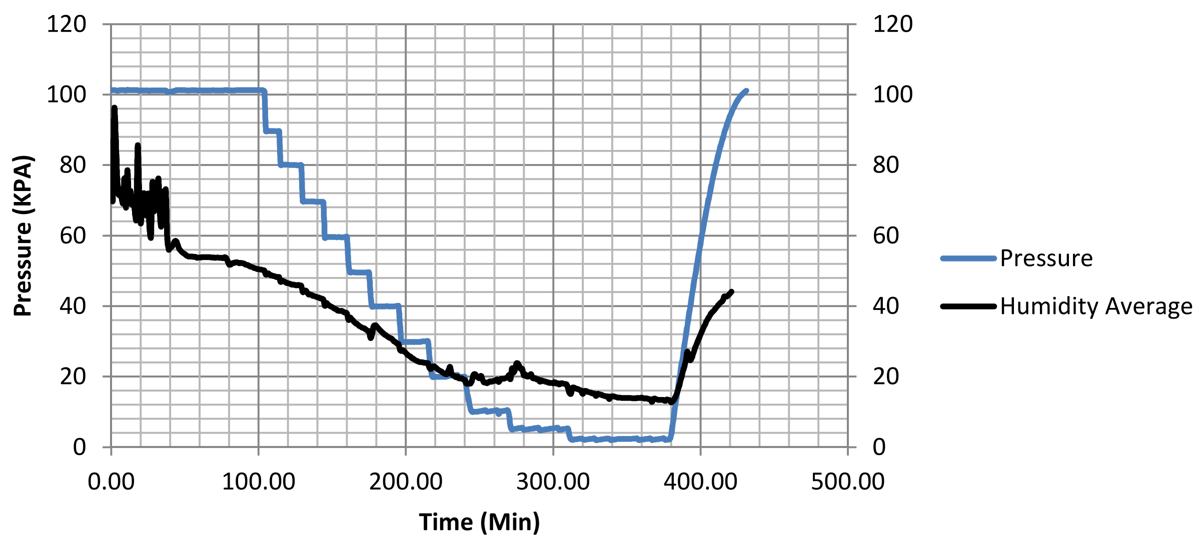

Fig. 15 Relative humidity vs time and pressure.

The data presented above show that any convection is limited. We see no spontaneous movement of water vapor from one part of the chamber to another. Additionally, the air temperature in the chamber is constant throughout the interior. We see no transfer of heat energy. We estimate the Rayleigh number to be about 6.

Forced Convection Results: Data and Analysis - Wind Speed and Air Circulation Measurements.

Raw wind speed data recorded by the sensors in LPTB are presented below (Figs. 16-20). Each of the three sensors are designed to measure the same physical quantity (wind velocity) using different physical methods. The theoretical curves used in our analysis are generated by these methods.

Note, that of all three sensors only the hot wire and Pitot tube attain a reliable linear response at all pressures. The vane showed non-linear behavior after pressure dropped below 25 kPa as expected. We re-affirm that the vane is a poor tool for work at these pressures.

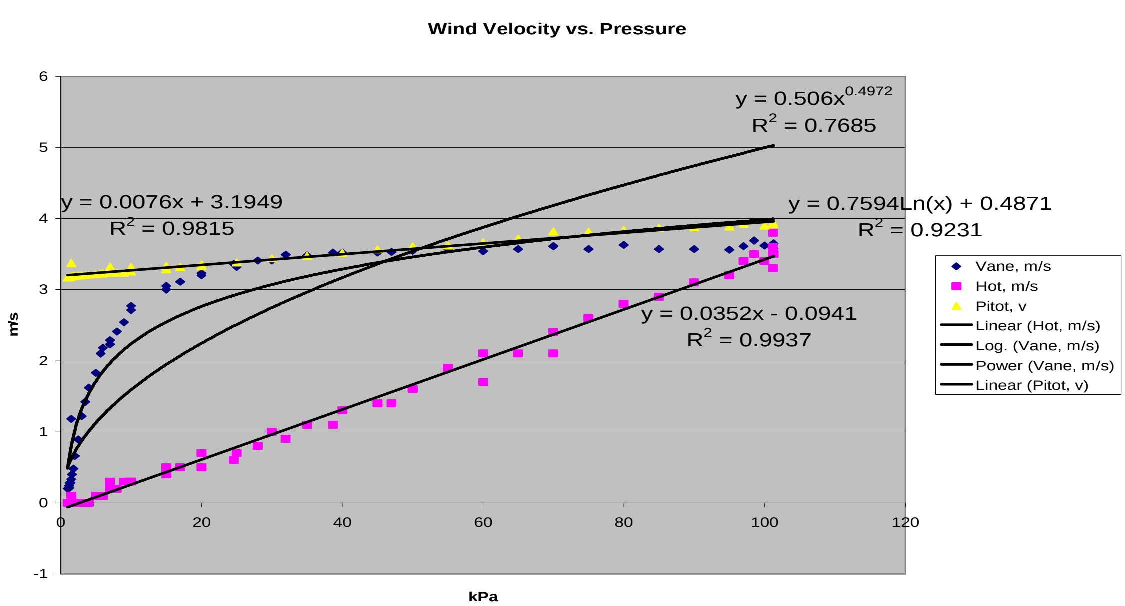

Figure 16. Uncalibrated Sensor Response Data Under Different Pressures.

We are now ready to analyze the data for each sensor to investigate the potential for forced convection creating meaningful heat exchange.

We graphed the data (Fig 12.) recorded by the vane anemometer, hot – wire anemometer, and the pitot tube. The hot-wire and pitot tube recorded a linear plot for most of the range. However, the vane produced non-linear results well before the pressure dropped significantly.

We expect that any off-world greenhouse would operate with a pressure between 25-10 kPa. However, we also note that the wind velocity generated by the fans is extremely low, too low to meet the forced convection criteria in the theory section. By using Equation 4 we calculate Rn = 16000**U.** The fans need to generate wind speeds of 67 m/s to meet reach the critical value turbulence. The flow velocity indicates a very laminar flow that is not even close to forming the boundary layer, much less turbulence.

Pitot Tube Results.

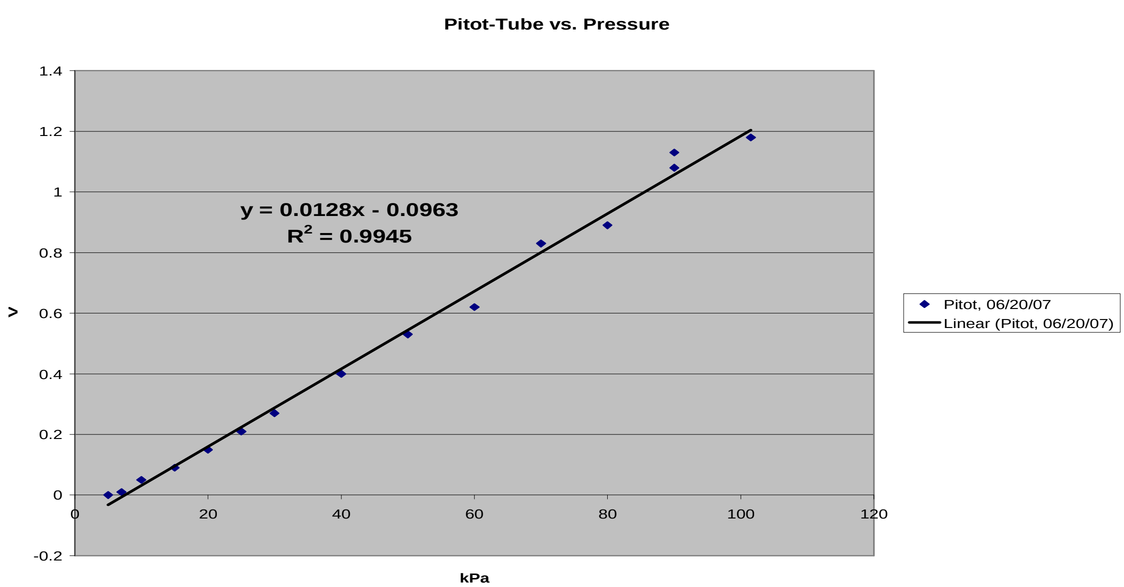

Fig. 17. Pitot Tube Data Represented by Volts as Measured by the Transducer.

The data, collected by the Pitot tube (Fig 13), maintained linear behavior until the pressure reached 5 kPa when it became asymptotic. At this time we do not know if the asymptotic response is a "law" of this particular method or simply a characteristic of the tube used in the experiment. Obviously, more tests are needed.

Furthermore, the linear nature of the response indicates that the sensor would need very little calibration. Doctors Rygalov and Wheeler (2008) suggest the introduction of a correction that can be used before the unit is deployed.

$$U_R = U_c\left(\sqrt{\frac{P_C}{P}}\right)$$

Where the "c" indicates quantities measured during the calibration phase at 101 kPa. Once this is correction is made, the unit will operate sufficiently.

In sum, the data indicates that the use of this sensor would be sufficient in the environment in which we would operate it.

Dynamic Pressure Anemometer (Vane Anemometer) Results.

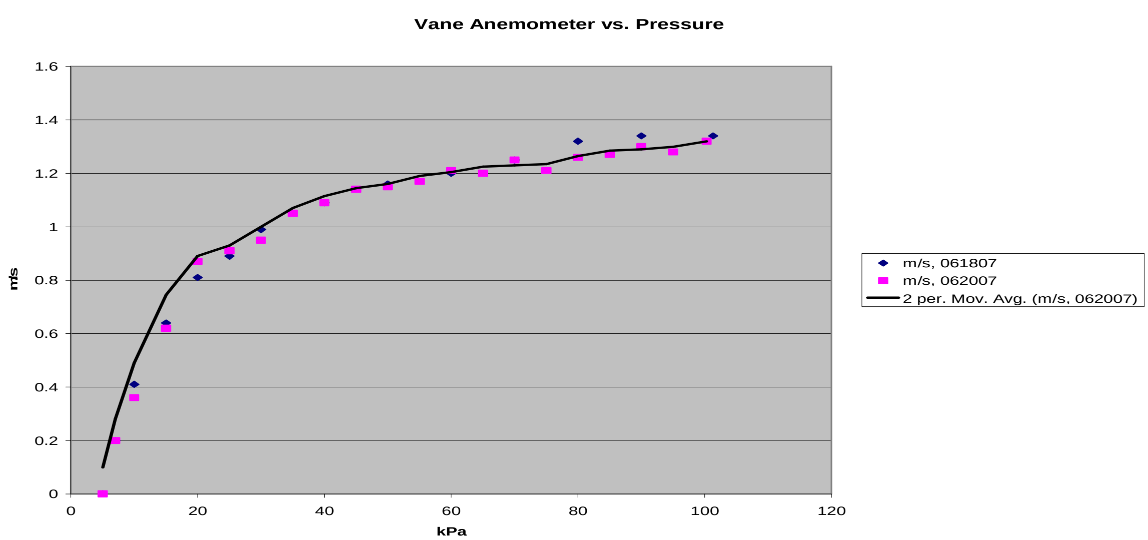

Fig. 18. Raw Vane Anemometer Data Within Wide Range of Pressures ~ 1.0 kPa and 101.3 kPa.

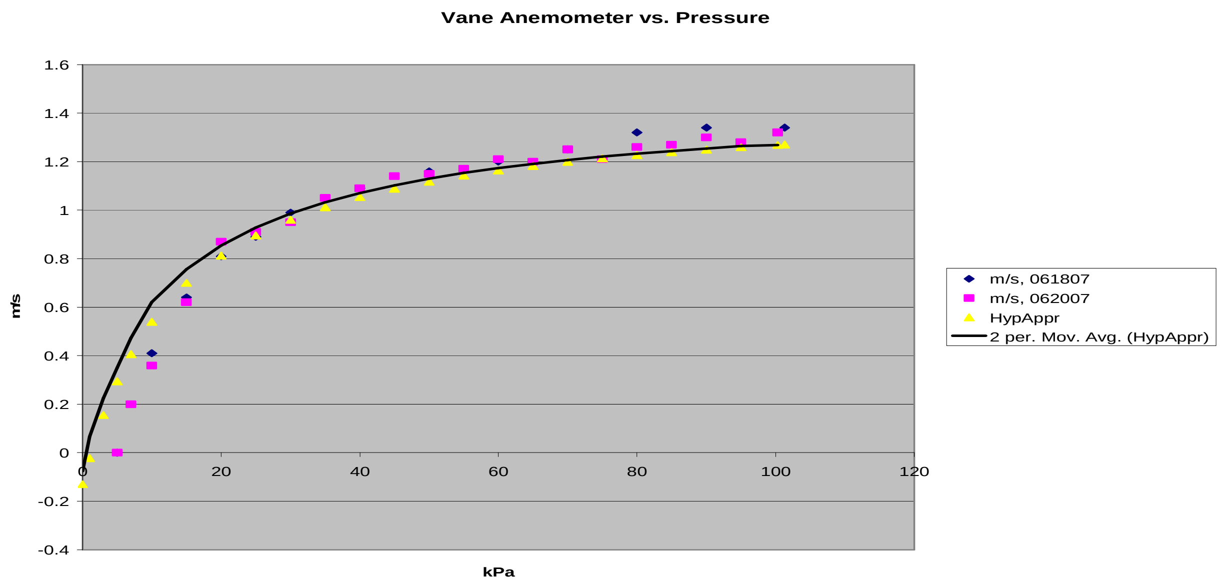

Fig. 19. Vane Data with Calibration Corrections Applied (correlation coefficient $R^2 = 0.91$).

The data presented clearly shows that this anemometer is profoundly affected by the low pressure environment. Consequently, a correction must be applied in order to improve the sensors ability to reliably operate.

In the theory chapter we derived an accurate, but ungainly, calibration modification (12). However, that correction contains friction and drag. Friction and drag characteristics will not likely be constant, even if the same manufacturer used the same production techniques for different individual anemometers. This is a complication that experimenters and operators would like to avoid. After some discussion, the following correction is proposed (Rygalov & Wheeler, Air Circulation Under Reduced Pressures, 2008).

$$\mathbf{U} = \mathbf{U_0}\sqrt{\frac{(T_0)}{T}}\sqrt{\frac{P}{P_0}} - \mathbf{U}_m$$

Where

U= Flow velocity (M/S)

$\mathbf{U}_0$ = Flow velocity during calibration

T_0 = Calibration temperature (K)

T = Temperature (measured) (K)

P = Pressure (measured) (kPa)

P_0 = Calibration Pressure (kPa)

$\mathbf{U}_m$ = minimal detectable velocity (m/s)

When applied, the above calibration produced a reduction in non-linear response similar to the earlier formula (12).

Hot - Wire Anemometer Results.

The data, presented in Fig. 16, provides strong evidence that our theoretical derivation of the hot wire response is correct and that stable linear behavior is seen across most of the pressure range.

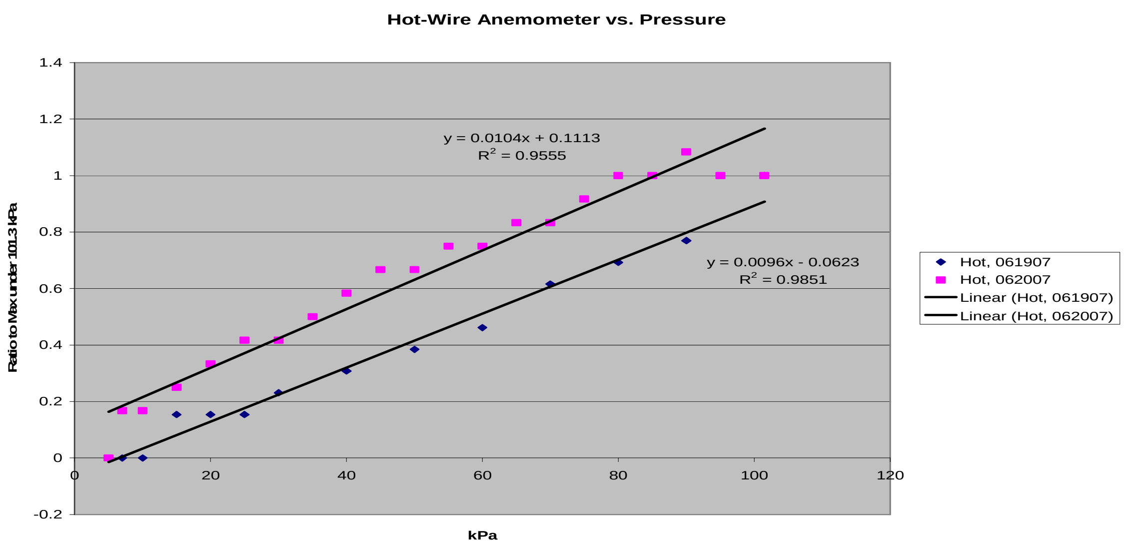

Fig. 20. Hot Wire Data Under Different Pressures: Two Different Linear Approximations for Two Air Circulation Rates

rates

The data, as seen in Fig. 16, indicates a dramatic decrease in response for the sensor when atmospheric pressure drops below the range of 7 kPa to 5 kPa. The sensor failed to register any results below this point and ceased data collection. This happens because the air density could no longer support convection. Meaningful conduction has stopped as well. In this low pressure area, only radiation remains and is the least significant of all methods of heat exchange. Therefore, the hot wire anemometer range of response ends near 5kPa and below.

CHAPTER V

IMPLICATIONS AND OVERALL CONCLUSIONS

Overall Conclusions

Despite the long history of Biospheric Science, it is still in its infancy. More data is needed to better understand the internal relationships of Closed Ecological Systems.

The greenhouse system, when deployed, is similar to a multi-cellular life form. It needs to take in energy and dispose of waste products. This process, for the most part, is regulated in the human body involuntarily. The brain receives signal data from the environment through various chemical pathways and selects the appropriate responses to keep the body functioning. Biospherics tells us that CES designers and operators must conduct their work with these principles in mind (Perchurkin, Somova, Gitelson, & Huttenbach, 1996). If the brain does not receive accurate data from the body's sensors, the body and the brain die. The greenhouse operates under the same conditions. If it does not make adjustments to the environmental conditions (energy intake, nutrient flow, heat regulation, etc) it will fail to operate.

The failure of a greenhouse on Earth is an inconvenience. Repair parts and new plants can be easily gathered. Outside of the Earth-Moon system, this is a death sentence for a human crew or settlers. All of the life forms in a CES, including humans, depend on the stable functioning of all other organisms. These supporting organisms are, in turn, regulated by the environment. Humans, and their technology, are the only means of regulating this environment in space or on another world. If control cannot be maintained, the environment and potentially some of the organisms in that environment fail (perish). As pointed out in the introduction, this entire system is linked together. Failure in one part of the ecosphere means failure for the ecosphere itself.

The ability for a sensor to collect reliable data is related to the environment in which it is placed. The operational principles of various dynamic sensors are the consequence of their construction (they operate by the laws of classical mechanics). The sensors operate well in "standard environments" where the laws of mechanics govern. This is not the case when both the Mach and Reynolds numbers are low. In these environments statistical mechanics dominate. Therefore, designers and operators must bridge the gap between physical and statistical mechanics.

We have shown that a few simple corrective formulas applied to the existing algorithms have a dramatic impact on data reliability. These formulas come from basic physical principles (Bernoulli's Principle, Ideal Gas Law, Convective Heat Exchange, etc) and are easily accessible to any designer or operator. We have in effect started to bridge the gap. Our efforts are but the first step in attempting to bridge the gap. We will need to continue experimentation to get the best level of sensitivity and reliability possible.

The alternative is "in-situ" calibration. This would be inefficient and could place the mission as well as, and more importantly, human lives in jeopardy. When operators arrive on site, all of their equipment must be in operational condition to optimize their chances of survival. In contrast, an off-world greenhouse must be in operation before the arrival of the operators. It is imperative that all control sensors are calibrated to the environment before the greenhouse is deployed.

In addition, these new calibration procedures allow further experiments in this area of research. In the past it was not possible to perform these calibrations. The preferred method was multiple tests of multiple sensors in the operational environment. Data from one sensor was compared against another in the hopes of finding initial conditions that would provide best fit solutions. With these new calibration algorithms we removed a level of complexity and improved research efficiency.

Managing heat transfer in the low-pressure environment (or Small Knudsen Environment “SKE”) is still problematic. We predicted an environment where the transfer of heat, for the purposes of biological temperature regulation, is a radiation dominate environment. Our experiments are in agreement with our predictions. We failed to detect any indication of heat or mass transfer even with fans providing agitation. In sum, no meaningful convection (free or forced) was noted.

The operational conditions of the greenhouse require that the atmosphere inside be rarefied. This presents various challenges for monitors and operators. We tested three sensors (Pitot tube, vane anemometer, and hot wire anemometer) designed to measure wind speed. Only the Pitot tube and hot wire showed a linear response over most of the range requiring little correction. The vane exhibited the greatest range of nonlinear behavior and required extensive correctional algorithms. All non-dynamic (humidity, pressure, and temperature) sensors presented reliable functioning throughout the procedure.

As stated above, we found that the correction functions can be derived from simple classical and fluid mechanics. This does not negate the need for sensors that operate on statistical mechanical principles. For example, Doppler and sonic sensors show great promise in obtaining improved data responses in SKE. These sensors, as well as use of statistical models, will improve our understanding of SKE. The more we understand these exotic environments, the greater our chances of mission success and survival.

In terms of dynamic monitoring and control of the heat transfer process, we see that research and improvements need to continue. At present, the best sensors monitor only small portions of the flow. This would require “clusters” of multiple sensors to be added to the design. As pointed out previously, this increases overall mass and reduces productive volume. The vane, which samples a larger flow area, is unreliable without detailed and complex calibration and, therefore, of limited utility. These facts make the current ideas about monitoring and control undesirable. New methods need to be developed. We conclude that the SKE is difficult to regulate. We expect that the success of greenhouse operations relies on a high level human intervention. This conclusion is unacceptable.

In addition, the Reynolds number shows that the fans needed to generate a turbulent flow in the greenhouse are too large for practical consideration in a deployable design. Even if we can achieve higher fidelity and precision in monitoring, we still lack the physical ability to replicate conditions that lend to efficient and reliable heat transfer. In light of these facts, much work is needed to maximize utility and mission success. The system is currently not workable and new designs (both operational and control) need to be created.

Based on the work presented here we present the following operational conclusions:

1) We agree with Rygalov (2002), optimal pressure is around 25 kPa. Operators and experimenters are strongly advised not to operate greenhouses below this pressure. We simply do not have the ability, at this time, to effectively monitor and hence, control the system below this point.

2) Given the fan sizes required, we must find another way to create turbulent flow or reduce the amount of waste heat. In summation, investigations must continue if this biosphere is to ever see deployment.

Bibliography

National Weather Service. (2001, July 31). SKEW T LOG P DIAGRAM AND SOUNDING ANALYSIS. *RTM - 230*. Kansas City, MO, United States of America: NOAA.

American Society of Mechanical Engineers. (1971). *Fluid Meters. Their Theory and Application.* New York: ASME.

Berkovich, Y. e. (2009). Vegtable Production Facility as Part of a Closed Life Support System in a Russian Martian Space flight Scenario. *Journal of Advanced Space Sciences*.

Cess, R. (1973). Free-Convection Boundary -Layer Heat Transfer. In W. Rohsenow, & J. Hartnett (Eds.), *Handbook of Heat Transfer* (pp. 1-16).

Clancy, L. (1975). *Aerodynamics.* London: Pitman Publishing Limited.

Clawson, J. M. (2000). Development of An Inflatable Greenhouse for a Modular Crop Production System. In R. M. Wheller, & Martin-Brennan (Eds.), *NASA Technical Memorandum 2000-208577* (pp. 77-89). Kenedy Space Center: U.S. Gov.

Corey, K. A., Barta, D. J., Edeen, M. A., & Henninger, D. L. (1997). Photosynthesis and resperation of a wheat stand at reduced atmospheric pressure and reduced oxygen. *Adv Space Res*, *20*(10), 1861-1867.

Corey, K. A., Fowler, P. A., & Wheeler, R. M. (2000). Plant Responses to Rarified Atmospheres. In R. M. Wheeler, & C. Martin-Breenan (Ed.), *Mars Greenhouses: Concepts and Challenges. Proceedings from a 1999 Workshop* (pp. 48-57). Kennedy Space Center: US Gov.

Engineering Tool Box. (n.d.). *Reynolds Number*. Retrieved November 15, 2013, from Engineering Tool Box: www.engineeringtoolbox.com/reynolds-number-d_237.html#.Uo5ZjCdsgZM

Engineering ToolBox. (n.d.). *Dry Bulb, Wet Bulb and Dew Point Temperature*. Retrieved October 10, 2013, from Engineering ToolBox: http://www.engineeringtoolbox.com/dry-wet-bulb-dew-point-air-d_682.html

Extech-Instruments. (2001). Hot Wire Thermo-Anemometer, Model 407123, . 1-5.

Fefferman, C. (2013). *Navier-Stokes Equations.* Retrieved November 19, 2013, from Clay Mathematics Institute: http://www.claymath.org/millennium/Navier-Stokes_Equations/

Fowler, P. A., Wheeler, R. M., Bucklin, R. A., & Corey, K. A. (2000). Low Pressure Greenhouse Concepts for Mars. In R. M. Wheeler, & C. Martin-Breenan (Ed.), *Mars Greenhouses: Concepts and Challenges. Procedings from a 1999 Workshop* (pp. 116-123). Kennedy Space Center: US Gov.

Fritschen, L. J., & Gay, L. W. (1979). *Environmental Instrumentation.* Berlin: Springer-Vertag.

Gill, A. E. (1982). *Atmosphere–ocean dynamics.* New York: Academic Press.

Gitelson, I., Lisovsky, G., & MacElroy, R. (2003). *Manmade Closed Ecological Systems.* New York: Taylor and Francis.

Grace, J. (2006). *Structural Equation Modeling and Natural Systems.* Cambridge: Cambridge University Press.

Holman, J. (2002). *Heat Transfer.* New-York: McGraw-Hill.

Hoy, W., & Roos, T. (2005). *Grashof Numbers/Background*. Retrieved April 26, 2012, from Grashof Numbers: http://www.owlnet.rice.edu/~ceng402/proj05/hoy/hoyroos/background/background.html

KANOMAX USA INC. (2004). Anemo-Master Model 6804, Operational Manual.

Kennard, E. (1938). *Kinetic Theory of Gases.* New York: McGraw-Hill.

Kitaya, Y., & Hirai, H. (2007). Thermal Situation of Plant Reproductive Organs Affected by Gravity and Light Intensity. *Japanese Scoiety of Microgravity Applications, 24*(4), 325-329.

Koelle, H. H. (2000). *Environmental Control & Life Support Systems for MOONBASE 2015.* Berlin: H.R. Mitt.

Mehrabian, M. A. (2003). Effect of pressure on free convection heat. *ENGINEERING MODELLING, 16*(1-2), 55-61.

Monteith, J. L., & Unsworth, M. (1990). *Principles of Environmental Physics* (2nd ed.). Oxford: Butterworth Heinemann.

NASA. (2000). Mars GreenHouses:Concepts and Challenges, Proceedings from a 1999 Workshop. (R. M. Wheller, & C. Matrin-Brennan, Eds.) Kennedy Space Center: U.S.

NASA. (2008, January 22). Low Pressure Test Bed User Manual. Kennedy Space Center, Florida: US GOV.

Pechurkin, N. (1994). Biospherics: A New Science. *Life Support & Biosphere Science, 1*(2), 85-87.

Perchurkin, N., Somova, L., Gitelson, I., & Huttenbach, R. (1996). The Health of Biological Life Support Systems. *Advanced Space Resaearch, 18*(12), 265-268.

Pontyak Resources Corporation. (n.d.). *Pontyak Resources Center*. Retrieved 2009, from Pontyak Resources Center: The Design Kit: pontyak.com/fans/fanaffinitylaws.html

Probstein, R. F. (1963). Heat Transfer in Rareified Gas Flow. In J. A. Clark (Ed.), *Fundamental Research in Heat Transfer* (pp. 33-60). New York: Pergamon Press.

Rayleigh, L. (1916). On Convection Currents in a Horizontal Layer of Fluid, When the Higher Temperature is on the Under Side. *Phil. Mag., 32*(192), 529-546.

Reynolds, O. (1883). An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. *Phil Trans R Soc, 174*, 935-982.

Rygalov. (2008).

Rygalov, & Wheeler. (2008). Air Circulation Under Reduced Pressures. *Advanced Topics in Sp St 519 CESLS*. Grand Forks, ND.

Rygalov, V. Y., Fowler, P. A., Metz, J. M., Wheeler, R. M., & Bucklin, R. A. (2002). Water Cycles in Closed Ecological Systems: Effects of Atmospheric Pressure. *Life Support & Biosphere Science, 8*, 125-135.

Rygalov, V. Y., Wheeler, R. M., Fowler, P. A., & Bucklin , R. A. (2007). Unpublished data. Kennedy Space Center, Florida , United States.

Schnider, P. J. (1973). Mathematical Methods. In R. W.M., & H. J.P. (Eds.), *Handbook of Heat Transfer* (pp. 19-76). New York: Mc-Graw-Hill.

Schwartzkopf, S. (1991). *Lunnar Base Controled Life Support Systems.* Lockheed Misiles & Space Company. Lockheed.

Schwinn. (2007). Schwinn 12 Function Bicycle Computer Manual.

SETRA. (2007). Very Low Differential Pressure Transducer: SETRA HVAC/R-Model 264. SETRA.

Turcotte, D., & Schubert, G. (2002). *Geodynamics.* Cambridge : Cambridge University Press.

Turner, J. S. (1973). *Buoyancy Effects in Fluids.* Cambridge: Cambridge University Press.

Wyer, S. (1906). A treatise on producer-gas and gas-producers. *The Engineering and Mining Journal*, 23.