Temperature Control by Means of a Gas Gap

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MSC412/422

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Abstract

Title: Temperature Control By Means of a Gas Gap

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Year: 2013

The purpose of this project is to develop a temperature control system that uses a helium-argon gas mixture to control the temperature on the surface of an electrically heated sample. This type of system is commonly used in reactor irradiation experiments where the temperature on the test specimen needs to remain constant. In practice a helium-neon gas mixture is used but due to availability and costs argon was used as a substitute for neon.

Literature was consulted in order to gain more insight into several aspects involved with such a system, such as gas mixtures and their properties as well as various forms of heat transfer. A theoretical analysis and design of the system was done in order to determine the feasibility of the system as well as the limitations of the system. The theoretical analysis included a numerical transient model that was used to predict the system performance and for comparison with experimental results.

The system is designed in such a manner that it can be experimentally built tested in order to validate the assumptions made during the theoretical analysis and to verify the theoretical predictions. The experiments prove that it is possible to control the temperature on the surface of a heated sample using a gas gap consisting of a mixture of helium and argon. The system temperature responses are quite close to the theoretical predictions, especially at higher temperatures. The thermal conductivities in all of the tests are significantly lower than expectations suggesting other mechanisms of heat transfer had a larger effect than anticipated. The presence of these mechanisms may be used advantageously if control over higher heat input is required.

The aim of the project was to prove the feasibility of a system that uses a gas mixture to control the temperature on a heated sample which has been proven possible. Further research and development could greatly improve the performance of this type of system and this type may be implemented in other applications as well.

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Louis Kruger, my father, for his continued support and motivation as well as the assistance he provided in the development of the electronic components.

List of Included Documents

1. Project Protocol

   The project protocol is compiled before the project commences. It serves as a contract between the student and the supervisor. The protocol describes the scope of the project, the project deliverables and the schedule of the project.

2. Project Final Report

   This report describes the entire project from commencement to completion. The purpose of the report is to describe the work done to the project to the project supervisor and stakeholders. The report includes research done on topics relevant to the project as well as background information, the theoretical analysis and designs and the results of the experiments done along with conclusions and recommendations for future work. Also included in the final report are the project schedule and costs and the data required in order to replicate the project.

Project Protocol

Temperature control by means of a gas gap

J.A. Kruger

29321299

MSC412/422 Research Project

February 2013

Supervisor: Prof J.F.M. Slabber

Signed: ________________   ________________

J.A. Kruger   Prof J. Slabber

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Contents

1. Introduction

1.1. Background

In many cases of reactor irradiation experiments there is a test capsule that contains an object or material which is to be tested under irradiation. In order for these experiments' results to be accurate and useful the experiments should be done at a constant or controlled temperature.

The amount of heat generated by a reactor cannot easily be changed or varied and in certain cases it might be necessary to have a fixed or predetermined temperature on the outside of the reactor.

1.2. Problem Statement

The temperature of an electrically heated sample is to be controlled by varying the thermal conductivity of the gas mixture around the sample.

The gas gap around the sample consists of a mix of two noble gasses namely helium and argon. The thermal conductivity of the gas mixture will depend on the ratio to which the two gasses are mixed.

The objective of the project is design and test a temperature control system to control the temperature of an electrically heated sample by varying the thermal conductivity of the gas surrounding the sample.

1.3. Scope

The project will include the analysis, designing, building and testing of a temperature control system in order to verify and validate the theoretical results.

The project will not include any in detail analysis or experiments of other methods of temperature control.

Some simplifications and assumptions will be made in order to simplify the analyses and models, any such assumptions or simplifications will be clearly stated and justified in the relevant sections of the final report.

2. Project Deliverables

2.1. Theoretical Analysis

A thorough theoretical analysis and design of a temperature control system consisting of a heating element of a specified power input surrounded by a gas gap which can be filled with a mixture of helium and argon gas.

The theoretical part of the project will include a complete functional analysis of the system, in order to ensure that the system performs all the required functions and that no unnecessary functions or tasks are included.

The analysis will consist of the determination of the effective thermal conductivity and fluid properties of the gas mixture and the amounts of each gas required for a specific ratio. The temperature on the heater surface due to steady state heat conduction for various heat inputs and thermal conductivities will be determined. The effects of natural convection on the heat transfer of the system will also be investigated. The transient responses of the system will be calculated or simulated and their effects taken into account.

The design will include a mechanical design of the system setup and a control system which will be able to regulate the gas mixture ratios of the gasses in the system and be able to purge the gasses in the system if a different ratio is required.

2.2. Experimental Analysis

Several experiments will be designed in order to experimentally test the functioning and performance of the system. These experiments will include the testing of the heating element and a complete system test.

2.3. Validation and Verification of Results

The experimental results will be processed and interpreted in order to validate the results and to verify the theoretical predictions.

2.4.Conclusions and Recommendations

Once the experimental results have been processed and interpreted conclusions can be drawn as to the effectiveness of the system. Recommendations will be made as to how the system might be improved, recommendations for further research or investigation will also be made.

3. Amendments

The project protocol outlines the scope of work of the project and the completed project deliverables should comply with the deliverables as set out in the project protocol.

If as the project progresses problems arise or any part of the final deliverables change, the protocol may be updated accordingly after the proposed changes have been discussed by the student and the supervisor and both have signed off on the proposed changes.

4. Project Schedule

A schedule of the project and the project milestones is created in order to manage the project more easily and track progress. The schedule will be used to give the student an indication of how far the project should have progressed by a certain point in time.

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Final Report

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Nomenclature

List of Symbols

A	Area	m^2
C	Concentration	mol/m^3
c_p	Specific Heat Capacity	J/kgK
D	Diameter	m
D_{12}	Diffusion Coefficient	m^2/s
$\dot{e}_{gen}$	Internal Heat Generation	W/m^3
F_{cyl}	Geometric Factor	-
Fo	Fourier Number	-
Gr	Grashof Number	-
g	Gravity	m/s^2
h	Convection Heat Transfer Coefficient	W/m^2℃
I	Electric Current	A
J	Bessel Function	-
j	Mass Flux	mol/sm^2
k	Thermal Conductivity	W/m℃
L	Length	m
M	Molar Mass	kg/mol
m	Mass	kg
Nu	Nusselt Number	-
n	Moles	-
Pr	Prandtl Number	-
P	Power	W
p	Pressure	Pa
Q	Heat	W
$\dot{q}$	Heat Flux	W/m^2
Ra	Rayleigh Number	-

R	Resistance	Ω
$\bar{R}$	Universal Gas Constant	$J/kmol\,K$
R_{gas}	Gas constant (Symbol in Subscript)	$J/kmol\,K$
r	Radius	m
T	Temperature	K / ℃
t	Time	s
V	Volume	m^3
x	Mole Fraction	-
y	Mass Fraction	-
α	Thermal Diffusivity	m^2/s
α_s	Seebeck Coefficient	V/℃
β	Volume Expansion Coefficient	$1/K$
ρ	Density	kg/m^3
μ	Viscosity	Kg/ms

Constants

Absolute Temperature:	$0℃ = 273.15\ K$
Universal Gas Constant:	$\bar{R} = 8.3145\ m^3Pa/mol\,K$

Abbreviations and Acronyms

CFD	Computational Fluid Dynamics
GC	Gas Chromatography
LPM	Litre Per Minute
PID	Proportional Integrator Differentiator

1. Introduction

1.1. Background

In virtually all reactor irradiation experiments there is a test capsule that contains an object or material which is to be tested under irradiation. In order for these experiments' results to be accurate and useful the experiments should be done at a constant or controlled temperature.

The amount of heat generated by a reactor cannot readily be changed or varied and in certain cases it might be necessary to have a fixed or predetermined temperature on the surface of the specimen.

1.2. Objective

The temperature of an electrically heated sample is to be controlled by varying the thermal conductivity of the gas mixture around the sample.

The gas gap around the sample consists of a mix of two noble gasses namely helium and argon. The thermal conductivity of the gas mixture will depend on the ratio to which the two gasses are mixed.

The objective of the project is to design and test a temperature control system to control the temperature of an electrically heated sample by varying the thermal conductivity of the gas surrounding the sample.

1.3. Scope

The project will include the analysis, designing, building and testing of a temperature control system in order to verify and validate the theoretical results.

The project will not include any in detail analysis or experiments of other methods of temperature control.

Some simplifications and assumption will be made in order to simplify the analyses and models, any such assumptions or simplifications will be clearly stated and justified in the relevant sections of this report.

1.4. Protocol Compliance Matrix

The purpose of the protocol compliance matrix is to ensure that all of the requirements of the project as defined in the project protocol are met and to give an indication to the reader as to where in the final report the requirements are being addressed.

Table 1.1 Protocol Compliance Matrix

Requirement	Protocol		This Report	
	Section	Page	Section	Page
Literature Study	2	2	2	3
Functional Analysis	2.1	2	3	24
Determine Effective Thermal Conductivity of Gas Mixture	2.1	2	4.2	27
Temperature Estimation	2.1	2	4.3.1	37
Transient Model	2.1	2	4.3.3	46
System Design	2.1	2	4.5	55
Control System	2.1	2	4.6	59
System Testing	2.2	2	5 &6	65 & 70
Discussion of Results & Conclusions	2.3 & 2.4	2 & 3	7 & 9	84 & 88
Recommendations	2.4	3	9	88

2. Literature Study

2.1. Research Reactors

A lot of research and development is going into nuclear energy in order to make nuclear energy safer, cleaner, more efficient and more sustainable. Coal is a diminishing resource and coal fired power stations are large contributors to global pollution.

Research reactors are smaller nuclear reactors built for the sole purpose of experimentation and research rather than power production. Large nuclear reactors used in power generation are also used for research purposes.

The main purpose of research reactors is to provide a source of neutrons for research and experimentation purposes. Power generation reactors' main purpose is to generate heat for electricity generation. The power produced by research reactors is in the region of 100 MW, with a few producing more, whereas power reactors produce around 3000 MW thermal power. Research reactors operate at lower temperatures and require less fuel but they usually require highly enriched uranium.

Research reactors' uses include testing and analysis of materials, medical research and developing and testing of isotopes. They are used in many fields of research such as nuclear, fission research, materials development and medicine.

Neutron beams are used to study the dynamics and structure of materials at atomic level. Neutron scattering is used for examining samples under different conditions such as variations in temperature, pressure and magnetic fields. Neutron activation is used to produce radioisotopes, which are used in various industries, by bombarding a particular element with neutrons so that it gains a neutron. One such element is Yttrium-90 which is used to treat liver cancer and is produced by bombarding Yttrium-89 with neutrons.

Research reactors are also used for industrial processes such as Neutron Transmutation Doping (NTD) which changes the properties of silicon so that it becomes highly electrically conductive. The irradiated silicon is used in computer and electronic applications since the silicon becomes a semiconductor and is then used in transistors and integrated circuits.

During testing materials are subjected to intense neutron irradiation in order to study their changes, certain steels become brittle, whereas other alloys may resist embrittlement. Such alloys can be used in nuclear reactors. (Nuclear Research Reactors, 2011)

2.2. Irradiation Experiments

There are several methods of performing irradiation experiments in a research or test reactor. These methods include static capsule, actively controlled experiments and pressurised water loop testing.

Static capsule experimenting is the simplest type of irradiation experiment performed. The test specimen (material or fuel) is typically sealed in aluminium, stainless steel tubing or zircaloy and surrounded with an inert gas. In certain cases the capsules are unsealed which allows the specimen to be in contact with the reactor's primary coolant to prevent excessive temperatures. The capsule is placed in a holder (basket) at the desired irradiation position in the reactor. Static capsules are designed specifically for a particular experiment's requirements and are less expensive than other types but provide less control over operating parameters.

Static capsules may be fitted with special passive instruments such as neutron flux wires or temperature sensors to give an indication of the temperatures reached during tests. The temperature of a static capsule can be controlled to a small extent, by incorporating a small gas jacket usually filled with an inert gas. The size of the jacket and the gas used depends on the desired temperature of the specimen. The height of a static capsule can vary from a few centimetres to the full height of the core and the diameter depends on the specimen size and the position in the reactor and can vary from 12mm to about 130mm.

The next method of testing provides continuous monitoring and control of experimental parameters during irradiation by using instrumentation leads in the capsules, this type of experiment is commonly referred to as lead experiments. The containment of the experiment is similar to the static capsule with the main difference being a tube attached between the experiment containment and the reactor wall. This tube (referred to as an umbilical tube) houses instrumentation leads such as thermocouples and temperature control gas supply lines that lead outside to measurement and control equipment.

Temperature is the most common parameter to be monitored and controlled during testing. The temperature of the experiment capsule is controlled by varying a mixture of two gasses with different thermal conductivities in a small insulating gas jacket between the specimen and the experiment container. The gas with the lower thermal conductivity is referred to as the insulator gas and the gas with the higher thermal conductivity is referred to as the conductor gas. Helium (conductor) and neon (insulator) are typically used but helium and argon can also be used for a wider range of temperature control. The gasses are mixed automatically according to the feedback from the thermocouples to control the capsule temperature, and the mixing system has a range of 2% to 98% of a gas with the other gas making up the remainder. Measurements are taken by at least two thermocouples per capsule and are usually used in pairs to allow long service in the high radiation environment. The gas temperature control system provides a continuous flow of the gas mixture in order to minimize temperature variations. Measurement of the exhaust gas is also possible. Alarm systems are usually installed to notify operators of temperatures outside the control range or gas bottles needing replacement. It also includes automatic gas verification systems to ensure that the correct gasses are connected to the system as well as helium purge systems that are used to cool the capsules.

Helium is selected as the conductor gas due to its heat transfer characteristics and low potential of neutron activation. The insulator gas selection is a more difficult selection since the two most promising choices have some undesirable characteristics. Argon is an inexpensive choice with good insulation characteristics but is easily activated by a high neutron flux. The activation product (Ar-41) has a reasonable short half life of 1.82 hours which can be accommodated for by delaying the gas until the Ar-41 has decayed to an acceptable level. Neon has a significantly lower activation potential and the activation product (Ne-23) has a much shorter half life of 37.2 seconds and thus allows for prompt radiation monitoring of experiment effluent gasses. The disadvantage of neon is that its insulating properties aren't nearly as good as that of Argon and is much more expensive. But both neon and argon have been successfully used during testing, the choice of which gas to be used depends on the experimental needs. (Grover, 2006)

2.3. General Heat Conduction

Heat transfer and temperature is related to each other but they are different quantities. Temperature only has magnitude whereas heat transfer is a vector quantity and has both magnitude and direction. The driving force behind heat transfer is temperature difference, the greater the temperature difference, the greater the heat transfer. Many engineering heat transfer problems require the determination of the temperature distribution through a medium so that the quantities of interest such as the heat transfer rate, thermal expansion or thermal stress can be calculated at various points for the solution of the problem.

In order to specify the temperature at a point requires the specification of the point. This is done by selecting an appropriate coordinate system such as rectangular, cylindrical or spherical coordinates, depending on the geometry being analysed. A point is specified in cylindrical coordinates by three directions, r the radius from the origin, ϕ the angle with respect to the positive x-axis and z the height above the origin. For cylindrical geometries, cylindrical coordinates are best suited since it describes the surfaces of the geometry the best since the lateral surface can be described by a constant value of the radius.

Heat transfer can be classified as being one, two or three dimensional, depending on the magnitudes of the heat transfer in each direction and the desired level of accuracy. The most general case the heat transfer through a medium is three dimensional, thus the temperature distribution through the medium varies in all three principle directions. Heat transfer is one dimensional if the temperature in a medium only varies in one direction and the heat transfer in the other directions are negligible or zero. Heat transfer in a hot water pipe can be considered as one dimensional since the heat transfer from the hot water to the ambient is mainly in the radial direction and the heat transfer in the other directions is usually negligible.

The rate of heat conduction in a medium is proportional to the temperature difference and the area normal to the direction of heat transfer, but inversely proportional to the distance in that direction. This can be expressed in differential form by Fourier's law as:

$$\dot{Q} = -kA\frac{\partial T}{\partial n}$$

With $\dot{Q}$ the rate of heat conduction through the medium, k the thermal conductivity of the medium, A the cross sectional area and n the normal vector to the point where the heat transfer is calculated.

In general the thermal conductivity of a material varies with temperature, but sufficiently accurate results can be obtained by assuming a constant thermal conductivity at the average temperature. In isotropic materials the thermal conductivity is the same in all directions.

The general heat conduction equation is given by:

$$k\nabla^2 T + \dot{e}_{gen} = \rho c\frac{\partial T}{\partial t}$$

With k being the thermal conductivity which is assumed constant and $\dot{e}_{gen}$ the internal heat generation of the medium.

The general heat conduction equation expanded in cylindrical coordinates is given by:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{dr}\right) + \frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{e}_{gen} = \rho c\frac{\partial T}{\partial t}$$

But this can be simplified with the following assumptions:

- One dimensional heat transfer
- Constant thermal conductivity
- No heat generation in the medium
- Steady state conditions.

Then the general heat conduction equation reduces to:

$$\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = 0$$

The general solution to the above equation is given by:

$$T(r) = c_1\ln(r) + c_2$$

The values of the integration constants are determined by using the boundary conditions.

The heat conduction equations are derived using an energy balance on a differential element inside the medium, thus they do not consider the thermal conditions on the surfaces of the medium. The temperature distribution and the heat flux in a medium depend on the surface conditions of the medium, thus in order to solve the heat conduction equations boundary conditions are required.

There are six different boundary conditions that can be used to solve the heat conduction equation. Which boundary condition and how many boundary conditions that are to be used depends on the problem being solved.

The boundary condition types according to Cengel (2006) are:

- Specified temperature boundary conditions
- Specified heat flux boundary conditions
- Convection boundary conditions
- Radiation boundary conditions
- Interface boundary conditions
- Generalised boundary conditions

The first two will be briefly discussed in this report.

The temperature of an exposed surface of a body can usually be measured fairly easily. One of the simplest methods of specifying thermal boundary conditions is to specify the temperature. For example for one dimensional heat transfer through a cylinder the temperature boundary condition on the outer surface can be specified as:

$$T(r_o) = T_1$$

If the energy interactions on the surface are known it may be possible to determine the heat transfer to that surface and thus the heat flux. This information can be used as a boundary condition and can be expressed using Fourier’s law:

$$\dot{q} = -k\frac{\partial T}{\partial r}$$

The sign of the specified heat flux is positive if the heat flux is in the positive direction according to the coordinate system. (Cengel, 2006)

2.4. Transient Heat Conduction

If the temperature through a medium varies with respect to time as well as position it is referred to as a transient heat transfer problem. If the temperature does not change with respect to time it is referred to as steady state heat transfer. Most heat transfer problems in practise are transient in nature, but for simplification the problem can be analysed as steady state if the transient effects are small or depending on the required quantities such as maximum heat transfer rate.

There are two main types of transient heat transfer processes, processes that ultimately reach steady state conditions and processes that operate for a relatively small short time period in an environment with continuously changing temperatures.

Depending on the complexity of the problem and the simplifications that can be made, transient heat transfer problems can be solved analytically or numerically. Analytical solutions are generally more accurate but become difficult to obtain or solve on large problems or systems.

The simplest analytical method of solving transient heat conduction problems is the lumped system analysis. The lumped system analysis is based on the assumption that the temperature in a body does not vary with position but with time only. In certain cases the lumped system analysis is a great simplification without a loss of accuracy, for example a solid copper ball can be analysed using the lumped system approach. The lumped system analysis can also be used for first estimations of a more complex system or to estimate initial conditions.

In general temperature is a function of position and time, there are two types of heat transfer analysis where the surface resistance is considered small relative to the overall resistance, thus heat transfer is assumed to be pure conduction and convection at the surface is neglected. The second and most general type is where the surface resistance and the internal resistance both have significant values. Convection heat transfer at the surface of the body is considered.

The process of solving both these types of analysis is the same with the only difference between the two being the boundary conditions. Several simplifications can be made in order to obtain a solution, such as no internal heat generation and one dimensional heat transfer. One method of solving these types of problems is known as separation of variables which results in product solutions similar to Fourier series'.

The solution for a long cylinder (heat transfer in the radial direction only) with no internal heat generation is given by:

$$\frac{T - T_\infty}{T_0 - T_\infty} = \sum_{n=1}^{\infty} \frac{2\mathrm{J}_1(\lambda_n)}{\lambda_\mathrm{n}\mathrm{J}_0^2(\lambda_n) + \mathrm{J}_1^2(\lambda_n)} \mathrm{e}^{-\lambda_\mathrm{n}\mathrm{Fo}} \mathrm{J}_0\left(\frac{\lambda_\mathrm{n}\mathrm{r}}{\mathrm{r}_0}\right)$$

Where J_0 and J_1 are the Bessel functions of the first kind, λ_n is the solution of:

$$\lambda_n \frac{J_1(\lambda_n)}{J_0(\lambda_n)} = \frac{hr_o}{k}$$

And Fo is the Fourier number given by:

$$Fo = \frac{\alpha t}{r_o^2}$$

Due to the exponential decay function ($e^{-\lambda_n Fo}$) the terms in the summation decrease as n increases, thus evaluation of the first few terms provide sufficient accuracy. In the case where the Fourier number is smaller than 0.2 a one term approximation can be used with an error smaller than 2 percent.

Even though it is possible to obtain analytical solutions with the equations above, they are still quite complex. For convenience a number of graphical and tabular solutions have been created for one dimensional heat transfer in simple geometries. One of the graphical solutions is known as the transient temperature charts, was presented by M.P. Heisler 1947 and is referred to as Heisler charts.

Solving multidimensional heat transfer problems can be done using the same methods as for a dimensional case using a superposition approach known as the product solution. This involves describing the heat transfer in the body as the product of two or more one dimensional solutions. For example the solution for a short cylinder can be obtained by:

$$\left(\frac{T(r,z,t)-T_\infty}{T_i-T_\infty}\right)_{\substack{short\\cylinder}} = \left(\frac{T(z,t)-T_\infty}{T_i-T_\infty}\right)_{\substack{plane\\wall}} \left(\frac{T(r,t)-T_\infty}{T_i-T_\infty}\right)_{\substack{infinite\\cylinder}}$$

The figure below graphically illustrates how a solution for a short cylinder can be obtained.

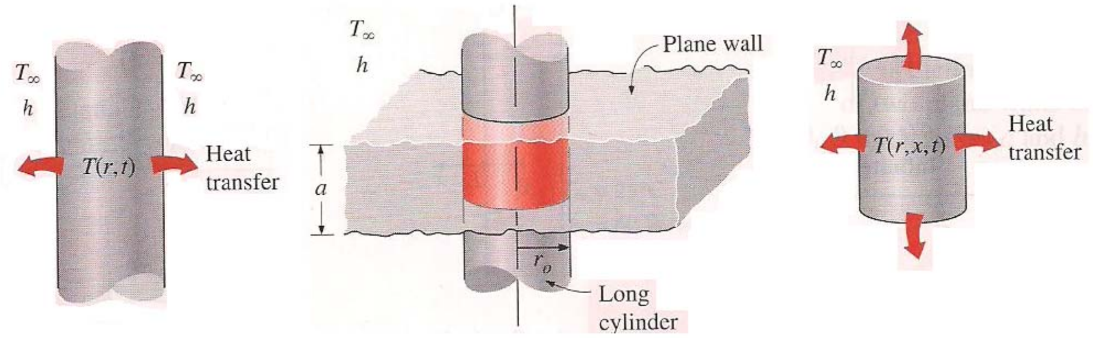

Figure 2.1 Solution of the Heat Transfer through a Short Cylinder (Cengel, 2006)

In many transient heat transfer problems the geometry of the body is not simple or the boundary conditions may not be uniform. In such cases numerical solutions offer the best method by which the problem can be solved.

There are several software packages available that may be used to solve these types of problems, such as ANSYS, Matlab etc. These packages provide a relatively easy method to solve difficult problems but care should taken when using software packages and their solutions are only as accurate as the information given to them.

Several numerical methods can be used to solve heat transfer problems. The numerical solutions are derived from the governing equations such as the energy equation. The geometry is broken up into small points known as nodes and small control volumes known as elements. Nodes and elements have different boundary conditions depending on their location in the geometry. The governing equations are then setup for each different node or element, linearised and solved for each node or element.

There two main methods, the first is known as the finite difference method by which the geometry is broken up into nodes and the equations are solved for each node. The second approach is known as the finite volume method where the geometry is broken up into control volumes or elements.

2.5. Convection Heat Transfer

Conductive heat transfer occurs between two stationary bodies or fluids, convective heat transfer is associated with bulk fluid motion. The rate equation for convective heat transfer can be expressed as:

$$q = hA\Delta T$$

Convective heat transfer occurs due to a temperature difference. The equation above gives the relationship between the heat flux and the temperature difference, where h is the convection heat transfer coefficient.

The determination of the heat transfer coefficient is not a simple process since it is dependent on the mechanism of fluid flow, fluid properties and the geometry of the system.

In viscid flow fluid particles immediately in contact with a solid boundary are stationary, and a thin layer of fluid close to the surface, known as the boundary layer, will be in laminar flow regardless of the nature of the flow in the free stream. The conduction effects are always present and play a role in any convection process. If the flow is laminar then all the heat transfer between a fluid and a surface is by molecular means. If the flow is turbulent, there is mixing of fluid particles at different temperatures and the heat transfer is increased. Thus the distinction between laminar and turbulent flow will be a major consideration in convection heat transfer. The thermal and hydrodynamic boundary layers both play a significant role in convective heat transfer.

There are two main types of convective heat transfer, they are determined by the driving force behind the fluid motion. Natural convection is when the fluid motion is a result of the heat transfer, when a fluid is heated or cooled, the change in density and buoyant effect produce circulation in which the fluid moves of its own accord. Forced convection is when fluid motion is the result of external effects such as pumps or fans.

The Prandtl number is defined as the ratio between the momentum diffusivity and the thermal diffusivity and is observed to be a combination of fluid properties, thus the Prandtl number itself may be considered a fluid property. (Welty, Wicks, Wilson, & Rorrer, 2008)

The Prandtl number can be calculated using the following equation:

$$Pr = \frac{v}{\alpha} = \frac{\mu c_p}{k}$$

The velocity and temperature profiles of a fluid flowing past a heated surface is shown in the figure below:

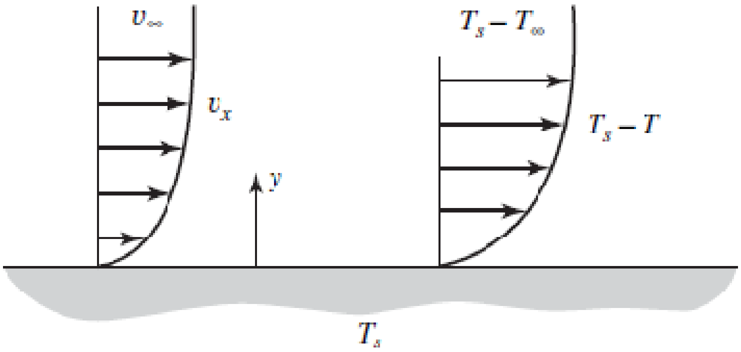

Figure 2.2 Velocity and Temperature Profiles of a Fluid flowing Past a Surface (Welty, Wicks, Wilson, & Rorrer, 2008)

In the case shown in the figure above the heat transfer rate between the fluid and the surface may be written as:

$$q = hA(T_s - T_\infty)$$

Because the heat transfer at the surface is by conduction:

$$q = -kA\frac{\partial}{\partial y}(T - T_s)|_{y=0}$$

The heat transfer due to convection must be equal to the heat transfer due to conduction, thus:

$$h(T_s - T_\infty) = -k\frac{\partial}{\partial y}(T - T_s)|_{y=0}$$

Rearranging and multiplying with a representative length L:

$$\frac{hL}{k} = \frac{\partial(T_s - T)/\partial y|_{y=0}}{(T_s - T_\infty)/L}$$

The right hand side of the above equation is the ratio of the temperature gradient at the surface to the overall temperature gradient and the left hand side can be considered as a ratio of the conductive thermal resistance to the convective thermal resistance of the fluid, which is referred to as the Nusselt number.

$$\mathrm{Nu} = \frac{hL}{k}$$

Another important factor in natural convection is the Grashof number defined as:

$$Gr = \frac{\beta g \rho^2 L^3 \Delta T}{\mu^2}$$

2.5.1. Natural Convection

In many convective heat transfer problems there are no successful mathematical models, and even in the cases where a mathematical model does exist it is still necessary to verify the results experimentally. A lot of experiments have been conducted to get data for various problems and geometries.

The system that is the easiest to analyse analytically is natural convection of fluid flow adjacent to a vertical wall.

Since the fluid properties are temperature dependant, the values used in calculations will have an effect on the results. In general the fluid properties are evaluated at the film temperature, defined as:

$$T_f = \frac{T_s + T_\infty}{2}$$

The region of flow plays a significant role in the heat transfer, thus it is important to distinguish between the two since different correlations exist depending on if the flow is laminar or turbulent. Transition from laminar to turbulent flow in natural convection boundary layers adjacent to vertical plates or plane surfaces have been determined to occur near or at:

$$\mathrm{GrPr} = \mathrm{Ra} = 10^9$$

The product of the Prandtl and Grashof numbers is often referred to as Ra, the Rayleigh number.

Churchill and Chu have collected a large amount of experimental data for convection adjacent to vertical planes and propose a single equation for the Nusselt number:

$$Nu_L = \left[0.825 + \frac{0.387Ra^{\frac{1}{6}}}{\left(1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}}\right]^2$$

In the case of vertical cylinders the expressions for vertical plane surfaces may be used provided that the effect of the curvature is not too great. A vertical cylinder can be evaluated using vertical plane correlations when:

$$\frac{D}{L} \geq \frac{35}{Gr^{0.25}}$$

The physical meaning of the above relation is the limit where boundary layer thickness is small relative to the diameter. (Welty, Wicks, Wilson, & Rorrer, 2008)

Heat transfer in enclosures is quite complex because in general the fluid inside the enclosure does not remain stationary, the fluid adjacent to the hotter surface tends to rise and the fluid adjacent to the colder surface tends to fall. This causes a rotary motion within the enclosure that can enhance the heat transfer. The orientation of the enclosure does play a role in the motion of the internal fluids, for example an enclosure with the hot surface on top will have no convection currents whereas an enclosure will develop convection currents if the hotter surface is on the bottom.

The convection heat transfer in an enclosure is analogous to the heat conduction across the fluid layer provided that thermal conductivity (k) is replaced by the product of the thermal conductivity and the Nusselt number. (Cengel, 2006)

Considering two horizontal concentric cylinders, of diameters, D_i and D_o, and the characteristic length is the spacing between the cylinders:

$$L_c = \frac{D_o - D_i}{2}$$

The recommended relation for the Nusselt number by Raithby and Hollands (1975) is:

$$Nu = 0.386 \left(\frac{Pr}{0.861 + \mathrm{Pr}}\right)^{0.25} \left(F_{cyl} Ra_L\right)^{0.25}$$

Where F_{cyl} is the geometric factor for concentric cylinders given by:

$$F_{cyl} = \frac{\left(\ln\left(\frac{D_o}{D_i}\right)^4\right)}{L_c^3 \left(D_i^{-3/5} + D_o^{-3/5}\right)^5}$$

This relation is applicable for:

$$0.7 \leq Pr \leq 6000 \; and$$

$$10^2 \leq F_{cyl} Ra_L \leq 10^7$$

Very little analytical work has been done for vertical concentric cylinders, Mohammed (2007) has presented experimental results with vertical concentric cylinders with a heat flux in the centre and air in the annulus. In most cases CFD analysis is used to determine the effect of natural convection in vertical concentric cylinders or at least to get an initial estimation.

2.6. Thermal Conductivity and Heat Transfer of Gasses

Thermal conductivity (k) is defined as a measure of a material's ability to conduct heat. (Cengel, 2006) Materials or substances with high thermal conductivities such as metals conduct heat very well whereas substances with low thermal conductivities such as gasses do not conduct heat very well.

Temperature is a measure of the kinetic energy of the particles of a substance. In gasses the kinetic energy is due to the random translational, vibrational and rotational motion. When two more molecules with different kinetic energies collide, some of the energy of molecules with the higher kinetic energy (due to a higher temperature) is transferred to the molecules with lower kinetic energy and thus heat is transferred. With an increase in temperature the movement of the molecules increase and they collide more, thus the heat transfer increases.

The gas kinetic theory defines the thermo physical and transport properties of a substance in terms of the motion of its particles. The kinetic theory models the gas molecules as rigid and elastic spheres that only influence each other when they approach each other to within a distance smaller than the sum of their radiuses. When a molecule is not being influenced by another molecule, it follows the laws of classical mechanics.

The random molecular motions and intermolecular collisions are responsible for diffusion in fluids, thus expressions for viscosity (μ), thermal conductivity (k) and diffusivity (D) can be derived. The simplest equations are based on a solution of the Boltzmann transport equation with the equilibrium assumption. More accurate results can be obtained when considering that all forms of diffusion occur due to nonequilibrium. Boltzmann's equation cannot be solved analytically but approximate solutions have been derived, one of the most well known solutions was derived by Chapman in 1916 and Enskog in 1917.

According to the Chapman-Enskog model the dynamic viscosity of a gas can be determined from:

$$\mu = 2.669 \times 10^{-6} \, \frac{\sqrt{MT}}{\tilde{\sigma}^2 \Omega_\mu} \;\; [kg/ms]$$

Where M is the molar mass of the gas in kg/mol, T the temperature in Kelvin, $\tilde{\sigma}$ the collision diameter according to the Lennard-Jones model and Ω_μ the collision integral for thermal conductivity and viscosity.

The Chapman-Enskog model also predicts the thermal conductivity for a monatomic gas:

$$k = \frac{5}{2} c_v \mu = \frac{15}{4} \left(\frac{R_u}{M} \right) \mu$$

Where R_u is the universal gas constant in $J/mol \;\; K$

(Ghiaasiaan, 2011)

Thus thermal conductivity is a function of temperature and molar mass. The thermal conductivity of a gas increases with an increase in temperature and a decrease in molar mass. Thus helium has a higher thermal conductivity than argon at the same temperature. According to Cengel (2006) thermal conductivity is independent of pressure in a wide range of pressures.

2.6.1. Thermal Conductivities of Selected Gasses

The table below lists the thermal conductivities of some gasses at various temperatures.

Table 2.1 Thermal Conductivities of gasses at 100K to 600K (Bejan & Kraus, 2003)

	Thermal Conductivity $[mW/mK]$										
Temperature [K]	100	150	200	250	300	350	400	450	500	550	600
Argon	6.3522	9.5054	12.427	15.143	17.683	20.073	22.332	24.479	26.527	28.488	30.372
Carbon dioxide	0	0	0	12.897	16.747	20.887	25.11	29.317	33.465	37.358	41.533
Carbon monoxide	10.021	14.905	19.199	23.039	26.545	29.794	32.833	35.702	38.431	41.044	43.562
Helium	73.632	96.857	117.9	137.46	155.9	173.45	190.29	206.52	222.23	237.48	252.33
Hydrogen (normal)	68.059	100.76	132.27	160.44	185.63	210.2	233.94	256.84	280.4	304.11	327.99
Krypton	0	4.7716	6.3942	7.9417	9.3899	10.743	12.014	13.216	14.36	15.454	16.504
Neon	22.51	30.298	36.923	42.828	48.261	53.356	58.191	62.814	67.259	71.549	75.704
Nitrogen	9.9841	14.527	18.623	22.365	25.828	29.079	32.181	35.183	38.123	41.025	43.901
Oxygen	9.2232	13.938	18.367	22.568	26.635	30.654	34.673	38.705	42.738	46.753	50.729

2.7. Gas Mixtures

2.7.1. Ideal Gas Laws

While studying the compressibility of gasses, Robert Boyle made the observation that the pressure exerted by the gas is inversely proportional to the volume of a fixed amount of gas. Thus as the pressure increases, the volume decreases and vice versa. All gasses behave in this manner and this is referred to as Boyle's law. Mathematically Boyle's law can be expressed as:

$$p \propto \frac{1}{V}\ for\ a\ constannt\ n\ and\ T$$

If a proportionality constant is introduced the pressure and volume of a gas can be equated:

$$p = c\frac{1}{V}\ or\ pV = c$$

From the above follows that the product of the pressure and volume of a gas sample under one set of conditions is equal to the pressure-volume product at another set of conditions for a constant temperature and gas amount.

$$p_1V_1 = p_2V_2$$

The French scientist J. Charles discovered that the volume of a fixed amount of gas at a constant pressure decreases with a decrease in temperature. When the volume versus the temperature are plotted and extended to lower temperatures, they all converge to the same point, -273.15°C which is the basis for the Kelvin temperature scale.

When temperatures in the Kelvin scale are used with volume measurements the following relationship can be established:

$$V = cT$$

Where c is the proportionality constant, this is known as Charles' law and states that at a constant pressure and amount of gas the volume is directly proportional to the temperature. Similar to the relationship obtained with Boyle's law the volume divided by the temperature of a gas at a set of conditions is equal to the volume divided by the temperature at another set of conditions.

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

The laws of Boyle and Charles can be combined to obtain the general or combined gas law, but is only valid when the amount of gas remains constant.

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

The relationship between the volume and the amount of gas was first defined by Avogadro, he stated that at a constant temperature and pressure the volume of a gas is directly proportional the amount of particles in the gas, this is known as Avogadro's hypothesis.

All three these relationships can be combined into a mathematical equation by introducing the proportionality constant R, known as the gas constant.

$$pV = nRT$$

This is known as the ideal gas law, gasses at low temperatures and pressures all behave in a manner that is close to the relation defined by the ideal gas law.

In reality there is no such thing as an ideal gas, at certain conditions such as low temperatures and pressures gasses behave like ideal gasses but as temperature and pressure increase their behaviour no longer satisfy the ideal gas law.

The reason for the deviations is that the ideal gas law is based on the assumption that the gas particles have no size and there are no forces between them, which is why the ideal gas law is valid at low temperatures and pressures since the volume of the gas is large compared to the size of the particles.

The assumption that there are no forces between the particles is also not valid since all gasses can be liquefied, (some require extreme low temperatures). When a particle is about to strike the wall of the container, the other particles near the particle exert a slight force on the particle and pull it away from the wall. Thus the particles strike the wall with less force than if there were no forces between the particles, thus the observed pressure is lower than predicted by the ideal gas law.

Van der Waals developed an equation to correct for the errors associated with non ideal behaviour, known as the Van der Waals equation.

$$\left(p + a\left[\frac{n}{V}\right]^2\right)(V - bn) = nRT$$

Where a and b are experimentally determined constants, a corrects for the intermolecular forces and b accounts for the volume of the gas particles.

2.7.2. Partial Pressures

In a mixture of gasses each exerts its own pressure, known as its partial pressure. The total pressure of a gas mixture is the sum of all of the partial pressures of the gasses in the mixture, this is also known as Dalton's law.

$$p_{tot} = p_1 + p_2 + ..$$

In a mixture of gasses, each gas behaves independently of the other gasses, thus they can be treated separately. In order to determine the total pressure of two ideal gasses in a container at a temperature T, the pressure exerted by each gas can be calculated using the ideal gas law:

$$p_aV = n_aRT \quad p_bV = n_bRT$$

Using Dalton's law the pressures of each gas can be added to determine the total pressure:

$$p_{tot} = p_a + p_b = n_a\left(\frac{RT}{V}\right) + n_b\left(\frac{RT}{V}\right)$$

$$= (n_a + n_b)\left(\frac{RT}{V}\right)$$

$$p_{tot} = n_{tot}\left(\frac{RT}{V}\right)$$

In gas mixtures a quantity known as the mole fraction is introduced, which is defined as the number of moles of a specific substance in the mixture divided by the total amount of moles in the mixture.

$$x_a = \frac{n_a}{n_{tot}}$$

2.7.3. Transport Properties

The thermal conductivity and viscosity of a gas mixture can be determined using the Wilke mixture rules. These rules have been derived from the gas kinetic theory (Wilke, 1950). The average deviation between the calculated values and the experimentally obtained values for thirteen gas mixture experiments conducted by Wilke is 1.9%, thus these equations are quite accurate.

$$\mu_{eff} = \sum_{j=1}^{n} \frac{x_j \mu_j}{\sum_{i=1}^{n} x_i \phi_{ji}}$$

$$k_{eff} = \sum_{j=1}^{n} \frac{x_j k_j}{\sum_{i=1}^{n} x_i \phi_{ji}}$$

$$\phi_{ji} = \frac{\left[1 + \left(\frac{\mu_j}{\mu_i}\right)^{\frac{1}{2}} \left(\frac{M_i}{M_j}\right)^{\frac{1}{4}}\right]^2}{\sqrt{8}\left(1 + \left(\frac{M_j}{M_i}\right)\right)^{\frac{1}{2}}}$$

Where ϕ_{ij} is a dimensionless constant defined for the general form of the diffusion equation upon which the thermal conductivity and viscosity equations are based.

For a binary gas mixture the specific heat capacity at constant pressure may be predicted using the following:

$$C_{p,mix}^{0} = \sum_{i=1}^{0} x_i C_{p,i}^{0}$$

Where x_i is the mole fraction and $C_{p,i}^{0}$ the specific heat capacity at constant pressure for species i.

The Prandtl number of a binary gas mixture can be calculated in the same manner as with a pure substance since the Prandtl number is a dimensionless ratio. Thus the Prandtl number for a binary gas mixture can be determined using:

$$Pr_{mix} = \frac{\mu_{mix} C_{p,mix}}{k_{mix}}$$

2.7.4. Diffusion in Gas Mixtures

Diffusion is defined as the movement of molecules from a high concentration to a low concentration. Diffusion can occur in solids, liquids and gasses. The diffusion rate of gasses is much higher than that of solids due to gasses having lower densities than solids.

The binary mass diffusivity coefficient can be determined using the Chapman-Enskog model:

$$D_{12} = D_{21} = 1.858 \times 10^{-7} \frac{\sqrt{T^3 \left(\frac{1}{M_1} + \frac{1}{M_2}\right)}}{\tilde{\sigma}_{12}^2 \Omega_D P}$$

With P pressure in atmospheres, Ω_D the collision integral for mass diffusivity and:

$$\tilde{\sigma}_{12} = \frac{1}{2}(\tilde{\sigma}_1 + \tilde{\sigma}_2)$$

(Ghiaasiaan, 2011)

According to Fick's law of diffusion there is a linear relationship between the rate of diffusion and the concentration gradient in the rate of diffusion. The concentration can be defined in several ways such as density, mass fraction or mole fraction. Fick's law for the diffusion of gas A in a stationary binary mixture of gas A and B in a specified direction on a mole basis is expressed as:

$$j_A = -CD_{AB} \frac{dy_A}{dx}$$

where C is the mixture concentration (Cengel, 2006).

Diffusion is effected by gravity and often masks the gravitational effects. When for example a container is filled with two different gasses and the denser gas is filled from the bottom, THE denser gas will diffuse upwards and the lighter gas downwards, but when they reach equilibrium the mixture will not be uniform. At the top of the container the concentration will be slightly less than the average concentration and slightly higher at the bottom, but this effect is negligible on small scale experiments. (Diffusion | Infoplease)

2.7.5. Mixing Processes

Specialised equipment is seldom required to mix two or more gasses, they mix easily due to their low viscosities. Mixing given by turbulent flow in a length of pipe is usually sufficient. The rate of mixing can be increased by making the flow more turbulent by adding baffles in the pipe. (Sinnott & Towler, 2009)

There are two main methods for mixing gasses, the first is partial pressure mixing where the container which is to hold the gas mixtures is filled from cylinders or storage tanks at higher pressures. The mixing is done one gas at a time, the partial pressure of each component gas is calculated before hand and the pressure inside the container is controlled. When the pressure of the first component in the cylinder reaches the desired partial pressure, the next component is added. From the second component gas onwards the gasses are switched when the pressure in the container reaches the sum of the previous gasses' partial pressures and the current gas's partial pressure.

The second method is the one generally used to blend industrial and speciality gasses. In this process the gasses are mixed by their mass fractions, the cylinder or container that is to hold the gas mixture is placed on a sensitive scale, the scale is zeroed so that the weight of the container does not affect the mixture. For a binary gas mixture the container is filled with the first gas until the weight is the calculated weight of the gas, the second gas is then added until the total weight is the sum of the two component gasses' masses.

Other methods of gas mixing exist such as continuous blending, the use of each method depends on the application of the gas and the accuracy of the mix required.

2.7.6. Mixture Separation

Separating gasses is a quite difficult process since gas molecules have a lot kinetic energy and are constantly moving and colliding with each other and the laws of diffusion playing a role. Due to this gasses with different densities will not completely separate due to gravity, a concentration gradient will form with the concentration of the heavier gas a little higher at the bottom of the container and vice versa for the lighter gas.

Several methods of gas mixture separation exist, these methods can be divided into three main types: chemical, physical and physic-chemical. The method to be used depends on the characteristics of the gasses present in the mixture. Mixtures with reactive components can be separated by introducing a solvent into the mixture which then absorbs or bonds with one of the components, the solvent is then removed and the absorbed substance can then be recovered if needed.

Other methods commonly used to separate gasses are gas chromatography and membrane separation. Gas chromatography works by injecting a sample of the mixture into a moving gas stream known as the carrier gas, usually helium or another chemically inert gas. The carrier gas carries the mixture through a heated column coated with a thin film of a high molecular weight and thermally stable polymer. Separation occurs based on the affinity of the compounds to the polymer, the compound with the least affinity travels through the column first and the compound with the highest affinity travels through last. Gas chromatography is mainly used for analysis and cannot separate large quantities of gas.

Membrane separation involves the use of polymer membranes to separate gasses. Membrane separation involves passing the mixture through a polymer membrane that only allows one component to permeate through and blocking the others. The type of polymer used once again depends on the components of the mixture and which component is to be separated. A disadvantage of membrane separation is that the membranes can become expensive and can become blocked, a process known as fouling. Membrane separators are commonly built in a cross flow configuration since this reduces the changes of fouling and allows for a more compact design similar to heat exchangers.

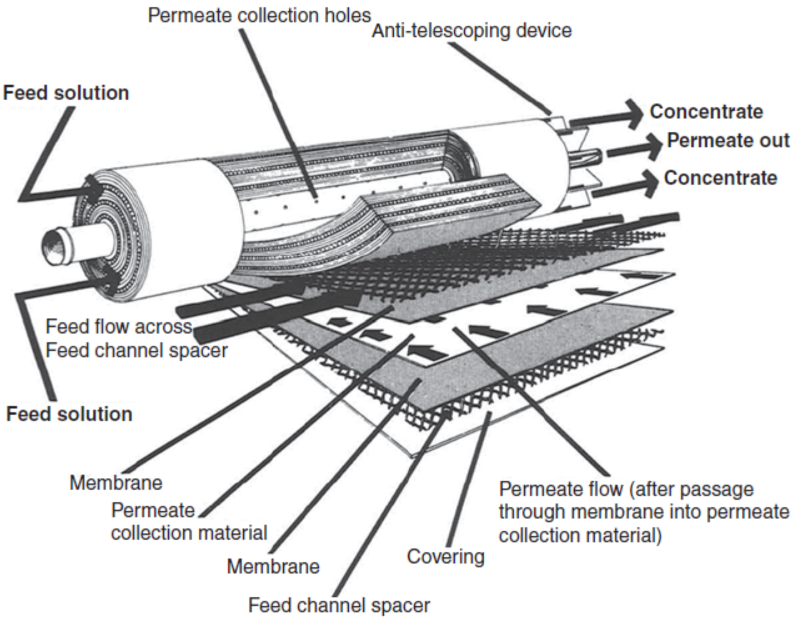

Figure 2.3 Example of a Spiral Wound Membrane Module (Sutherland, 2008)

2.7.7. Safety Aspects

The process of mixing gasses has a lot of risks, even when the gasses being mixed are not volatile or flammable. In some cases such as medical oxygen or diving gas the accuracy of the gas mixture is very important since incorrect mixtures can result in severe injury or death.

In all of the industries working with gas mixtures there are several safety regulations in terms of how the mixing is done and the requirements for safe operation. These regulations vary between different industries depending on the types of gasses being handled, but the same basic principles apply.

When working with unstable or potentially reactive gasses, it should be determined if the gasses are compatible with each other (reacts with each other) before mixing. The gasses and the mixture should also be compatible with the cylinder or container and the valves, so that the container and valve can withstand the pressure, temperature, doesn’t react with the gas and doesn’t leak.

Gas cylinders should be stored in a safe location, a well ventilated area, away from open flames or heat sources as well as combustible materials. Cylinders must be stored in such a way that prevents them from falling over to prevent damage to the valves.

Care should be taken that the correct equipment is used with gas cylinders and that there are no leaks present. All the equipment used with the gas, including hoses, pipes and valves should be able to handle the pressures.

The risks associated with the type of gas are important. Gasses are rated according to their risks, these include: toxic, corrosive, flammable, asphyxiant and inert. When working with gasses these risks should be known and mitigating measures should be employed. (Air Liquide, 2010)

2.8. Temperature Control

Several different devices for measuring temperature exist, these include thermocouples, resistance temperature devices, bimetallic temperature measurement devices and fluid expansion measurement devices.

The most common type is the fluid expansion temperature measurement device or thermometer. They generally come in two types, the mercury type and the organic liquid type. The mercury type used to be the most common but since mercury is hazardous they are being replaced by other types. The fluid is placed inside a sealed tube and as the temperature changes the fluid contracts or expands to give an indication of the temperature.

The most commonly used measurement device in industry is the thermocouple, which consists of strips of two dissimilar metals joined together at one end. Change in temperature at the junction induces an electrical current due to the Seebeck effect.

There are many forms of temperature control depending on the application. The simplest method is on/off control where the temperature is monitored and when the temperature reaches the desired value the system is turned off, and turned on when the temperature rises or drops above or below the desired value. Common applications include thermostats in soldering irons or thermal cut out switches in electrical machinery.

One of the other most common forms of temperature control is continuous control where the temperature measurement is used as feedback to the system and the system makes adjustments based on the temperature measurement. This method is generally more accurate since the system is constantly running as opposed to being turned on and off. PID controllers are often used in these systems since they are relatively simple, inexpensive and provide good accuracy but digital or computer based control systems are also used especially in large plants or systems.

2.8.1. Thermocouples

As stated above a thermocouple consists of two dissimilar metals joined at one end, the open circuit voltage is a function of the temperature and the composition of the metals. The voltage generated by the thermocouple is due to the Seebeck effect, for small changes in temperature the voltage is linearly proportional to the temperature.

$$\Delta e = \alpha_s \Delta T$$

Where α is the Seebeck coefficient of the junction.

Thermocouples are one of the simplest devices for measuring temperature, and can be manufactured in many sizes and shapes depending on the application, life expectancy and response time requirements. Thermocouples generally cover a wide range of temperatures and their output is reasonably linear over that range. A big advantage of a thermocouple is that it is not subject to self heating problems as with certain other temperature measurement devices.

Many different types of thermocouples exist, with the difference being the materials used to make the junction. The most common type is the type K thermocouple which has a nickel-chromium (positive side) and nickel-aluminium (negative side) junction. A type K thermocouple typically has a range of 0°C to 1090°C, the range of the thermocouple is dependent on the size of the junction wires. (ASTM Committee E20 on Temperature Measurement, 1993)

2.9. Design Approach

The design approach that is followed is firstly to determine the physical constraints of the experiment such as the available sizes of constant temperature baths. With the size of the constant temperature bath known the maximum size of the test capsule can be determined. Next the thermodynamic analysis is conducted in order to determine realistic values for the maximum and minimum amounts of heat transfer and control temperatures.

Once the thermodynamic analysis is complete, the heating element for the experiment can be sized. With the thermodynamic analysis the required thermal conductivity range is determined which is used to do a fluid analysis to determine the gas flow rates and pressures. With these values specified the gas control components such as the valves can be sized.

A mechanical analysis will be done in order to ensure that the test capsule can handle the temperatures and pressures involved in the system and to finalise the construction of the test capsule. With all the components required known and sized the electronic control system can be designed.

3. Functional Analysis

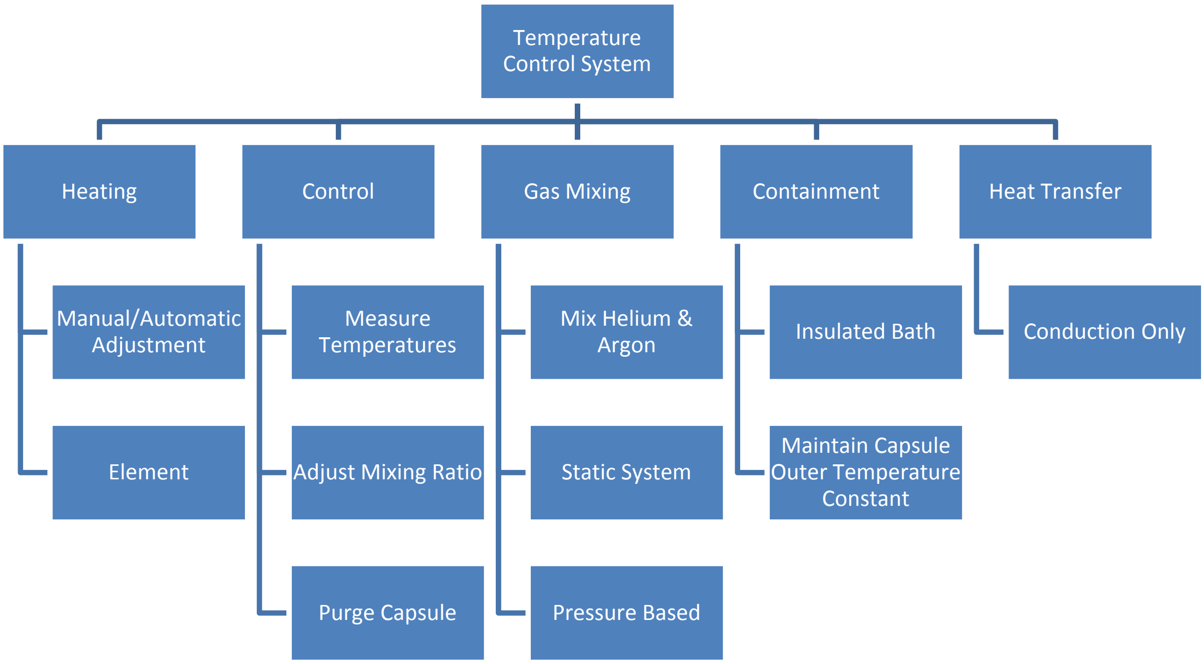

Figure 3.1System Functional Analysis

4. System Design

4.1. Basic System Layout

The system consists of a tubular cartridge heater installed into a sealed capsule made out of stainless steel filled with a mixture of helium and argon gas. The purpose of the heater is to simulate a test specimen and to introduce a heat flux.

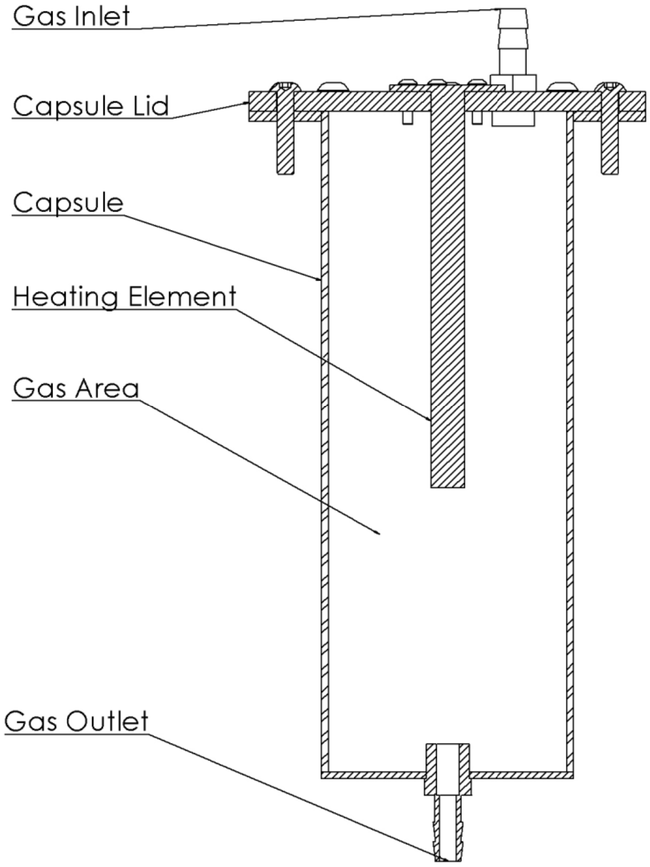

Figure 4.1 Basic Test Capsule Layout

The Helium and Argon is to be fed from compressed gas cylinders and the amount of each gas present in the capsule will be controlled by the partial pressures which determine the time which two solenoid valves in the gas lines remain open. When the heat input on the heater changes the gas ratio will also change by evacuating the gas currently in the capsule to the atmosphere and simultaneously filling it with the new mixture.

The figure below shows the system diagram and gas flow components of the system. All the solenoid valves are controlled by an electronic microcontroller, the flow meters and pressure reduction valves are set to fixed values in order to maintain constant pressures and flow rates through the system.

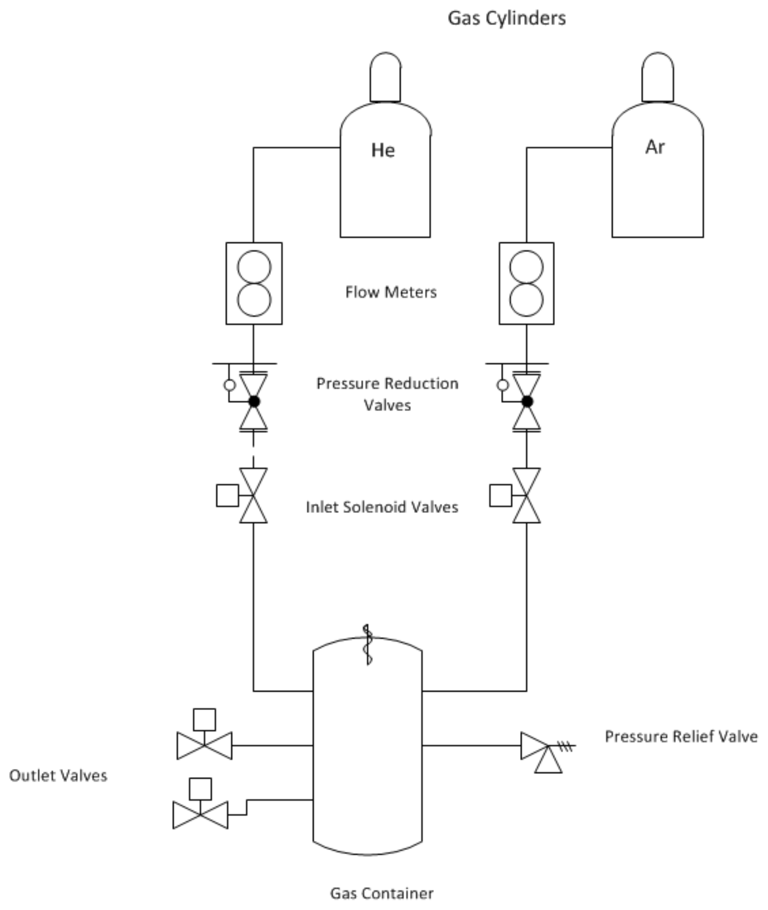

Figure 4.2 System Diagram with Gas Flow Components

4.1.1. General Assumptions

Helium and Argon are both assumed to behave as ideal gasses since they are both noble gasses and the operating pressure and temperature of the system is low. The mixture of the two gasses is assumed to be ideal, these assumptions will be validated during the experimental procedure.

Properties such as thermal conductivity, specific heat, and Prandtl number are assumed to be constant for the pure gasses, and the values for these are obtained from the average temperature since small temperature variations are expected.

4.1.2. System Specifications

The specifications of the system are listed in Table 4.1 below. Note that these values are estimated values for ideal conditions, and may differ in practice.

Table 4.1 System Specifications

Specification	Value
Conductor Gas	Helium (He)
Insulator Gas	Argon (Ar)
Heat Flux Range	$146 - 1284\ W/m^2$ @ $80℃$
Controllable Temperature Range	$93 - 810℃$ @ $1500W/m^2$
Thermal Conductivity Range	$0.0182 - 0.1596\ W/m^2$
Test Capsule Material	Stainless Steel
Test Capsule Inner Diameter	$73mm$
Test Capsule Wall Thickness	$1.6mm$
Test Capsule Length	$200mm$
Test Capsule Volume	$8.37 \times 10^{-4}m^3$

These values give an indication of the system capabilities regarding the heat flux range and the temperature range, these values are dependent on each other as well as the size of the gas gap.

4.2. Gas Mixture and Mixture Properties

The first part of the design is to determine the properties of the gas mixture, since these properties will have a large influence on what the system capabilities and limitations are. The performance of most heat transfer mechanisms depend on the fluid properties.

The gasses are mixed by the partial pressures of each gas, thus the starting point for the calculations is the partial pressures of the gasses. According to the ideal gas law a gas fill the entire volume of the container in which the gas is placed, thus the volume remains constant.

Since ideal gas is assumed the partial pressure of a gas in a mixture can be calculated using the mole fraction:

$$p_i = x_i p_{tot}$$

Where x_i is the mole fraction of the gas, thus for a 75% helium mixture the partial pressure of the helium can be calculated by:

$$p_{He} = x_{He} p_{tot}$$

$$= 0.75 \times 150\ 000$$

$$= 112.5\ kPa$$

The difference between the total pressure and the partial pressure of the first gas is made up by the partial pressure of the second gas, and the mole fraction of the second gas can be calculated by:

$$x_j = 1 - x_i$$

Thus:

$$p_{Ar} = (1 - x_{He})p_{tot}$$

$$= (1 - 0.75)(150000)$$

$$= 37.5\ kPa$$

The specified output pressure of the selected gas cylinders and regulators is given as 1000 kPa, but in order to reduce the gas usage the pressure is to be reduced to 150 kPa, the pressure reduction valves also maintain a constant pressure since the cylinder pressures will not remain constant and will decrease as the gasses are used. The two gasses have different densities, the gasses will be used at different rates and thus the cylinder pressures will differ with time.

In order to determine the thermodynamic and transport properties of the gas mixture a few other physical and chemical properties need to be determined. The number of moles for each gas can be calculated using the ideal gas law:

$$pV = n\bar{R}T$$

Since the temperature differs across the boundaries of the gas volume, calculations will be done at the average temperature between the two boundaries. The selected surface control temperature for the sample calculations is 80 degrees Celsius or a 75% Helium mixture and the outer temperature is fixed at 0 degrees Celsius.

Thus:

$$T_{ave} = \frac{80 + 0}{2}$$

$$= 40\ ℃$$

$$= 313.15\ K$$

The number of moles for each gas is then calculated as:

$$n_{He} = \frac{p_{he}V_{tot}}{\bar{R}T_{ave}}$$

$$= \frac{112.5(8.37 \times 10^{-4})}{(8.3145)(313.15)}$$

$$= 3.617 \times 10^{-5}\ mol\ He$$

$$n_{Ar} = \frac{p_{Ar}V_{tot}}{\bar{R}T_{ave}}$$

$$= \frac{37.5(8.37 \times 10^{-4})}{(8.3145)(310.65)}$$

$$= 1.206 \times 10^{-5}\ mol\ Ar$$

With the number of moles known the mass of each gas can be determined using the molar mass.

$$n = \frac{m}{M}$$

$$m_{he} = n_{He}M_{He}$$

$$= (3.617 \times 10^{-5})(4)$$

$$= 1.45 \times 10^{-4}\ kg\ He$$

$$m_{Ar} = n_{Ar}M_{Ar}$$

$$= (1.206 \times 10^{-5})(39.98)$$

$$= 4.82 \times 10^{-4}\ kg\ Ar$$

The above calculations were done for a range of mixing ratios ranging from 0% helium to 100% helium, the results are shown in the table below:

Table 4.2 Properties of He-Ar Mixture for Various Ratios

$\%He$	$p_{He}\ [kPa]$	n_{He}	$m_{He}\ [kg]$	$p_{Ar}\ [kPa]$	n_{Ar}	$m_{Ar}\ [kg]$	n_{tot}	$m_{tot}\ [kg]$	y_{He}	y_{Ar}
0	0.0	0.00	0.00	150.0	4.82E-05	1.93E-03	4.82E-05	1.93E-03	0.000	1.000
5	7.5	2.41E-06	9.64E-06	142.5	4.58E-05	1.83E-03	4.82E-05	1.84E-03	0.005	0.995
10	15.0	4.82E-06	1.93E-05	135.0	4.34E-05	1.74E-03	4.82E-05	1.75E-03	0.011	0.989
15	22.5	7.23E-06	2.89E-05	127.5	4.10E-05	1.64E-03	4.82E-05	1.67E-03	0.017	0.983
20	30.0	9.64E-06	3.86E-05	120.0	3.86E-05	1.54E-03	4.82E-05	1.58E-03	0.024	0.976
25	37.5	1.21E-05	4.82E-05	112.5	3.62E-05	1.45E-03	4.82E-05	1.49E-03	0.032	0.968
30	45.0	1.45E-05	5.79E-05	105.0	3.38E-05	1.35E-03	4.82E-05	1.41E-03	0.041	0.959
35	52.5	1.69E-05	6.75E-05	97.5	3.13E-05	1.25E-03	4.82E-05	1.32E-03	0.051	0.949
40	60.0	1.93E-05	7.72E-05	90.0	2.89E-05	1.16E-03	4.82E-05	1.23E-03	0.063	0.937
45	67.5	2.17E-05	8.68E-05	82.5	2.65E-05	1.06E-03	4.82E-05	1.15E-03	0.076	0.924
50	75.0	2.41E-05	9.64E-05	75.0	2.41E-05	9.64E-04	4.82E-05	1.06E-03	0.091	0.909
55	82.5	2.65E-05	1.06E-04	67.5	2.17E-05	8.68E-04	4.82E-05	9.74E-04	0.109	0.891
60	90.0	2.89E-05	1.16E-04	60.0	1.93E-05	7.71E-04	4.82E-05	8.87E-04	0.130	0.870
65	97.5	3.13E-05	1.25E-04	52.5	1.69E-05	6.75E-04	4.82E-05	8.00E-04	0.157	0.843
70	105.0	3.38E-05	1.35E-04	45.0	1.45E-05	5.78E-04	4.82E-05	7.13E-04	0.189	0.811
75	112.5	3.62E-05	1.45E-04	37.5	1.21E-05	4.82E-04	4.82E-05	6.27E-04	0.231	0.769
80	120.0	3.86E-05	1.54E-04	30.0	9.64E-06	3.86E-04	4.82E-05	5.40E-04	0.286	0.714
85	127.5	4.10E-05	1.64E-04	22.5	7.23E-06	2.89E-04	4.82E-05	4.53E-04	0.362	0.638
90	135.0	4.34E-05	1.74E-04	15.0	4.82E-06	1.93E-04	4.82E-05	3.66E-04	0.474	0.526
95	142.5	4.58E-05	1.83E-04	7.5	2.41E-06	9.64E-05	4.82E-05	2.80E-04	0.655	0.345
100	150.0	4.82E-05	1.93E-04	0.0	0.00	0.00E+00	4.82E-05	1.93E-04	1.000	0.000

Next the viscosity and thermal conductivity of the mixture can be calculated using the Wilke mixture rule adapted from Chapman-Enskog gas kinetic theory model.

$$\mu = \sum_{j=1}^{n} \frac{x_j \mu_j}{\sum_{i=1}^{n} x_i \phi_{ji}}$$

$$k_{eff} = \sum_{j=1}^{n} \frac{x_j k_j}{\sum_{i=1}^{n} x_i \phi_{ji}}$$

$$\phi_{ji} = \frac{\left[1 + \left(\frac{\mu_j}{\mu_i}\right)^{\frac{1}{2}} \left(\frac{M_i}{M_j}\right)^{\frac{1}{4}}\right]^2}{\sqrt{8}\left(1 + \left(\frac{M_j}{M_i}\right)\right)^{\frac{1}{2}}}$$

First the values for ϕ_{ij} are calculated, ϕ_{ji} is a 2x2 matrix since the mixture consists of only two components.

The viscosities for the pure components are given as:

$\mu_{He} = 193.061\ \mu P$

$\mu_{Ar} = 220.891\ \mu P$

(Yaws, 2010)

The thermal conductivities of the two pure components are interpolated from Table 2.1 at the average temperature:

$k_{he} = 0.1596\ W/mK$

$k_{Ar} = 0.0182\ W/mK$

When $i = j$ the equation above reduces to:

$$\phi_{ii} = 1$$

But

$$\phi_{ji} \neq \phi_{ij}$$

$$\phi_{12} = \frac{\left[1 + \left(\frac{193.061}{220.891}\right)^{0.5}\left(\frac{39.98}{4}\right)^{0.25}\right]^2}{\sqrt{8}\left(1 + \left(\frac{4}{39.98}\right)\right)^{0.5}}$$

$$= 2.475$$

$$\phi_{21} = \frac{\left[1 + \left(\frac{220.891}{193.061}\right)^{0.5}\left(\frac{4}{39.98}\right)^{0.25}\right]^2}{\sqrt{8}\left(1 + \left(\frac{39.98}{4}\right)\right)^{0.5}}$$

$$= 0.2735$$

Using the effective thermal conductivity equation to calculate the effective thermal conductivity of the mixture.

$$k_{eff} = \sum_{j=1}^{n} \frac{x_j k_j}{\sum_{i=1}^{n} x_i \phi_{ji}}$$

Expanding the summation above for a binary mixture:

$$k_{eff} = \frac{x_1 k_1}{x_1 \phi_{11} + x_2 \phi_{12}} + \frac{x_2 k_2}{x_1 \phi_{21} + x_2 \phi_{22}}$$

$$= \frac{(0.75)(0.1596)}{(0.75)(1) + (0.25)(2.389)} + \frac{(0.25)(0.0182)}{(0.75)(0.2735) + (0.25)(1)}$$

$$= 0.0988\ W/mK$$

The effective viscosity for the mixture can be calculated the same way. The thermal conductivity and viscosity for a range of mixtures have been calculated and the results are listed in Table 4.3 below.

Table 4.3 Effective Thermal Conductivity and Viscosity for Various Mixing Ratios

$\%He$	$k_{eff}\ [W/_{mK}]$	$\mu\ [\mu P]$
0	0.01820	220.891
5	0.02138	221.9173
10	0.02476	222.9549
15	0.02834	223.9982
20	0.03216	225.04
25	0.03622	226.0703
30	0.04057	227.0762
35	0.04522	228.0402
40	0.05022	228.9392
45	0.05559	229.7423
50	0.06139	230.408
55	0.06766	230.8804
60	0.07447	231.083
65	0.08188	230.9105
70	0.08997	230.2163
75	0.09885	228.7925
80	0.10862	226.34
85	0.11941	222.418
90	0.13138	216.3613
95	0.14471	207.1342
100	0.15960	193.061

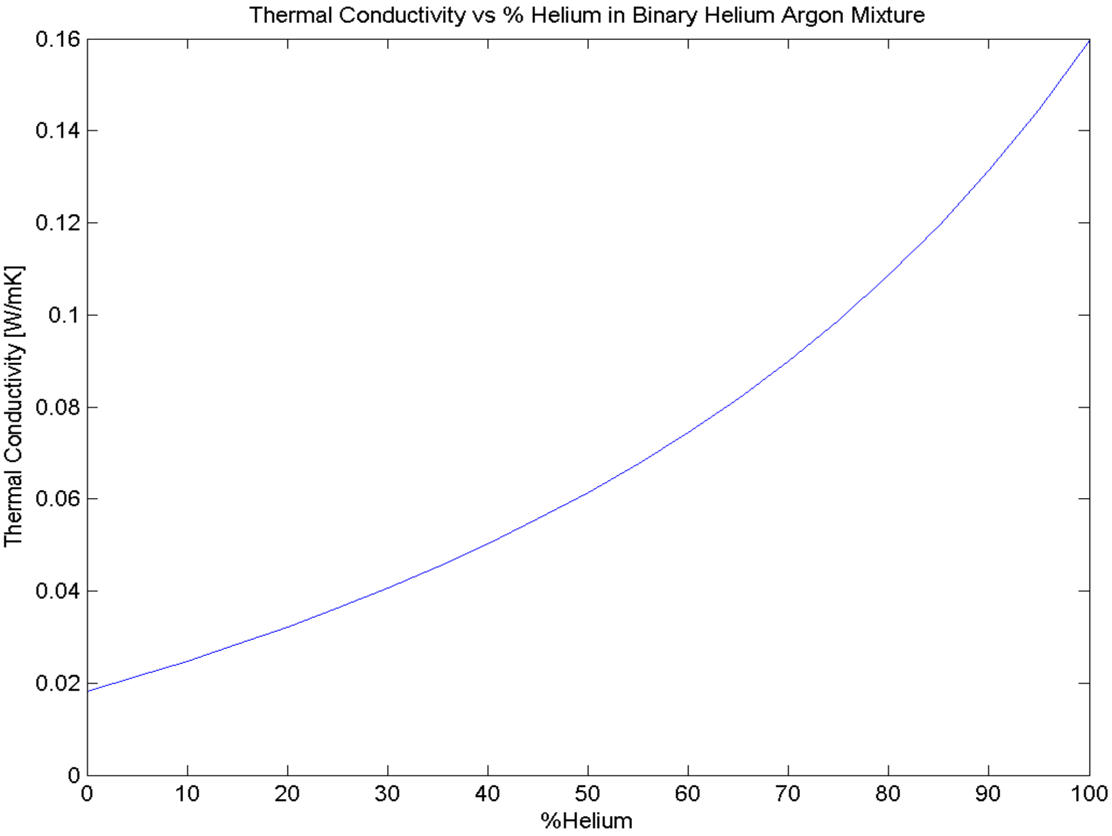

Figure 4.3 Thermal Conductivity vs % Helium in a Binary Helium Argon Mixture

From Figure 4.3 it is clear that the relationship between the thermal conductivity of the mixture and the fractions is not linear, thus a linear approximation would only be moderately accurate at very high and very low ratios.

The specific heat capacity at constant pressure can easily be calculated using the following mixture rule (Campo, Papari, & Abu-Nada, 2011).

$$C^0_{p_{mix}} = \sum y_i C^0_{p_i}$$

$$= (0.23)(5193) + (0.77)(520)$$

$$= 1599.42\, J/KgK$$

The density of the gas mixture can very easily be calculated by dividing the total mass by the volume:

$$\rho_{mix} = \frac{m_{tot}}{V}$$

$$= \frac{0.000627}{8.37 \times 10^{-4}}$$

$$= 0.75\, kg/m^3$$

With the specific heat capacity and dynamic viscosity known the Prandtl number can be calculated.

$$Pr_{mix} = \frac{\mu_{mix} {C_p}^{0}_{mix}}{k_{mix}}$$

$$= \frac{(228.8 \times 10^{-7})(1599.42)}{0.09885}$$

$$= 0.37$$

The table below lists the transport properties of the gas mixture for a ratio of 0% Helium to 100% Helium. A full table of all the properties of the mixture can be found in Appendix D.

Table 4.4 Transport Properties of a Binary He-Ar Mixture for Various Ratios @ 310 K, 200 kPa

$\%He$	$k\ [W/mK]$	$\mu\ [\times 10^{-7}\ kg/ms]$	$C_p\ [J/kgK]$	$\rho\ [kg/m^3]$	Pr
0%	0.01820	220.89	520.00	2.30	0.631
5%	0.02138	221.92	544.50	2.20	0.565
10%	0.02476	222.95	571.42	2.10	0.515
15%	0.02834	224.00	601.13	1.99	0.475
20%	0.03216	225.04	634.11	1.89	0.444
25%	0.03622	226.07	670.92	1.79	0.419
30%	0.04057	227.08	712.27	1.68	0.399
35%	0.04522	228.04	759.05	1.58	0.383
40%	0.05022	228.94	812.41	1.47	0.370
45%	0.05559	229.74	873.83	1.37	0.361
50%	0.06139	230.41	945.30	1.27	0.355
55%	0.06766	230.88	1029.51	1.16	0.351
60%	0.07447	231.08	1130.18	1.06	0.351
65%	0.08188	230.91	1252.69	0.96	0.353
70%	0.08997	230.22	1404.98	0.85	0.359
75%	0.09885	228.79	1599.42	0.75	0.370
80%	0.10862	226.34	1856.34	0.65	0.387
85%	0.11941	222.42	2211.58	0.54	0.412
90%	0.13138	216.36	2734.98	0.44	0.450
95%	0.14471	207.13	3582.94	0.33	0.513
100%	0.15960	193.06	5193.00	0.23	0.628

The mass diffusion rates are calculated in order to determine the time the gas mixture requires to reach equilibrium. The binary mass diffusivity coefficient is determined using the Chapman-Enskog model:

$$D_{12} = D_{21} = 1.858 \times 10^{-7} \frac{\sqrt{T^3 \left(\frac{1}{M_1} + \frac{1}{M_2}\right)}}{\tilde{\sigma}_{12}^2 \Omega_D P}$$

The values for $\tilde{\sigma}_1$, $\tilde{\sigma}_2$, $\tilde{\varepsilon}/k_B$ for each gas is obtained from Appendix K in Convective Heat and Mass Transfer.

$$\tilde{\sigma}_{He} = 3.542\ \dot{A}$$

$$\tilde{\sigma}_{Ar} = 2.551\ \dot{A}$$

$$\frac{\tilde{\varepsilon}_{He}}{k_B} = 93.3\ K$$

$$\frac{\tilde{\varepsilon}_{Ar}}{k_B} = 10.22\ K$$

Thus

$$\tilde{\sigma}_{12} = \frac{1}{2}(3.542 + 2.551)$$

$$= 3.0465$$

$$\frac{\tilde{\varepsilon}_{12}}{k_B} = \sqrt{(93.3)(10.22)}$$

$$= 30.879\ K$$

Dividing the average temperature by the result above:

$$\frac{k_B T}{\tilde{\varepsilon}_{12}} = \frac{313.15}{30.879}$$

$$= 10.14$$

From appendix L in Ghiaasiaan (2011):

$\Omega_D = 0.7424$

$$D_{12} = D_{21} = 1.858 \times 10^{-7} \frac{\sqrt{T^3\left(\frac{1}{M_1} + \frac{1}{M_2}\right)}}{\tilde{\sigma}_{12}^2 \Omega_D P}$$

$$D_{12} = (1.858 \times 10^{-7}) \frac{\sqrt{(310.65)^3\left(\frac{1}{4} + \frac{1}{39.98}\right)}}{(3.047)^2(10.06)(2)}$$

$$= 2.857 \times 10^{-6}\ m^2/s$$

With the diffusion coefficient known it is possible to determine the mass flux of helium and argon.

The concentrations of helium and argon are calculated as:

$$C_{He} = \frac{n_{He}}{V_{tot}}$$

$$= \frac{3.62 \times 10^{-5}}{8.37 \times 10^{-4}}$$

$$= 0.043\, mol/m^3\ \ Helium$$

$$C_{Ar} = \frac{n_{Ar}}{V_{tot}}$$

$$= \frac{1.21 \times 10^{-5}}{8.37 \times 10^{-4}}$$

$$= 0.014\, mol/m^3\ \ Argon$$

Using Fick’s first law to determine the mass fluxes:

$$\bar{J}_{He} = -(C_{He} + C_{Ar}) D_{12} \frac{dy_{He}}{dz}$$

$$= -(0.043 + 0.014)(2.857 \times 10^{-6})\left(\frac{0 - 0.75}{0.2}\right)$$

$$= 6.17 \times 10^{-7}\, mol/s\ \ m^2$$

$$\bar{J}_{Ar} = 2.04 \times 10^{-7}\, mol/s\, m^2$$

4.3. Thermodynamic Analysis

Since the heat transfer in the radial direction is much greater than in the other directions and the test capsule and heater both have a simple cylindrical geometry a one dimensional heat transfer analysis will be sufficient for the purposes of this project.

4.3.1. Heat Conduction

The first step is to setup the differential equation and to simplify it to a one dimensional steady state problem. The heat conduction for a specific heat input is assumed to be constant since sufficient time will be allowed for the system to stabilise before measurements are taken. The transient effects will be briefly considered later on in this report.

First the heat conduction through the gas gap is determined. Starting with the general heat conduction equation in cylindrical coordinates:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{e}_{gen}=\rho c\frac{\partial T}{\partial t}$$

Assuming one dimensional heat transfer, no heat generation in the medium and steady state condition the equation simplifies to:

$$\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right)=0$$

Assuming the thermal conductivity to be constant (does not vary with respect to r) and integrating yields:

$$\frac{\partial T}{\partial r}=\frac{c_1}{r}$$

Integrating again yields the general solution to the differential equation:

$$T(r)=c_1\ln(r)+c_2$$

The boundary conditions are as follows:

The temperature on the outer radius is maintained at a constant temperature of 0°C, mathematically:

$$T(r_o)=0$$

The inner surface is subjected to a constant heat flux, $\dot{q}$

$$-k\frac{dT(r_i)}{dr}=\dot{q}$$

Substituting the boundary conditions into the general solution:

$$\frac{dT(r_i)}{dr} = \frac{c_1}{r_i} = -\frac{\dot{q}}{k}$$

$$c_1 = -\frac{\dot{q}r_i}{k}$$

$$0 = -\frac{\dot{q}r_i}{k}\ln(r_o) + c_2$$

$$c_2 = \frac{\dot{q}r_i}{k}\ln(r_o)$$

Thus

$$T(r) = \frac{\dot{q}r_i}{k}\ln\left(\frac{r_o}{r}\right)$$

The above equation can be used to determine the steady state temperature gradient through the gas gap. The figure below shows the steady state temperature distribution through the gas gap for various heat flux values.

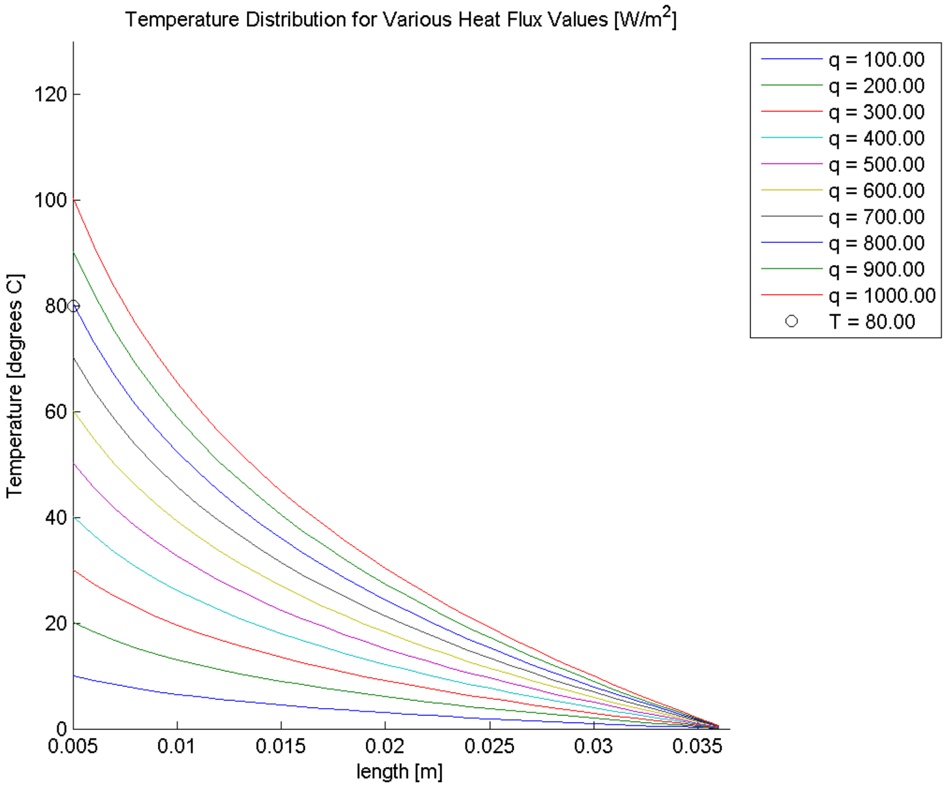

Figure 4.4 Temperature Distribution for a 75% He Mixture for Various Heat Flux Values

A calculation was done with a specified heat flux of $1500\ W/m^2$ to estimate the temperature on the surface of the heater and the results are shown the table below:

Table 4.5 Internal Surface Temperature for a Specified Heat Flux

$\%\boldsymbol{He}$	$\dot{\boldsymbol{q}}\ [\boldsymbol{W/m^2}]$	$\boldsymbol{T_i}$ [℃]
0%	1500	819.18
5%	1500	697.28
10%	1500	602.25
15%	1500	526.09
20%	1500	463.69
25%	1500	411.63
30%	1500	367.54
35%	1500	329.72
40%	1500	296.93
45%	1500	268.22
50%	1500	242.89
55%	1500	220.37
60%	1500	200.23
65%	1500	182.11
70%	1500	165.72
75%	1500	150.84
80%	1500	137.27
85%	1500	124.86
90%	1500	113.48
95%	1500	103.03
100%	1500	93.42

The purpose of the system is to adjust the thermal conductivity in order to maintain a constant temperature on the surface of the heating element. By rearranging the derived heat conduction equation the required thermal conductivity for a certain heat flux can be determined.

At the inner radius:

$$k_{eff} = \frac{\dot{q} r_i}{T_i} \ln\left(\frac{r_o}{r_i}\right)$$

Substituting the known values:

$$k_{eff} = \frac{0.005\dot{q}}{75} \ln\left(\frac{0.0475}{0.005}\right)$$

From the above equation it can be seen that the relationship between the effective thermal conductivity and the heat flux applied at the inner boundary is linear.

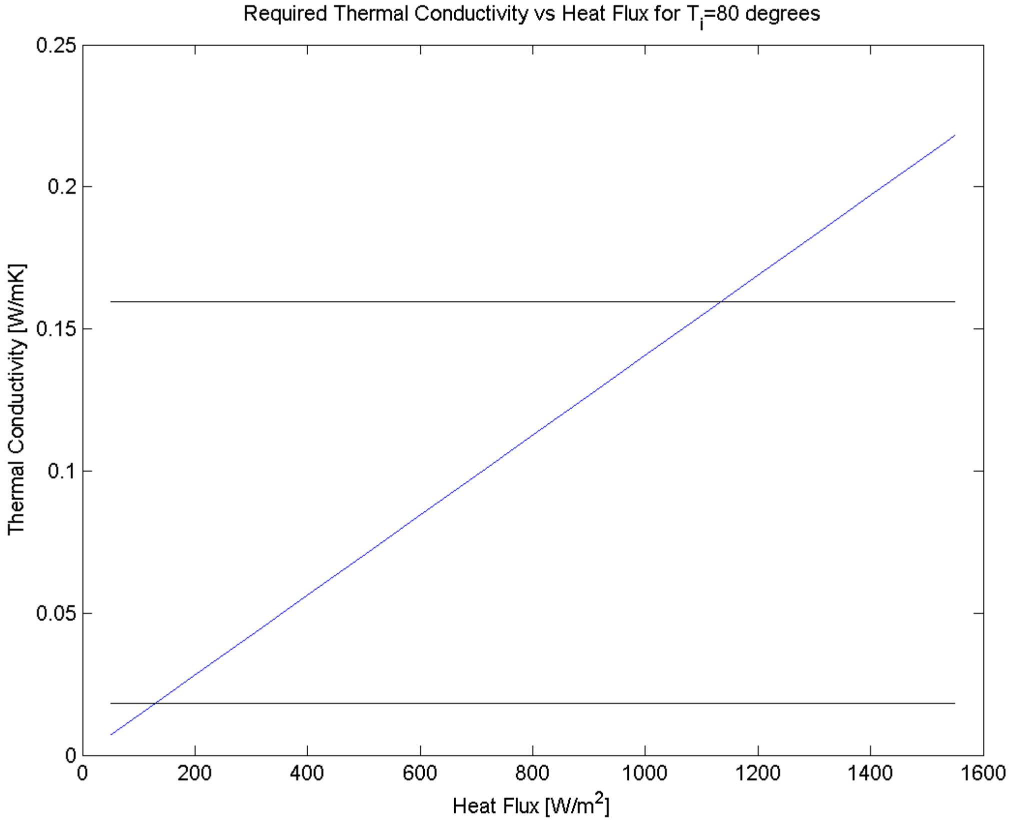

Figure 4.5 Required Thermal Conductivity vs. Heat Flux to Maintain Element Temperature @ 80°C

With the derived heat conduction equation a range for the heat flux that the system can deal with can be determined. The maximum and minimum heat flux will be when the capsule is filled with only the conductor gas and the insulator gas respectively.

Due to the size of the container and the physical properties of the pure gasses the system does have limits, if the applied heat flux goes above or below certain values the system will not be able to maintain the surface temperature on the element. The figure below shows the maximum allowable heat flux for the percentage helium in the mixture.

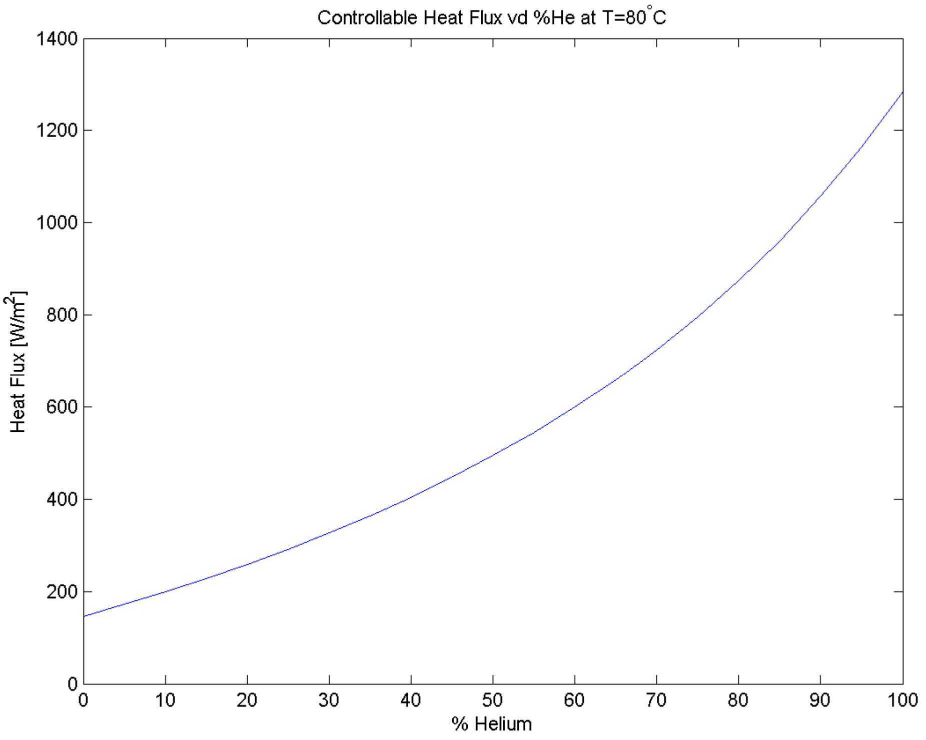

Figure 4.6 Allowable Heat Flux vs %He at T=80°C

4.3.2. Internal Convection

The effects of the natural convection inside the capsule are also considered since this can have an effect on the heat transfer through the insulating gas. Since very little about concentric vertical cylinders are covered in literature CFD is used to obtain an estimation of the effects of natural convection in the capsule.

The CFD model consists of the internal fluid volume of the capsule according to the dimensions of the test capsule and a constant heat flux boundary condition on the interior and a constant temperature boundary condition on the outer surfaces as shown below:

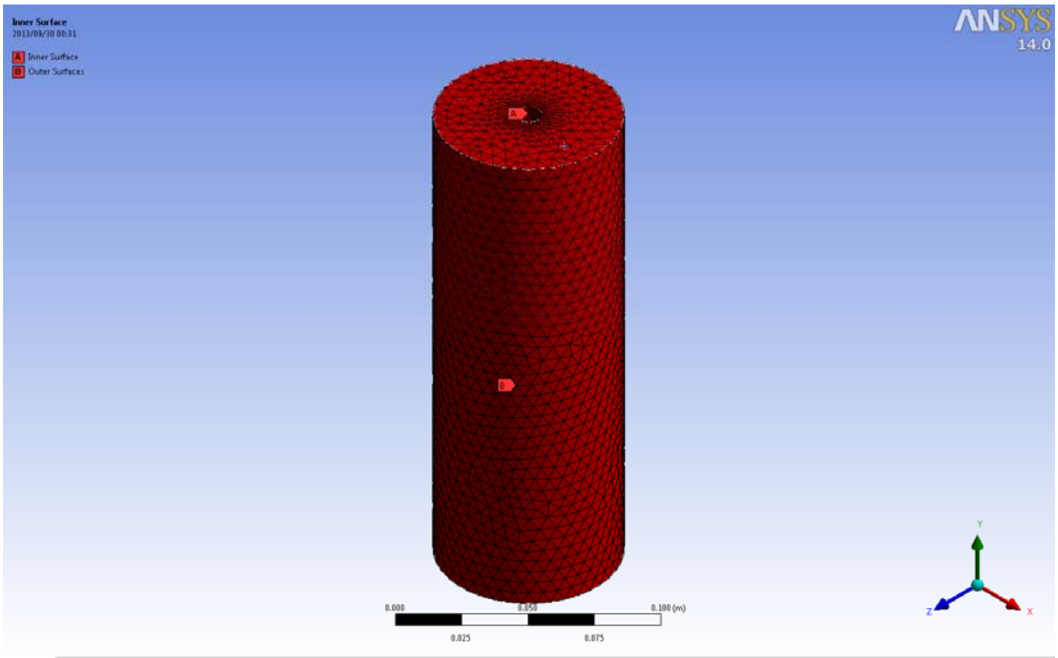

Figure 4.7 CFD Model & Mesh

Two steady state analyses were done, firstly with no fluid motion whatsoever in order to simulate pure conduction and secondly with the effects of gravity taken into account in order to take the differing densities and fluid motion into account to simulate heat transfer by convection as well.

Each of the above mentioned analyses was done for a 0%, 50% and 100% helium mixture with a constant heat flux of $1500\ W/m^2$. The expected temperature values at these conditions are calculated using the analytical equation derived in the previous section are listed in Table 4.5.

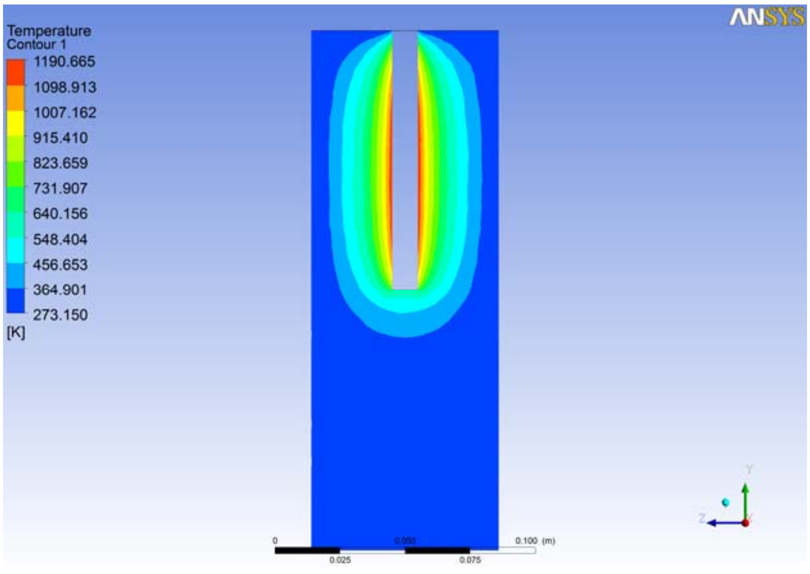

Figure 4.8 Temperature Distribution for a 0% He Mixture

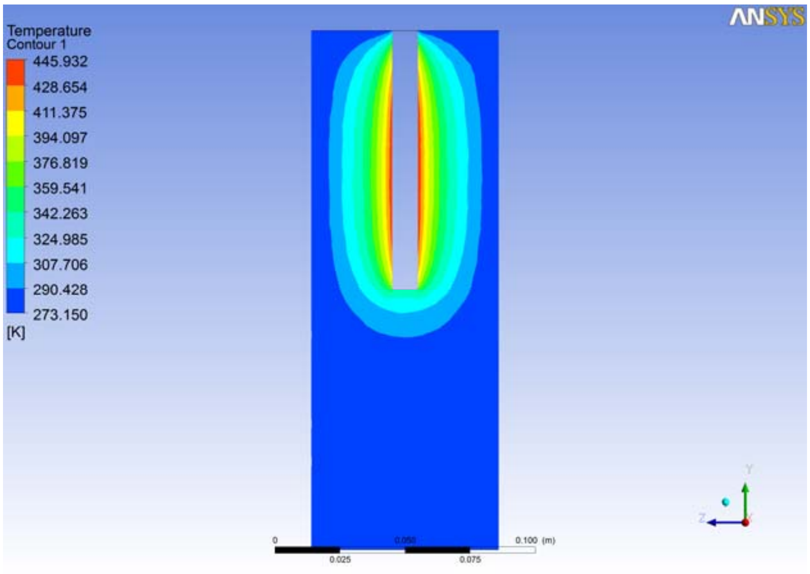

Figure 4.9 Temperature Distribution for a 50% He Mixture

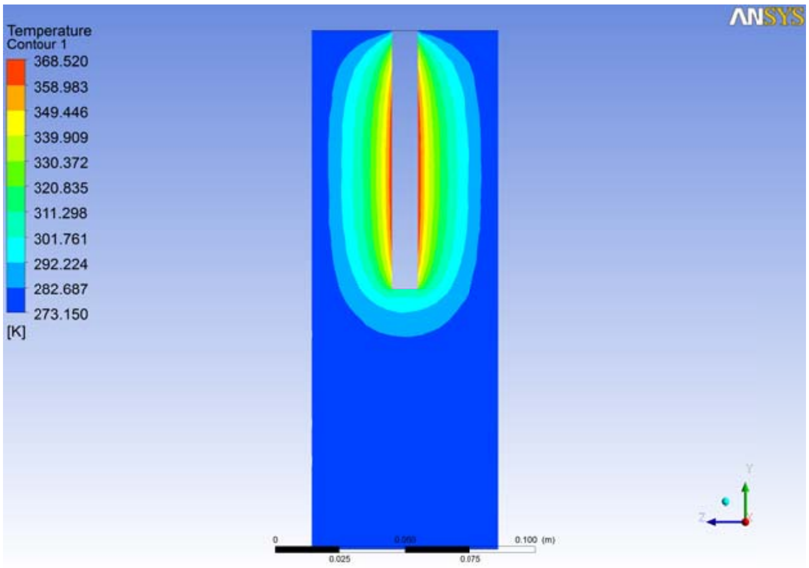

Figure 4.10 Temperature Distribution for a 100% He Mixture

Figures 4.8 to 4.10 above show the results of the CFD analysis of the pure conduction case. These results closely resemble that of the analytical calculations and the differences can be attributed to numerical error and heat transfer in other directions not accounted for by the analytical calculations.

The simulation is done with the same conditions as before but with the effect of gravity and the velocity of the gasses entering the capsule taken into account. The initial values for the velocity were estimated from the fluid and flow analysis as described in section 4.4 of this report. The results of the simulations for the three mixtures are shown in the figures below:

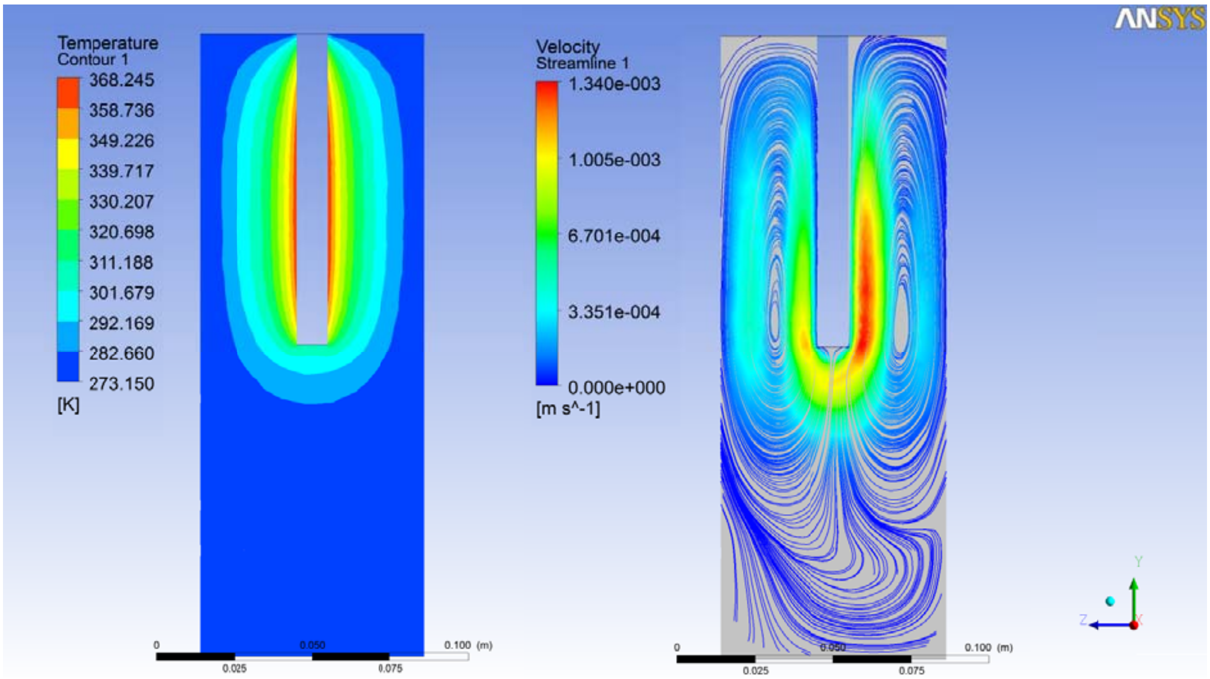

Figure 4.11 Temperature & Velocity Profiles 100% for a He Mixture

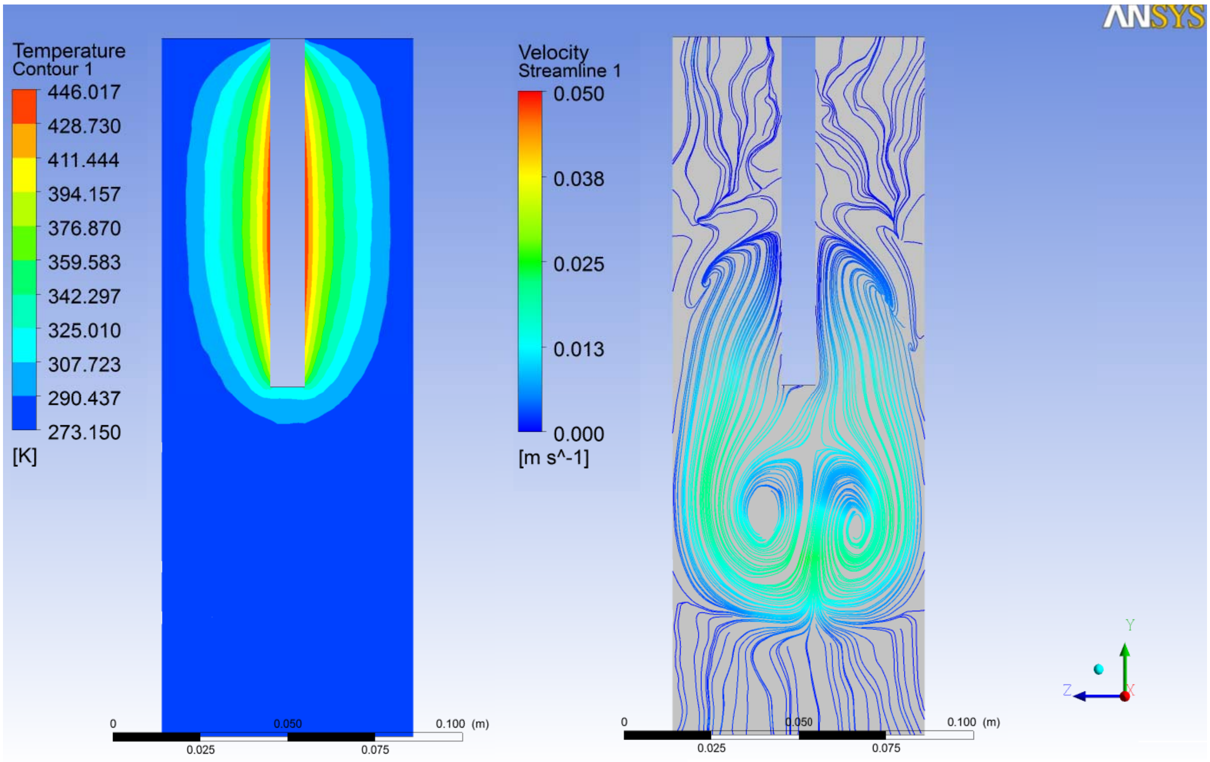

Figure 4.12 Temperature & Velocity Profiles for a 50% He Mixture

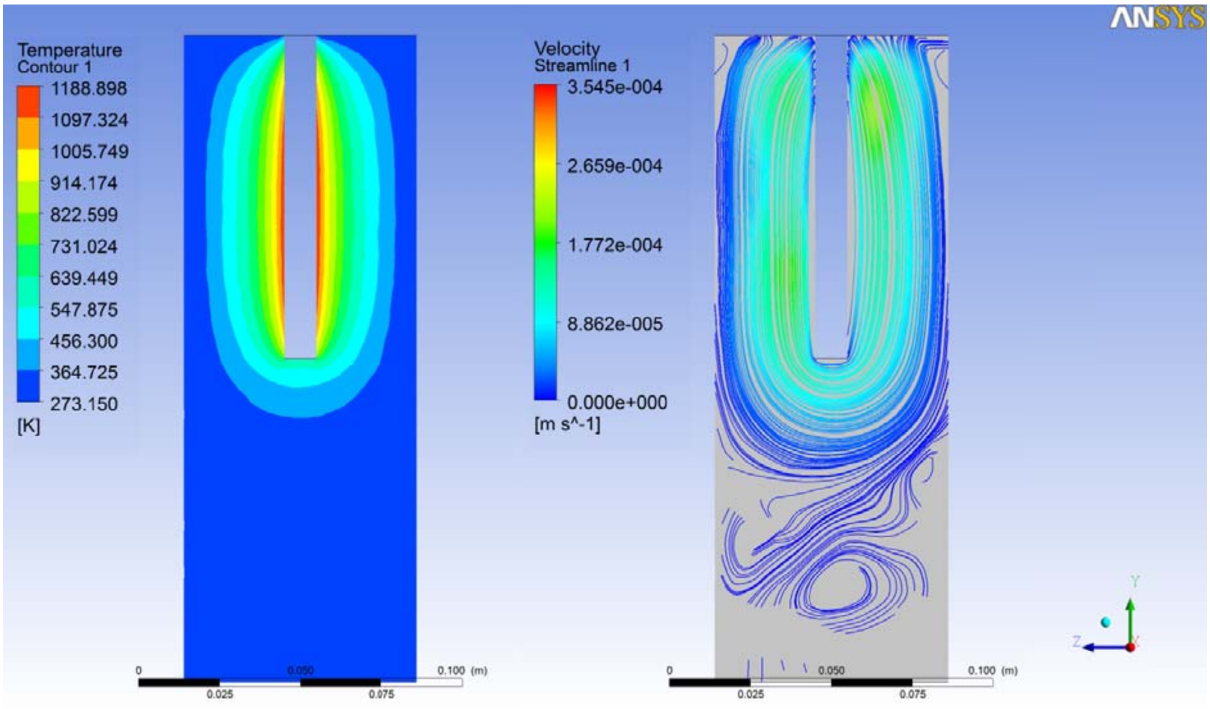

Figure 4.13 Temperature & Velocity Profiles for a 0% He Mixture

When comparing the results of the two simulations for each of the mixtures a very small difference in the maximum temperatures is observed in all three cases, the reason for this being the low velocity at which the gasses enter the capsule.

At higher velocities the maximum temperature begins to noticeably decrease from the pure conduction values.

4.3.3. Transients

All the calculations up to this point have been based on the assumption that temperature does not change with time. In reality this assumption is not always valid, since time does affect the temperature and thus the heat transfer.

The analytical solution of second order partial differential equations is quite complex and can be done using several different techniques such as separation of variables, Laplace transform or numerical methods. In this case a numerical approach was selected in order to get an estimation of the transient effects. The transient responses of the system and its components should be considered in order to know the operating points of the system. The transients should also be accounted for during the design of the control system. The accuracy of the numerical solution will be verified during experimental procedures.

When considering the transient effects on the heat conduction, the general heat conduction equation is once again considered.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{e}_{gen}=\rho c\frac{\partial T}{\partial t}$$

Simplifying to one dimension with no internal heat generation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right)=\rho c\frac{\partial T}{\partial t}$$

Assuming constant thermal conductivity:

$$\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)=\frac{r}{\alpha}\frac{\partial T}{\partial t}$$

Subject to the boundary conditions:

$$T(r_o,t)=0$$

$$-k\frac{dT(r_i,t)}{dr}=\dot{q}$$

And initial condition

$$T(r,0)=0^{\circ}\mathrm{C}$$

The initial condition of zero degrees Celsius is used as the constant temperature bath is filled with ice the average temperature of the system will be close to zero if sufficient time is allowed before starting the system.

This model only considers the transient behaviour in the situation of pure heat conduction and other mechanisms of heat transfer are not considered.

The numerical solution is calculated using Matlab and it's built in one dimensional parabolic partial differential equation solver, *pdepe*. The inputs to the solver are based on the differential equations shown above and the values of the constants used in the solution are obtained from the calculations done in section 4.2 of this report.

The solution was obtained for three control temperatures: 50, 65 and 80 degrees Celsius all with three different constant heat fluxes.

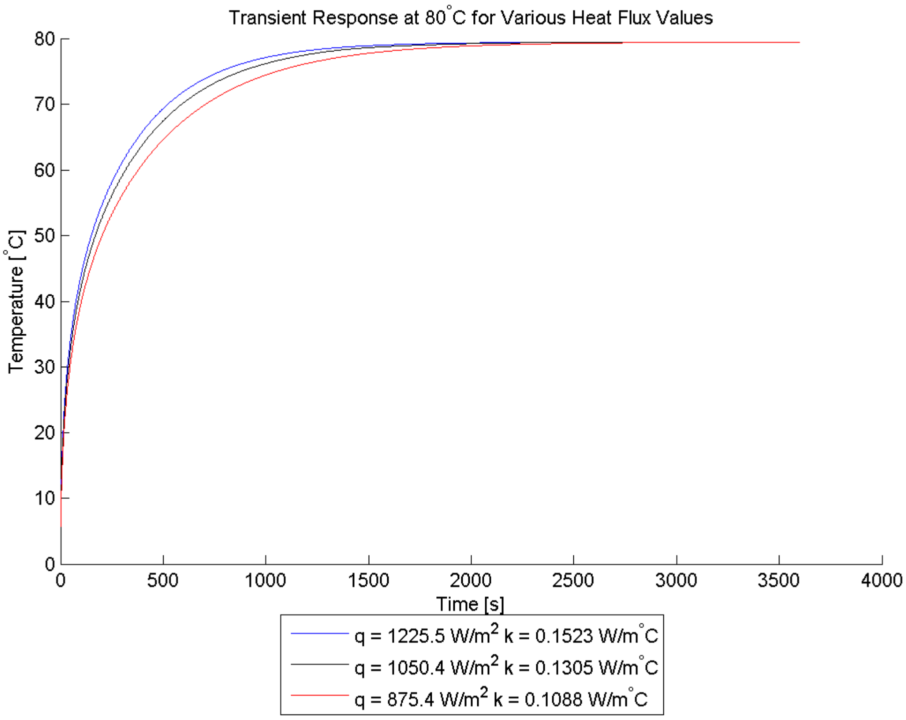

Figure 4.14 Predicted Transient Response for 80 Degrees Celsius

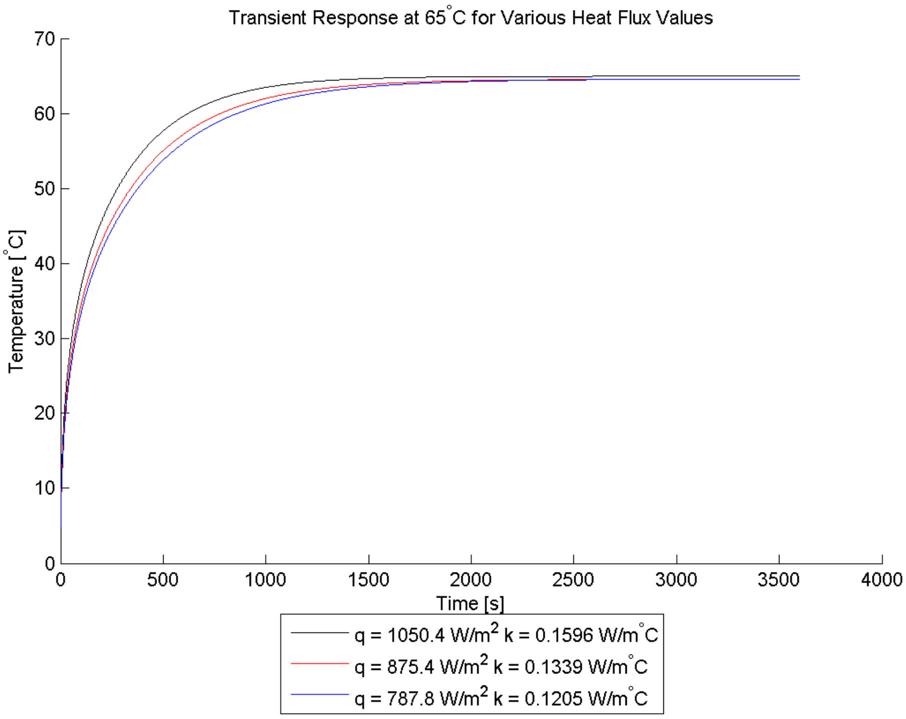

Figure 4.15 Predicted Transient Response for 65 Degrees Celsius

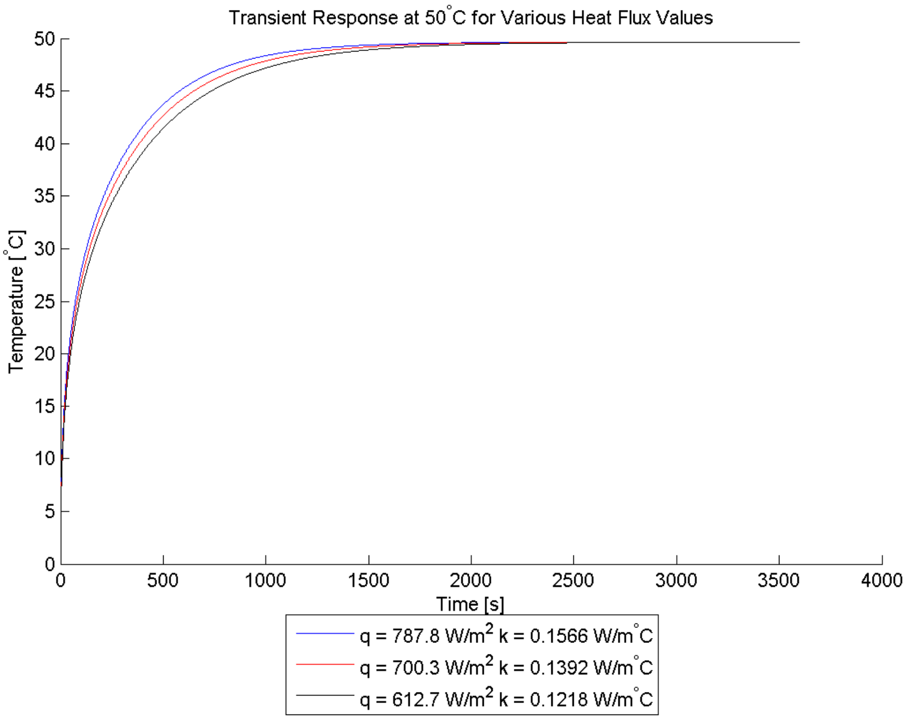

Figure 4.16 Predicted Transient Response for 50 Degrees Celsius

As seen from the figures above, the transient solution predicts a very slow response when starting at an initial temperature of zero degrees and immediately filling the container with the required mixture.

A method of increasing the speed of the system is to preheat the surface to a predetermined temperature with a pure argon mix and then filling the container with the appropriate mixture. A solution was obtained for the same three temperatures with preheating to half the required temperature. From the results it is noted that preheating significantly reduces the rise time but results in a less stable response with some overshoot.

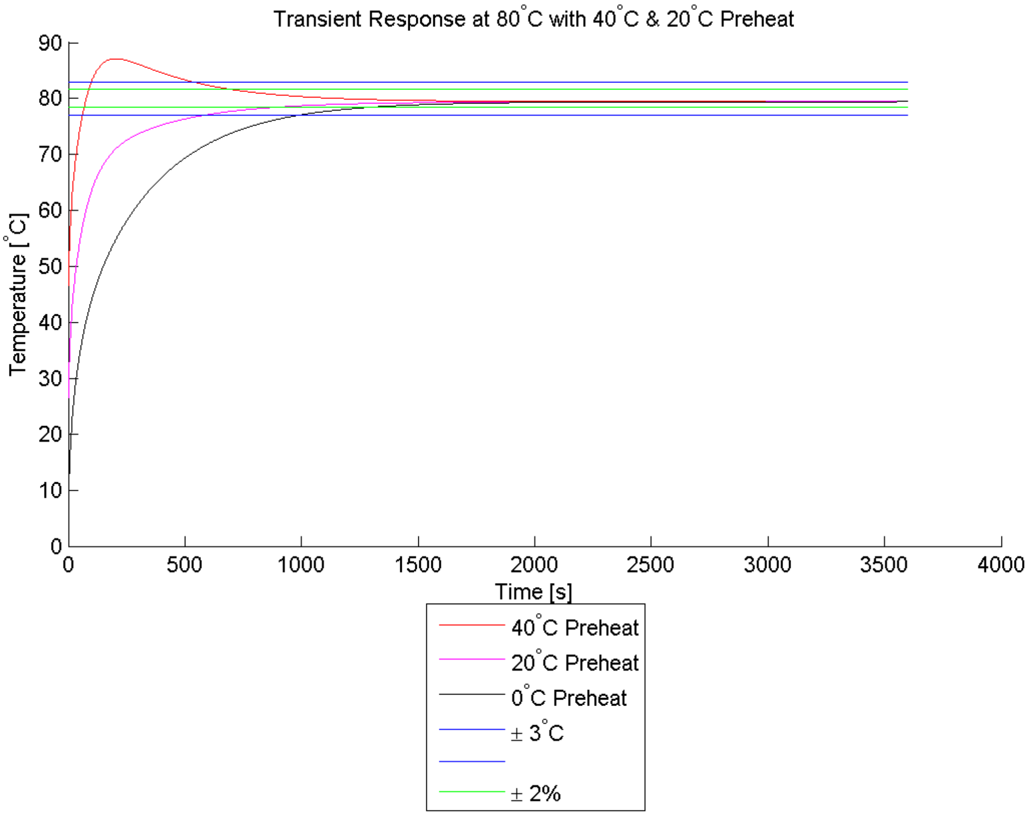

Figure 4.17 Transient Response at 80 Degrees Celsius with Preheating

The figure above shows the predicted transient response of the system at 80°C with 0°C, 20°C and 40°C. With the 40°C preheating the temperature overshoots to a maximum temperature of 87°C but reaches the ±3°C band (indicated in blue) as well as the ±2% band (indicated in green) the faster. With a 20°C preheat the system does not overshoot but does respond slower than with the higher preheat.

The results of the solutions at the three temperatures with preheating are shown in the table below:

Table 4.6 Transient Surface Temperature Estimation after 120 minutes

	0% Preheat			**25% Preheat**			**50% Preheat**		
Temperature [°C]	**±3°C [s]**	**±2% [s]**	**Final Temperature [°C]**	**±3°C [s]**	**±2% [s]**	**Final Temperature [°C]**	**±3°C [s]**	**±2% [s]**	**Final Temperature [°C]**
50	774	1220	49.65	380	837	49.65	374	676	49.65
65	784	1054	64.96	418	684	64.96	471	728	6.96
80	989	1277	79.44	580	874	79.45	531	703	79.45

Using the same model a solution was obtained for a variable mixture with a variable heat flux. According to the solution, the surface temperature is not greatly affected when the heat flux changes and the thermal conductivity is changed as a function of the heat flux.

4.3.4. Heat Source

The heat source of the system is an electric cartridge heater consisting of a stainless steel tube with a highly resistive wire inside.

The heater has an electrical resistance of 8.4 $k\Omega$ and has an electrical power rating of 6.3 Watt. The physical dimensions of the heater are: D = 10mm and L 100mm.

The internal heat generation is a function of the electrical current passing through the wire. The internal heat generation of the heater can be calculated by:

$$\dot{e}_{gen} = \frac{I^2 R_e}{\pi r_o^2 L}$$

$$= \frac{\left(\left(\frac{230}{8400}\right)^2 \times 8400\right)}{\pi \times 0.005^2 \times 0.1}$$

$$80.2\ kW/m^3$$

If it is assumed that the heat transfer from the heater is one dimensional in the radial direction, the heat flux on the outer surface can be determined.

$$\dot{q} = \frac{I^2 R_e}{A_s}$$

$$= \frac{\left(\frac{230^2}{8400}\right)}{\pi \times 0.01 \times 0.1}$$

$$= 2004.6\ W/m^2$$

The internal temperature distribution is determined to ensure that the internal temperatures do not become extremely high and damage the heater.

The heater is manufactured with a 1mm stainless steel 304 shell with the heater wire inside and filled with magnesium oxide powder, the thermal conductivity of stainless steel is 14.9 W/mK. (Cengel, 2006) and magnesium oxide is 0.6058 W/mK (Yaws, 2012).

The heater wire is embedded in the magnesium oxide and the effect of the wire is assumed negligible and the heat is then assumed to be generated in the magnesium oxide filler.

The outside temperature is to be controlled by the system and maintained at 75°C.

An equation for the heat transfer through the heater filler material is derived from the general heat conduction equation:

$$T_m(r) = T_{r_o} + \frac{\dot{e}_{gen}}{4k}(r_1^2 - r^2)$$

Subject to:

$$T_m(r_1) = T_{r_1}$$

$$\frac{dT_m(0)}{dr} = 0$$

The equation for the shell is given by:

$$T_{ss}(r) = \frac{T_{r_1} - 75}{\ln\left(\frac{r_1}{r_2}\right)}\ln\left(\frac{r}{r_2}\right) + 75$$

Subject to:

$$T_{ss}(r_1) = T_{r_1}$$

$$T_{ss}(r_2) = 75$$

Using the zero heat flux boundary condition to solve for the interface temperature:

$$-k_m\frac{dT_m(r_1)}{dr} = -k_{ss}\frac{dT_{ss}(r_1)}{dr}$$

$$= \frac{\dot{e}_{gen}r_1}{2} = -k_{ss}\frac{T_{r_1} - 75}{\ln\left(\frac{r_1}{r_2}\right)}$$

$$T_{\mathrm{r}_1} = \frac{-\frac{\ln\left(\frac{r_1}{r_2}\right)r_1\dot{e}_{gen}}{2} + 75k_{\mathrm{ss}}}{k_{\mathrm{ss}}}$$

$$= 75.25℃$$

The maximum temperature will be in the centre of the heater:

$$T(0) = 75.25 + \frac{80200}{4(0.6058)}(0.004^2 - 0^2)$$

$$= 75.78\ ℃$$

Thus the risk of internal overheating is quite low at the operating temperature range.

4.4. Gas Flow

In order to be able to control the thermal conductivity of the gas mixture, it is necessary to know the fluid behaviour of the gasses in the system.

The system has two inlet ports, one for each gas, and one outlet port. The flow rates of the inlets can be controlled manually by adjusting the flow regulators on the gas cylinders. The flow rates are required to be as high as possible so that the gas exchange process can happen as fast as possible, but the flow rates should be such that the valves controlling the amount of gas in the system have enough time to open and close. Since the temperature of the incoming gas is different from that of the gas in the system it will have an effect on the control temperature.

Once the two gasses are mixed it is not possible to separate them without the use of expensive speciality equipment, thus this system will not recycle the gas from the container. It will instead purge the container and refill it with the required new mixture.

The start up of the system should also be considered since initially the container will contain air, the system will upon start up flush the container with argon since argon is heavier than air and will force out the air. The same procedure will used to purge the system before adding a new mixture.

The system uses a pressure based mixing process, the control system will calculate the partial pressure of each gas according to the required mixture and add the gasses one at a time.

There are a few important values that need to be determined, first of all is the velocity with which the gas enters the capsule:

The flow rate is adjusted to 30LPM on the regulator, and the pressure reduction valve is assumed to have a negligible effect on the flow rate, this is converted to m^3/s:

$$Q = \frac{30}{60 \times 1000}$$

$$= 5 \times 10^{-4} m^3/s$$

The pipe which connects the gas cylinders to the test capsule has an internal diameter of 8mm and the capsule has an internal diameter of 73mm. Assuming the flow rate remains constant the pipe and inlet velocities can be calculated as:

$$v_p = \frac{Q}{A_s}$$

$$= \frac{5 \times 10^{-4}}{\frac{\pi}{4} \times 0.008^2}$$

$$= 9.95\, m/s$$

$$v_i = \frac{Q}{A_s}$$

$$= \frac{5 \times 10^{-4}}{\frac{\pi}{4} \times 0.073^2}$$

$$= 0.12\, m/s$$

Since the outlet valve will remain closed during filling the velocity will decrease as the pressure increases until the internal and inlet pressures are the same at which point the velocities will be approximately zero.

Assuming incompressible and frictionless flow the outlet velocity can be determined using the Bernoulli equation:

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} = \frac{p_2}{\rho} + \frac{v_2^2}{2}$$

$$v_2 = \sqrt{2(\frac{p_1}{\rho})}$$

This value will differ between mixtures, the calculated value for pure argon and pure helium is shown below:

$$v_{2_{Ar}} = \sqrt{2\left(\frac{150000}{2.303}\right)}$$

$$= 360.9 m/s$$

Converting the outlet velocity to a volume flow rate at the outlet:

$$Q = v_{2_{Ar}} A_c$$

$$= 360.9 \times \frac{\pi}{4} \times 0.008^2$$

$$= 0.018\, m^3/s$$

$$v_{2_{He}} = \sqrt{2\left(\frac{150000}{0.23}\right)}$$

$$= 1142.1\ m/s$$

$$Q = v_{2_{He}} A_c$$

$$= 1142.1 \times \frac{\pi}{4} \times 0.008^2$$

$$= 0.057\ m^3/s$$

The total gas volume includes the volume of the pipes between the valves and the capsule which is equal to $9.4 \times 10^{-4} m^3$.

The time required to fill the capsule can then be estimated using the inlet flow rate:

$$t_f = \frac{V}{Q}$$

$$= \frac{9.4 \times 10^{-4}}{5 \times 10^{-4}}$$

$$= 1.88\ s$$

and the purge time:

$$t_{p_{Ar}} = \frac{V}{Q}$$

$$= \frac{9.4 \times 10^{-4}}{0.018}$$

$$= 0.05\ s$$

This is slower than the minimum opening and closing time of the valves which is 10ms, thus there will be no delay in filling or purging of the capsule. The quick opening and closing times of the valves also allow very small quantities of each gas to be added at a time given that the controller is able to open and close the valves as fast.

4.5. Mechanical Design

This section describes the design of the test capsule and the complete system. Since the capsule will contain pressurised gas, the capsule design should be such that the capsule will be able to withstand the internal pressure. The capsule should also be able to contain the gas without any leaks and would therefore require good seals on the lid, the gas ports and the instrumentation ports. All of the welds need to be thoroughly inspected before assembly. The welds must act as a seal between the tube and the bottom lid as well as the tube and the top lid flange. A 1mm neoprene gas is used as a gasket between the top lid and the flange and the heater flange and the lid.

The capsule is constructed using a 76.2x1.6mm stainless steel tube of which both the top and bottom ends are sealed with lids also made from stainless steel. The top lid is removable and is attached by a flange and bolts, with a 1mm neoprene gasket and the bottom lid is welded in place. The image below shows a rendering of the test capsule with the lids and the fittings on the inlet ports:

Figure 4.18 Rendering of the Experimental Test Capsule

The stress in the capsule due to the internal pressure can be calculated using thin walled pressure vessel theory since the ratio of the internal radius to the wall thickness is larger than 10.

The circumferential stress is calculated as:

$$\sigma_1 = \frac{spr}{t}$$

$$= \frac{2 \times 150000 \times 0.0365}{1.6 \times 10^{-3}}$$

$$= 6.84\ MPa$$

and the longitudinal stress:

$$\sigma_2 = \frac{spr}{2t}$$

$$= \frac{2 \times 150000 \times 0.0365}{2 \times 1.6 \times 10^{-3}}$$

$$= 3.42\ MPa$$

Where s is a safety factor of 2.

Both these stresses are considerably lower than the yield strength of stainless steel (310 MPa) thus the capsule will be able to withstand the pressure.

Since electrical currents and water from the ice will be used close to each other the support structure is very important in order to prevent electrical short circuits. The support structure is used to assemble all of the mechanical parts such as the valves, temperature bath and capsule and so that the system is one neat complete unit and safe to use. The figure below shows the support structure with all of the components installed.

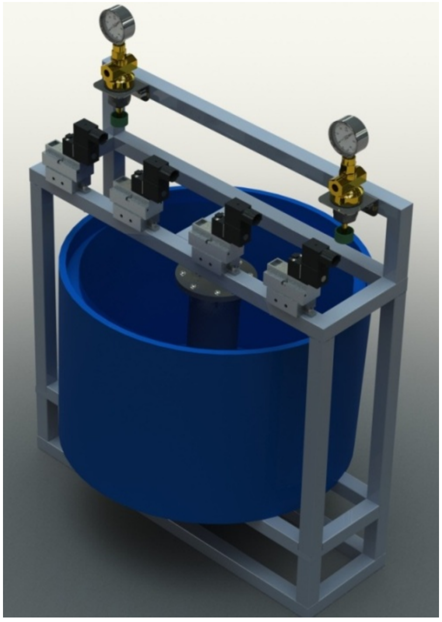

Figure 4.19 Main System Setup

The support structure is a quite simple design, the upper most rear cross member is used to mount the pressure reduction valves and for cable routing. The valves are mounted on the front of the top frame to allow access should they need to be replaced and to allow for the pipes at the back. The capsule is suspended by ropes from each of the four sides of the frame. The constant temperature bath is placed on the lower frame which is spaced away from the bottom to allow room for the temperature bath drain pipe and valve. For safety reasons the electronic components and power supplies are not mounted on the support frame. The figure below shows the parts and main dimensions of the support frame:

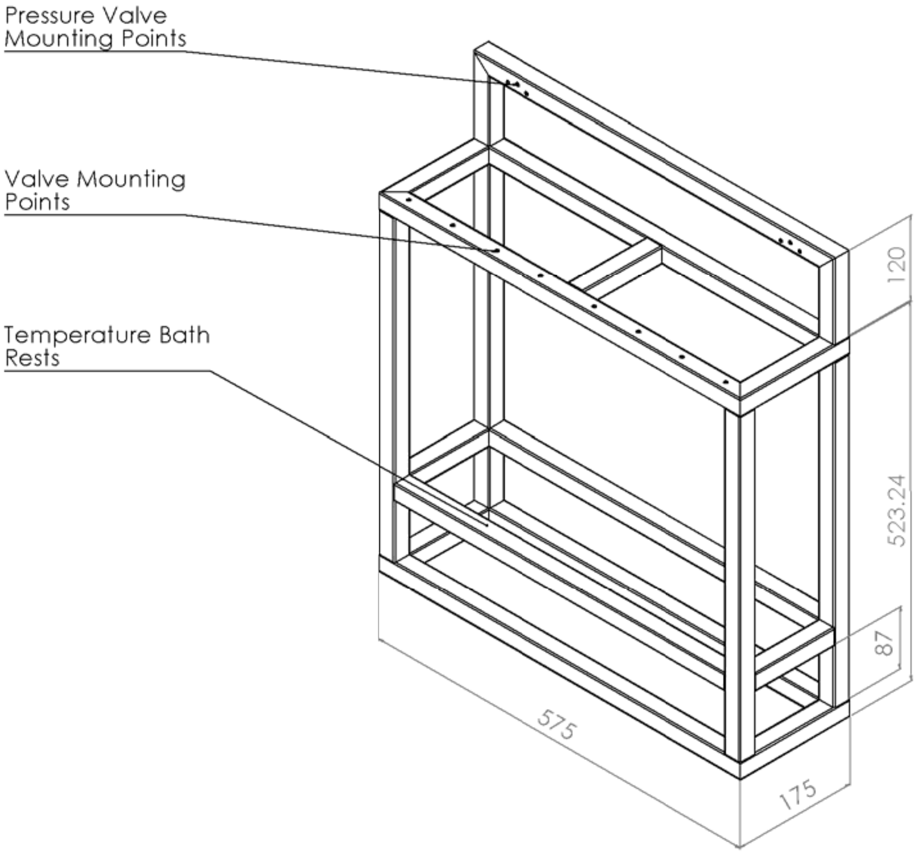

Figure 4.20 Support Structure Drawing

The temperature bath has a very simple design since it is not the focus of the project and ice can easily be added should it be necessary. The temperature bath consists of two plastic containers with 25 litre and 10 litre capacities respectively. The smaller container is fitted inside the larger container with an even gap all around between the two. The gap is filled with expanding polyurethane foam for insulation. The lid is made in a similar fashion using the lids of the two containers. A pipe with a ball valve is fitted to the bottom to ensure drainage when required.

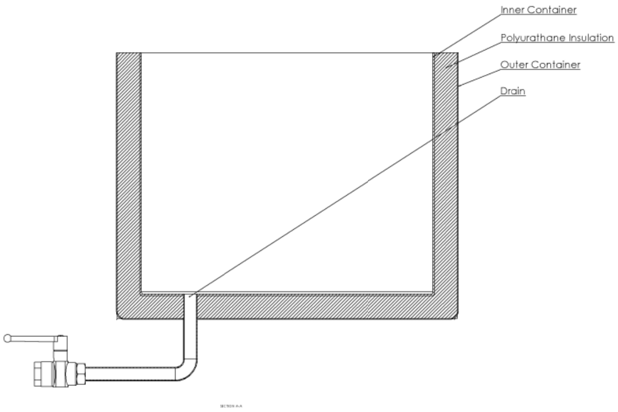

Figure 4.21 Constant Temperature Bath Section View

The valves that are used with the system are 4 way miniature single solenoid valves with ¼”BSP ports. The valves are used to control the flow of the gas to and from the capsule, the specific type of valve used is the ASCO Redi-Air series 220V AC valve, these valves have a maximum pressure rating of 1MPa. These valves have 4 directions of flow, two when the solenoid is de-energised and two when the solenoid is energised as shown below:

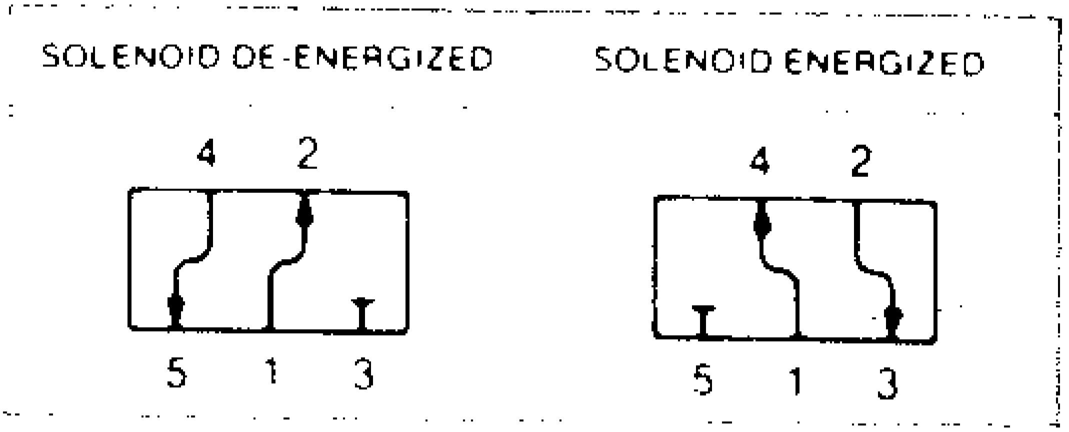

Figure 4.22 Solenoid Valve Flow Diagrams (ASCO)

The capsule and gas cylinders are connected to the valves in such a way when the power is off the valves on the inlet side are closed and the outlet valve is open, once the system is on the inlet valves are opened as required by the controller and the outlet valve is closed. This is done as a safety measure that in the event of a failure or malfunction the power can be turned off and the capsule will depressurize.

Pressure reducing valves are installed in the inlet lines before the valves in order to bring down the gas pressures from the cylinder pressures for safety purposes and to maintain a constant working pressure so that the effects of pressure on system performance is minimized.

The figure below show the inlet and outlet valve piping configurations:

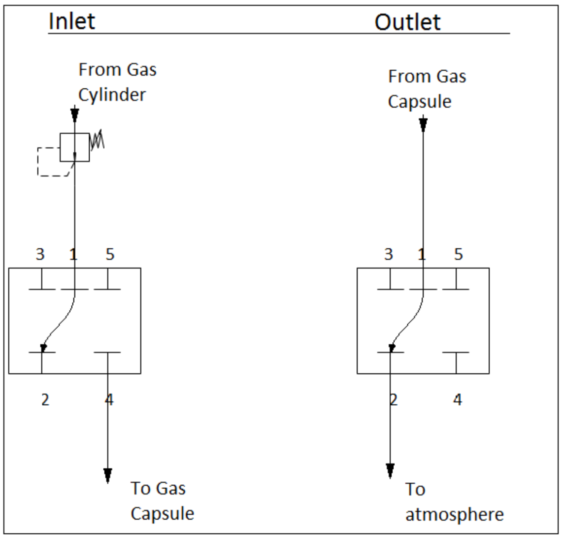

Figure 4.23 Valve Pipe Configurations

4.6. Control System

The control system consists of three main components, the measurement devices, the output devices and the micro controller that takes inputs from the measurement devices, makes decisions based on the inputs and determines the appropriate outputs.

The controller controls the gas mixture ratio based on the temperature reading on the surface of the heater and a pressure transducer installed inside the capsule. For safety and reliability reasons the controller will also control the power of the heater by making use of PWM or pulse width modulation since the heater is powered by 220V AC and would require powerful resistors to adjust the power manually. These types of resistors dissipate a lot of heat which would result in a loss of power to the heater.

4.6.1. Control System Hardware

The controller selected for the control system is an Arduino Uno, a relatively inexpensive controller based on the ATmega328 microcontroller with an open source C based programming language. It has a clock speed of 16 MHz with 5 analogue input pins and 13 digital I/O pins.

There are three measurement devices in the system, two temperature sensors and a pressure transducer. The first temperature sensor is a k-type thermocouple installed inside the heater.

Connecting the thermocouple wires directly to the controller pins or another set of wires creates another thermocouple which can influence the output. There is a lot of noise from the alternating current passing through the heater, therefore an amplifier circuit is added to the thermocouple. The amplifier used is the AD595 k-type thermocouple amplifier, the selection of this amplifier lies in that it has built in cold junction compensation. The second temperature sensor is a LM35 which is a high precision integrated circuit temperature sensor with a constant output of 10mV/°C. The pressure transducer is a MPX5700GP, a gauge pressure transducer which is mounted inside the gas capsule.

All of these sensors require 5V power and output analogue signals (voltages) which are connected to the analogue inputs of the controller where the voltages are converted to the appropriate units. The figure below shows the circuit diagram for the measurement devices:

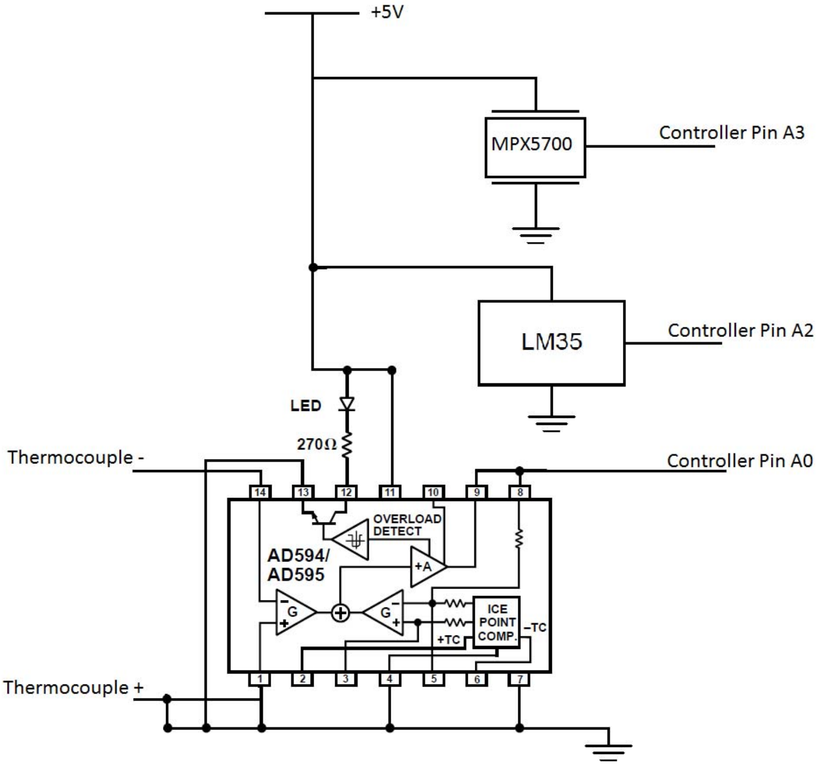

Figure 4.24 Measurement Devices Circuit Diagram

The output from the controller is a signal between 0V and 5V DC and the valves require 220V AC, thus a relay or similar device is needed. For this system a static switch circuit was designed since a static switch has no moving parts like a relay and the changes of failure due extensive use is minimised. The static switch circuit consists of an optocoupler and a triac along with a few other components. When a valve needs to be powered the controller sends a 5V signal to the input of the optocoupler, which has an internal led and light sensitive diode, the 5V signal turns on the led which completes the triac circuit. The main terminals of the triac are connected to live from mains and the valve respectively. When the optocoupler turns on a voltage is applied to the gate pin of the triac which completes the circuit between the two main terminals and turns on the valve. The circuit diagram for a single static switch is shown in the figure below.

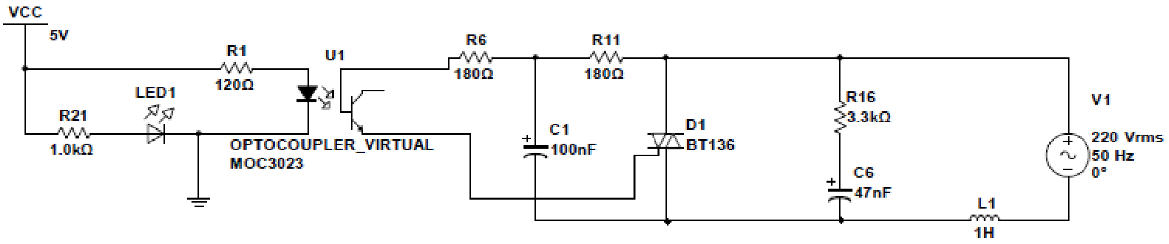

Figure 4.25 Static Switch Circuit Diagram

Where L1 represents the inductive load of the solenoid. The static switch acts only on live for each valve and earth and neutral are connected directly from the mains supply.

The heating element is controlled in a similar manner so the AC and DC voltages remain separate and the power to the heater can be controlled easier than using large resistors that generate a lot of heat and therefore energy loss. The heating element is controlled using pulse width modulation which, depending on the setting turns the heater on and off so that only a percentage of the power is applied to the heater.

The heater setting is determined by a switch and a set of resistors in series, the position of the switch determines the number of resistors in series and thus the voltage that is applied to the analogue input pin of the controller.

4.6.2. Control System Software

The controller is programmed using a C based language, the program is written on computer then compiled and uploaded to the controller. The program has two main parts, the first is the setup where all the initial setting are applied, input and output pins are assigned to variables etc. The second part is the main program loop, a set of commands which are constantly repeated as long as the controller is turned on.

The start up sequence for this system is defined in the setup section of the program. In this section pins connected to the valves and the heater are defined as output pins and the input pins are assigned to variables. The argon valve and the outlet valve are opened and capsule is flushed and filled with argon. A serial connection for when the controller is connected to a computer via USB is established and initial measurements are taken. With these measurements a failsafe function is called to ensure that the pressure and temperature inside the capsule are within limits and if not the system stops.

Several other functions are defined within the program, which include functions that measure the temperatures and pressure, using the transfer functions associated with each measurement device. The controller has a 10 bit analogue to digital converter which maps the input voltages to a value between 0 and 1023. In order to determine the value of the measurement this value first needs to be converted back to a voltage and then the transfer function of the device can be used to determine the value. For example the output of the LM35 temperature sensor is 10mV/°C, thus the equation in order to determine the temperature is given by:

$$T = \frac{\left(\frac{5000x}{10}\right)}{1024}$$

where x is the value read on the input pin.

A 5 point moving average filter is used on the temperature measurements since they can be affected by noise and this could cause spikes in the measurements. The filter takes the average of the previous 5 measurements as the current measurement.

$$T_n = \frac{T_{n-1} + T_{n-2} + T_{n-3} + T_{n-4} + T_{n-5}}{5}$$

A function that mixes the gas according to a specified ratio is defined. This function takes the desired ratio and operating pressure as inputs and calculates the required partial pressures for each gas. The argon valve is then opened and remains open until the partial pressure is reached after which the argon valve closes and the helium valve opens until the correct pressure is reached. This function has a third input parameter that when enabled checks if there has been a significant pressure drop and adds gas according to the required ratio if needed.

Other functions defined is the data output function which outputs all of the system data, measurements, calculated values and selected variables to the serial connection. There is also a failsafe function which checks the capsule temperature and pressure and if either of these exceed the specified value the capsule is purged and the heater turned off.

The main program loop repeats every two seconds, faster intervals can be used if needed but this interval was selected to allow the measurement devices to stabilise between readings and to conserve gas so that the gas mixture is not constantly changed. At the start of the main loop measurements are taken using the defined functions and the filter on the temperature sensor is applied. Once the measurements are taken a failsafe function is called to check that the system pressure and temperature are both within safe limits. In each iteration of the main program loop all of the measured data is output to the serial port and some of the crucial data such as temperature and pressure is also displayed on the LCD screen attached to the controller.

Initially the mixture is kept constant at 0% helium so as to allow the temperature on the heater surface to rise close to the selected control temperature so that the temperature increases faster. Once the temperature on the heater surface is close to the required value the main control starts. A tolerance of ±3°C is allowed since the measurement devices have the same tolerance.

One of the requirements of the system is that it should be able to operate independently of the heat flux value since in practice this is not known. The initial value of the thermal conductivity of the gas gap is known since initially the gas gap is pure argon. With the known value for thermal conductivity a value for the heat flux is estimated using the currently measured temperature and the equation derived in section 4.3.1 of this report, which is shown again below:

$$T(r) = \frac{\dot{q} r_i}{k} \ln\left(\frac{r_o}{r}\right)$$

The same equation is then used to determine the required thermal conductivity using the selected control temperature and the estimated heat flux. The required mixture ratio is then calculated using a rearranged version of the equation for thermal conductivity as described in section 4.2. The equation is rearranged to make x_1 (helium mole fraction) the subject and x_2 is defined as:

$$x_2 = 1 - x_1$$

Substituting the above equation and the values of the known constants into the equation yields:

$$x_1 = \frac{-\sqrt{0.1201 k_{eff}^2 - 0.1232 k_{eff} + 0.24} + 3.1250 k_{eff} + 0.0908}{2.185 k_{eff} + 0.1813}$$

Since ideal gas is assumed the mole fraction of helium is also the percentage helium in the mixture, the calculated helium fraction is then passed to the mixing function which then determines the pressures and fills the capsule with the required mixture.

Once an iteration of the main loop is completed the controller automatically starts another iteration and repeats the process using the values from the previous iteration to determine the new values if the temperature deviates out of the allowed tolerance. The figure below shows a flow chart of the control system functions:

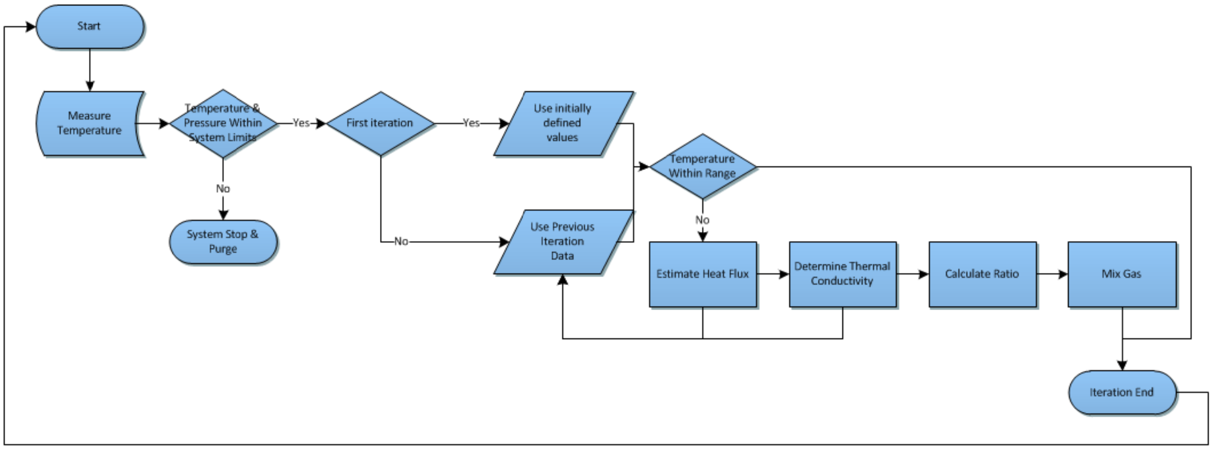

Figure 4.26 Control System Flow Chart

The heating element is also controlled in the main loop, the program takes a reading from the analogue input pin to determine the heater setting and with read value determines the factor of power the heater is to receive. This information is then passed on to the heater control function, it should be noted that even though the heater is controlled by the same controller as the gas mixture the gas mixture is not in any way directly influenced by the heater setting.

5. Experimental Procedures

In order to test the theoretical design and models several experiments are to be done. These experiments attempt to prove the validity of the assumptions made during the theoretical analysis and design and to determine the effectiveness of the system in a practical application. This section describes the experiments that are to be conducted and the procedures of these experiments.

The first experiment to be conducted is on the cartridge heater in order to determine the maximum temperature at various input power levels in open air and the temperature rise time. The results of this experiment are used to determine the uniformity of the heat flux produced by the heater and the results of this experiment are used for the fine tuning of the control system and since no theoretical data is available on the heater it has to be determined experimentally.

The main experiment is the test of the complete system. Several control temperatures are selected in order to test the performance of the system at various temperatures. When the temperature starts approaching steady conditions the power of heater is changed and the control system should adjust the mixture in order to maintain a constant temperature on the surface of the heater.

During the design and manufacturing process several other smaller tests will be conducted, such as the seals on the test capsule and the safety measures and the control system.

5.1. Experiment 1

As described in the previous section the system includes a cartridge heater that has a rating of 1500 W/m^2, but the heat distribution across the surface of the element is unknown. The purpose of the first experiment is to determine the uniformity of the heat flux produced on the surface of the heater and to experimentally determine the maximum heat flux of the heater. This experiment also tests the maximum temperature for several power levels and determines the rise time at each setting.

5.1.1. Equipment

The equipment required for this experiment is:

- Cartridge Heater
- 4x Thermocouples
- Data logger & Computer
- Multimeter
- Controller

5.1.2. Setup

The figure below shows a schematic layout of the experiment.

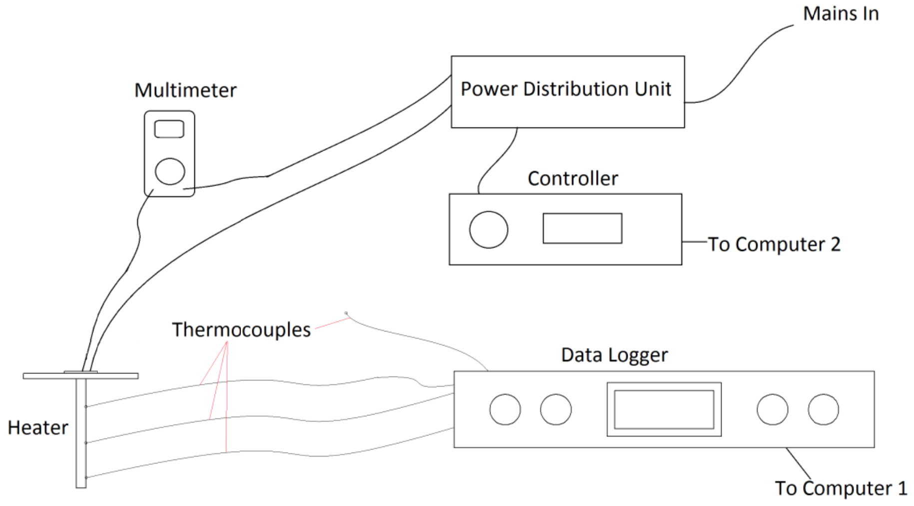

Figure 5.1 Schematic Layout of Experiment 1

For this experiment three thermocouples are attached at evenly spaced locations on the heater surface with a fourth to measure ambient temperature and connected to the data logger. The data logger is setup to take measurements at the same intervals as the controller.

The heater is connected to the appropriate static switch in the power distribution unit which is supplied with mains and connected to the controller. A multimeter set to measure current is connected in line with the heater.

The controller is loaded with just the heater control functions, the temperature measurement functions and the data logging functions.

5.1.3. Experimental Procedure

The heater was suspended from the support frame with the thermocouples attached and without the capsule in place. The data logger recording interval is set to 2 seconds (the same as the controller interval), the data logger, the data recording program for the controller and the controller are started simultaneously from the two computers.

The heater is then set to the first power level setting (50%) and left for 5 minutes after which the heater is then turned off and left to cool down for 5 minutes. The data from the controller and the data logger is then saved for processing, the system is then turned off and the heater left to cool down to ambient temperature.

The current measurement from the multimeter is recorded for each of the power level settings. This process is then repeated for all of the heater power level settings. The settings with which the experiment is done are 50%, 65% 80%, 90% and 100%.

The results of this experiment is then processed and evaluated and any necessary adjustments made to the main program before commencing with the next experiment. The results of this experiment are shown and discussed in sections 6.1 and 7 respectively.

5.2. Experiment 2

This is the main experiment in which the complete system is to be tested. The heater is to be set to a certain value and the system should adjust the gas mixture so as to maintain a constant temperature on the heater surface. Measurements will be taken of the temperature on the surface of the heater as well as several other temperatures and the internal pressures. The results of this experiment will be used to verify the results of the theoretical analysis and to draw conclusions as to the effectiveness of the system.

5.2.1. Equipment

The equipment required for this experiment is:

- Helium Gas
- Argon Gas
- Flow Regulators
- Pressure Reduction Valves
- Pressure Gauges
- Solenoid Valves
- Support Frame with valves and regulators installed
- Test Capsule
- Pressure Transducer
- Multimeter
- Controller
- Data Logger & Computer

5.2.2. Setup

The setup for this experiment consists of the support frame with three valves and the two pressure regulators installed on top and the test capsule suspended in the temperature bath. The temperature bath is filled with ice and the drain valve is closed.

The Valves and heater are all connected to the mains distribution board which is connected to the controller along with the measurement devices. The same thermocouples used in the previous experiment are used again with three additional thermocouples, one in the gas gap, one on the inner wall of the capsule and one in the temperature bath these are all connected to an independent data logger. The controller is connected to a computer and the data from the controller is captured using a Matlab program which provides real time graphs of the temperature measured by the controller. A multimeter set to measure current and is connected in line with the heater in order to get a indication of the current as well as a indication that the heater is working.

The figure below shows a diagram of the setup for this experiment:

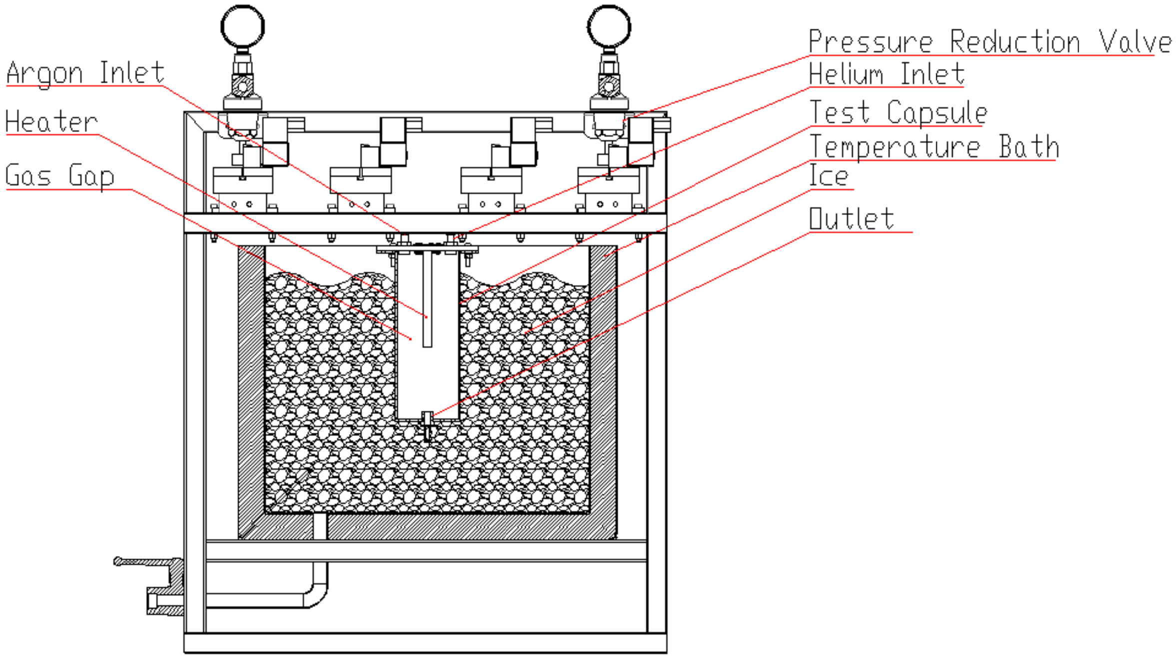

Figure 5.2 Main Experiment Setup

5.2.3. Procedure

Before the experiment is started both computers are setup so that they are ready to start recording data. The first step is to open the valves on the gas cylinders and to check for leaks in the gas lines and set the pressure on the pressure reduction valves to 150 kPa. The control temperature is specified in the controller programming and the program is uploaded to the controller.

Next the heater is set to maximum and the system is started, this is done in order to allow the temperature to rise faster, as soon as the temperature approaches the control temperature the system will start adjusting the mixture and the heater power is turned down to the centre position.

Leave the system to continue on its own, if the temperature starts settling below the selected control temperature outside the allowed tolerance, increase the heater power and vice versa if the temperature settles above the control temperature.

After each test run is completed the data is saved and the system is turned off and allowed to cool down to zero. The tests are repeated three times for each control temperature, after the test runs for a specific temperature is completed the controller program is adjusted for the next control temperature and the procedure is repeated.

6. Experimental Results

This section describes the results obtained from each of the experiments mentioned in the previous section as well as how the resulting data was processed. Each individual test was done at least three times and the results shown in this section are average values obtained from the three test runs. The full results of the experiments is too large to include in this report but are available on request. The results of the experiments are discussed in greater detail in the next section of this report.

6.1.Experiment 1

The figures below show the temperatures measured on the heater by the thermocouples attached to the top, bottom and centre of the heater and recorded by the data logger. Each of the figures show the measured temperatures as well the average temperature between the three.

The raw data obtained from the data logger and the controller was filtered using a two part filter. The first part is a maximum deviation filter to remove outliers which are most likely caused by disturbances or electrical noise. The second part is a 5 point moving average filter which is just used to smooth the data for plotting.

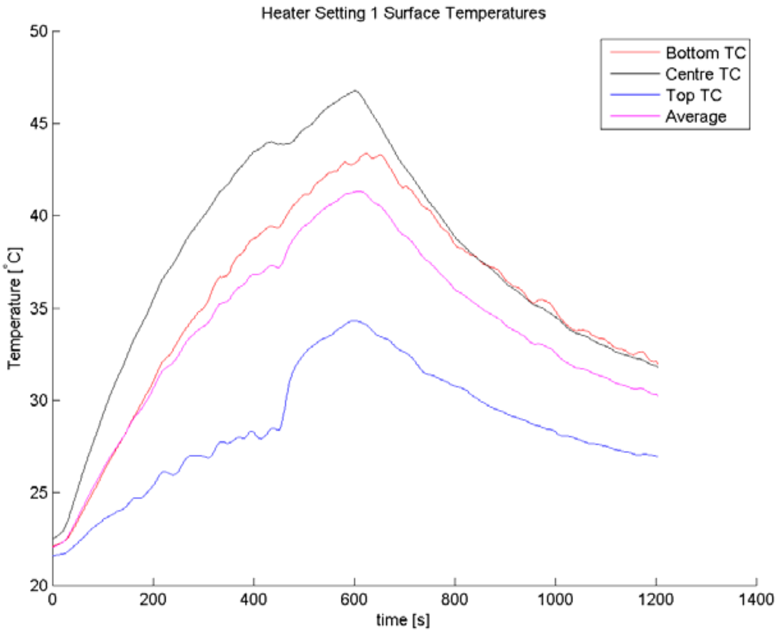

Figure 6.1 Heater Surface Temperatures at Setting 1

The average temperature reaches a maximum of 41.32°C in 5 minutes, thus at 50% power the heater temperature rises at an average of 8.26°C/min.

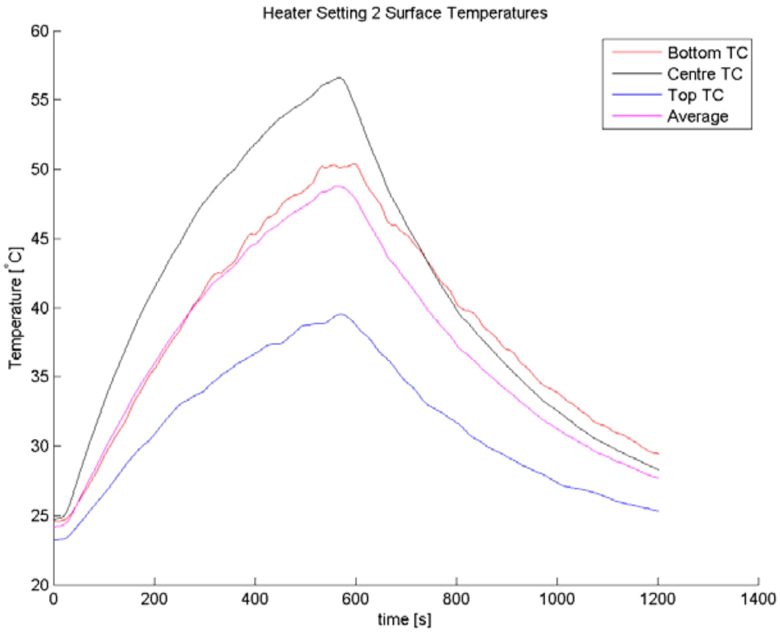

Figure 6.2 Heater Surface Temperatures at Setting 2

The average temperature reaches a maximum of 48.75°C in 5 minutes, thus at 65% power the heater temperature rises at an average of 9.75°C/min.

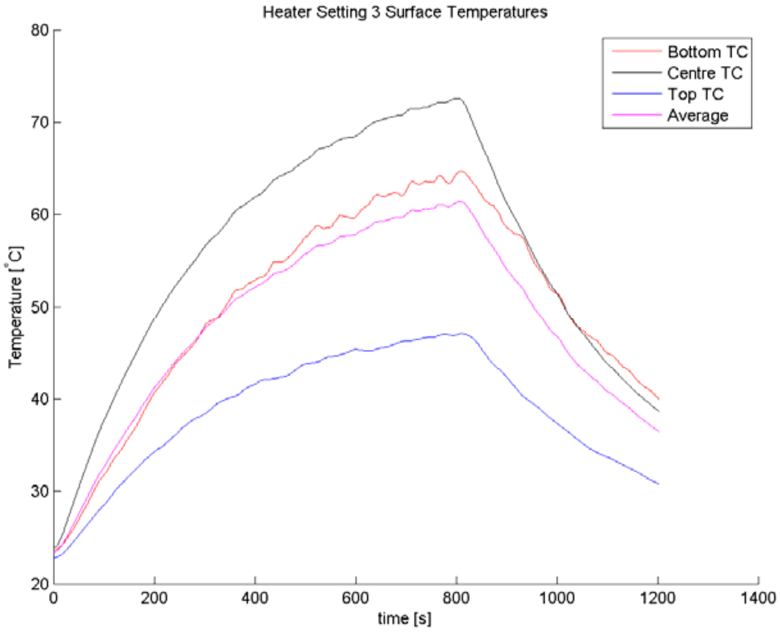

Figure 6.3 Heater Surface Temperatures at Setting 3

The average temperature reaches a maximum of 61.42°C in 5 minutes, thus at 80% power the heater temperature rises at an average of 12.28°C/min.

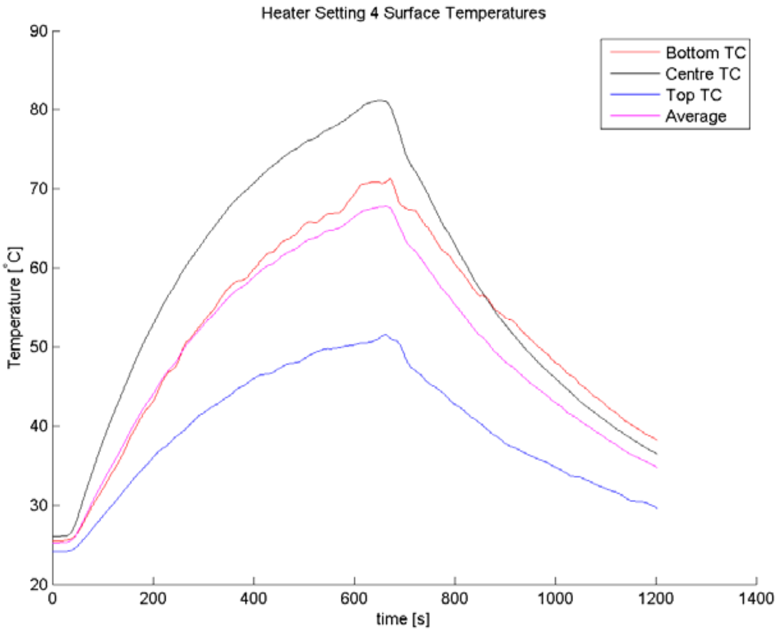

Figure 6.4 Heater Surface Temperatures at Setting 4

The average temperature reaches a maximum of 67.82°C in 5 minutes, thus at 90% power the heater temperature rises at an average of 13.56°C/min.

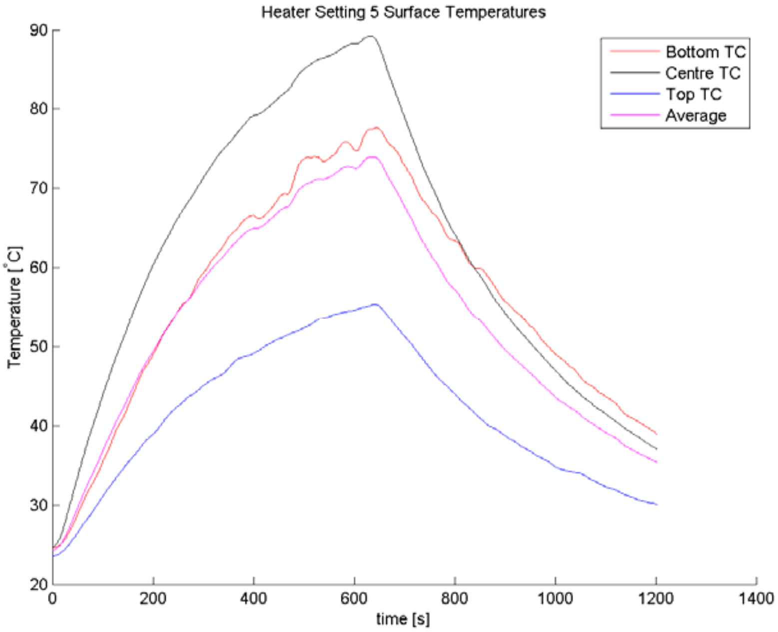

Figure 6.5 Heater Surface Temperatures at Setting 5

The average temperature reaches a maximum of 73.97°C in 5 minutes, thus at 100% power the heater temperature rises at an average of 14.8°C/min.

The next set of figures show the comparison between the two temperature sensors attached to the controller and the average temperature measured by the data logger at each of the five heater settings.

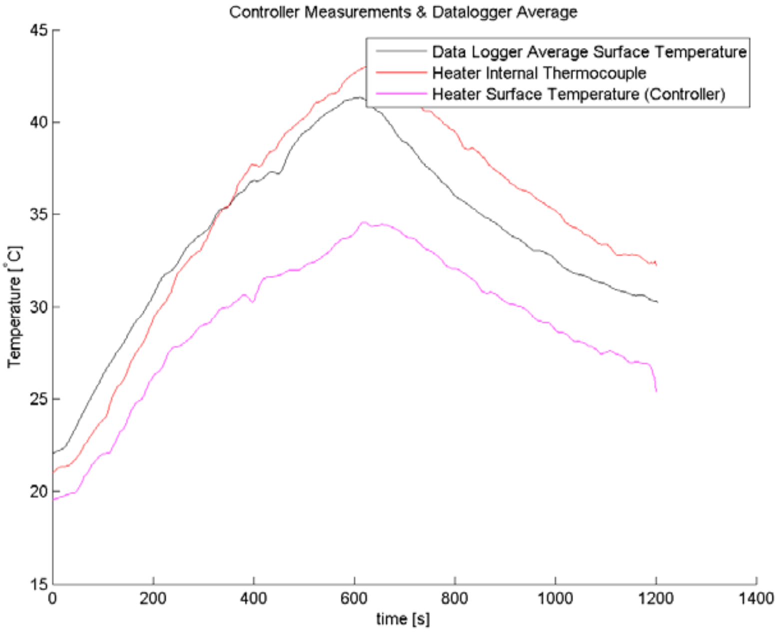

Figure 6.6 Comparison Between Data Logger and Controller Temperatures at Setting 1

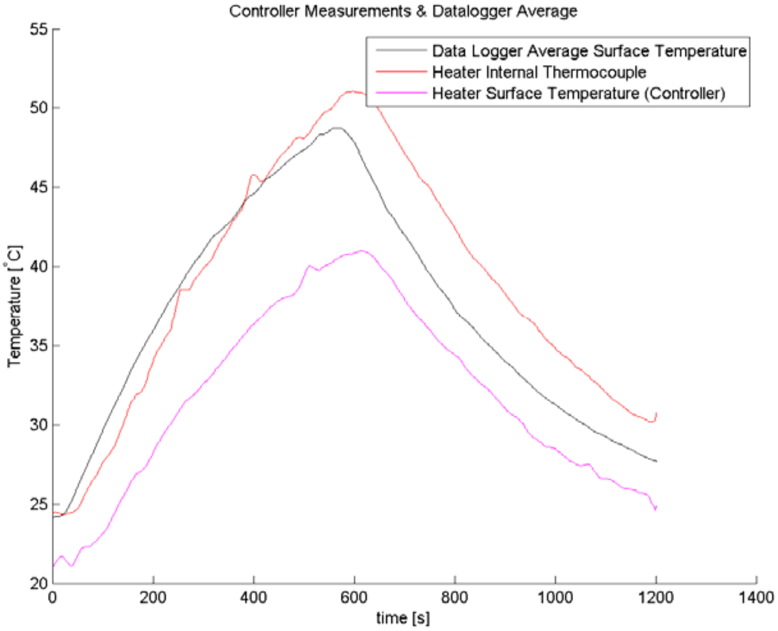

Figure 6.7 Comparison Between Data Logger and Controller Temperatures at Setting 2

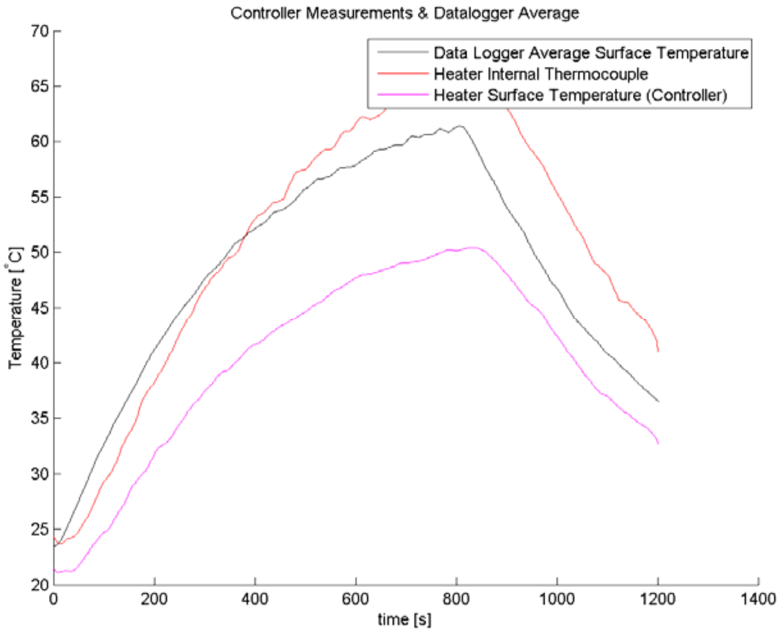

Figure 6.8 Comparison Between Data Logger and Controller Temperatures at Setting 3

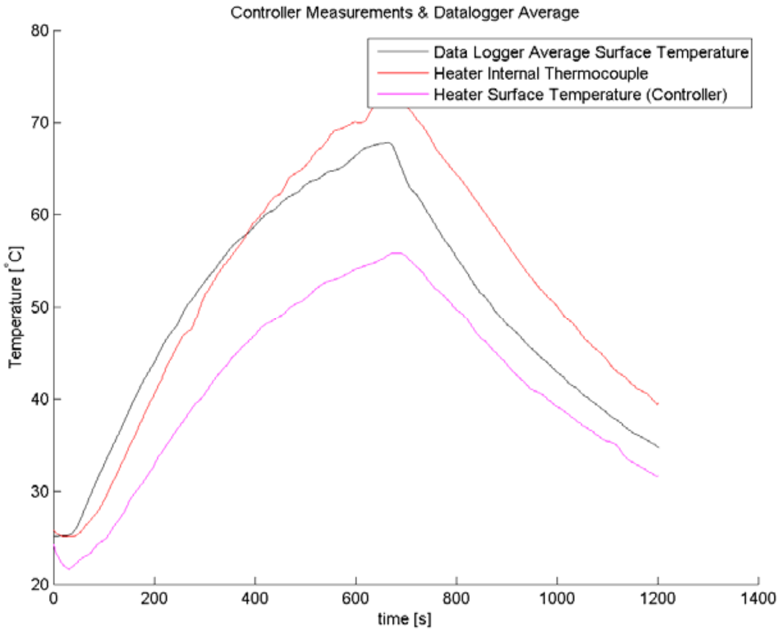

Figure 6.9 Comparison Between Data Logger and Controller Temperatures at Setting 4

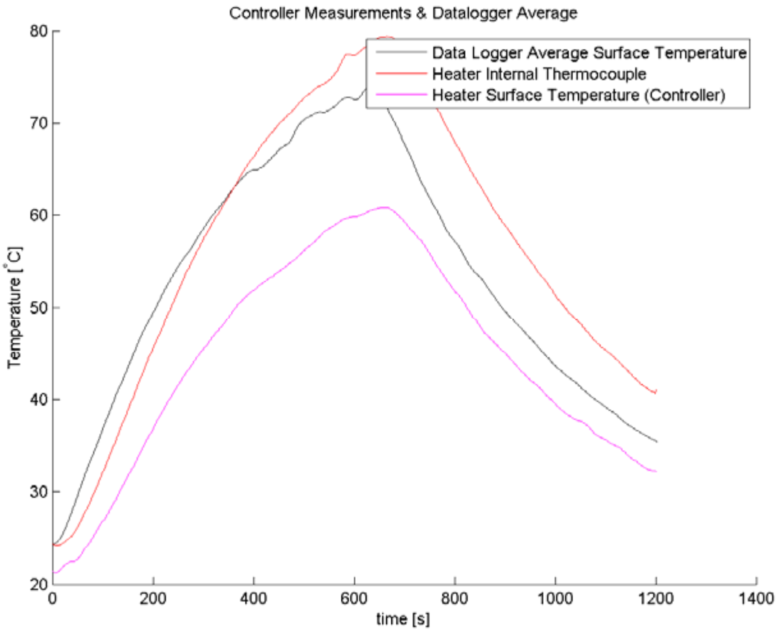

Figure 6.10 Comparison Between Data Logger and Controller Temperatures at Setting 5

In all of the above figures the temperature measured by the heater's internal thermocouple closely resembles the data logger temperature on the rising side and is somewhat higher on the cooling side of the curves. Since cooling is not of any significant importance and this difference can be explained by the surface loosing heat faster than the inside of the heater this difference is neglected.

6.2. Experiment 2

Using the results from the previous experiment adjustments were made to the controller programming so as to compensate for any major irregularities.

As described in section 5.2 the main experiment was done by setting the heater to 100% until the temperature approaches the selected control temperature and then set to 80% and adjusted as required. The control temperatures selected for this experiment was 35, 50, 65 and 80°C. According to the theoretical calculations done 80°C would be out of range for this setup but this temperature was selected due to observations made during the tests done with the other control temperatures. The time required to reach steady state are estimated using the results from the transient analysis.

The figures below show the results of each of the tests along with the theoretical predictions.

The first set of figures show the results at 35°C:

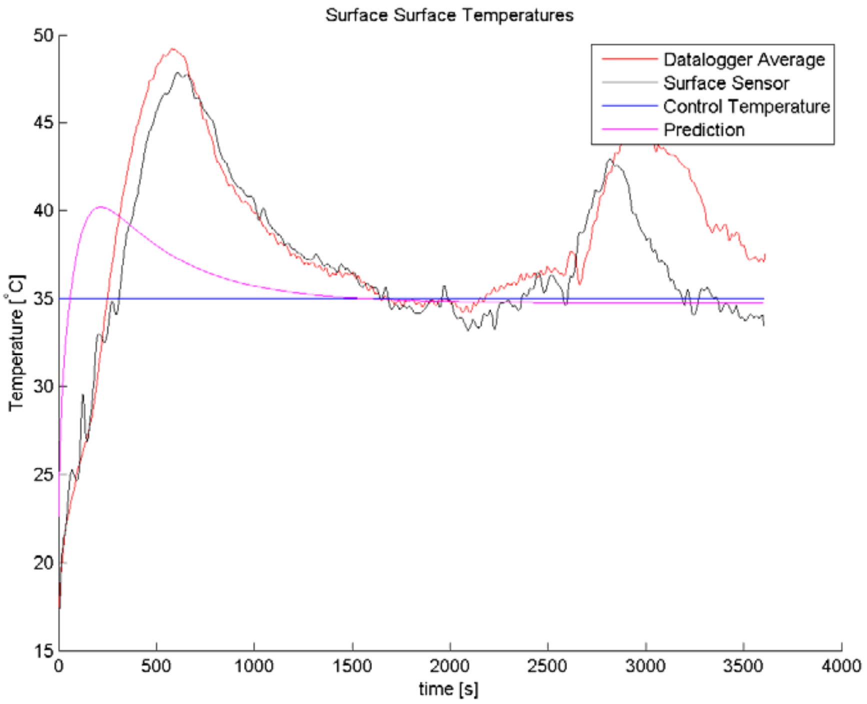

Figure 6.11 Temperature Response for 35°C

From the figure above it can be seen that the system overshoot is significantly larger than the predicted value and that the response is much less stable than predicted. The results from the controller and the data logger strongly correlate suggesting the difference is not mainly due to inaccurate measurement from the controller.

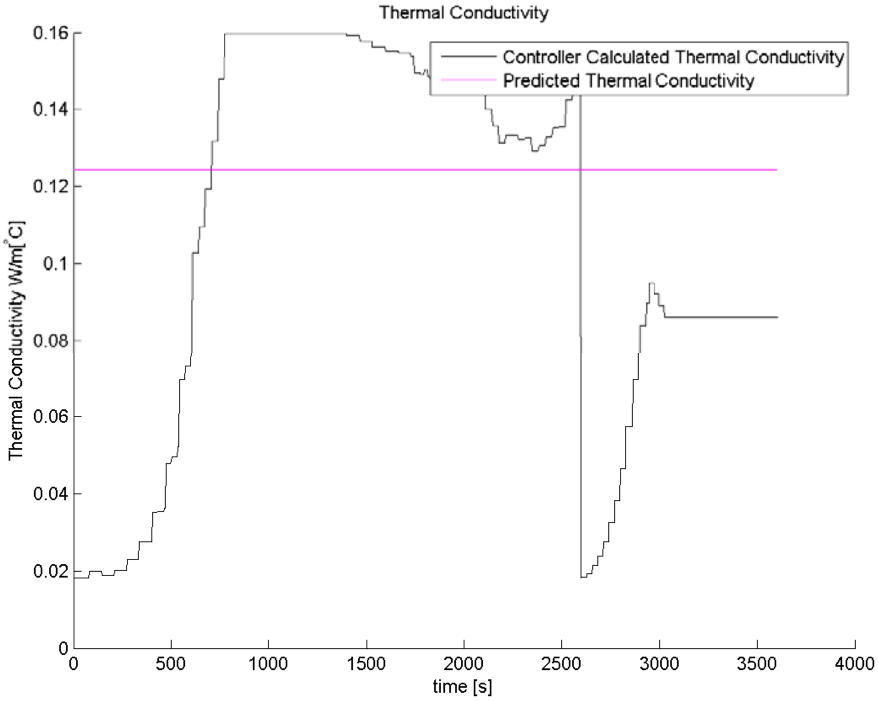

Figure 6.12 System Calculated and Estimated Thermal Conductivities vs Time for 35°C

The thermal conductivity calculated by the controller initially is much lower than the predicted thermal conductivity for the same heat input but approaches the predicted value as the surface temperature increases but overshoots and then starts decreasing when the surface temperature starts decreasing.

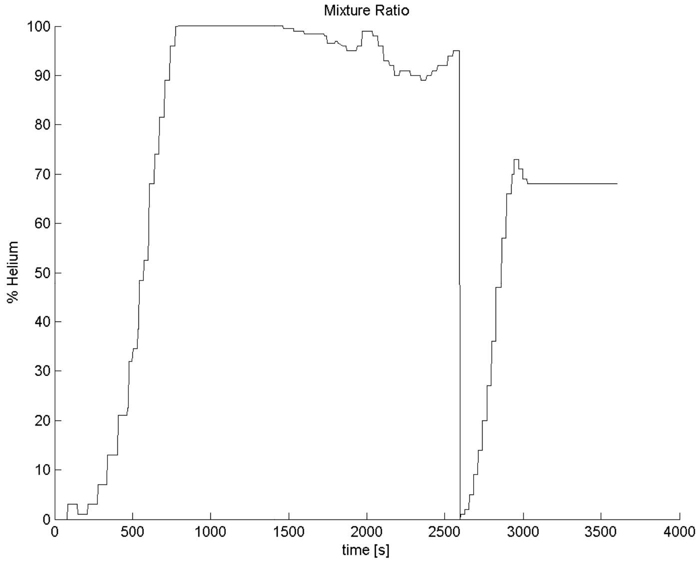

Figure 6.13 Gas Mixture Ratio vs Time for 35°C

The shape of the thermal conductivity and mixture ratio curves are the same due to the ideal gas assumption on which the system is based. The figure above shows the gas mixture ratio over the time period of the test at 35°C

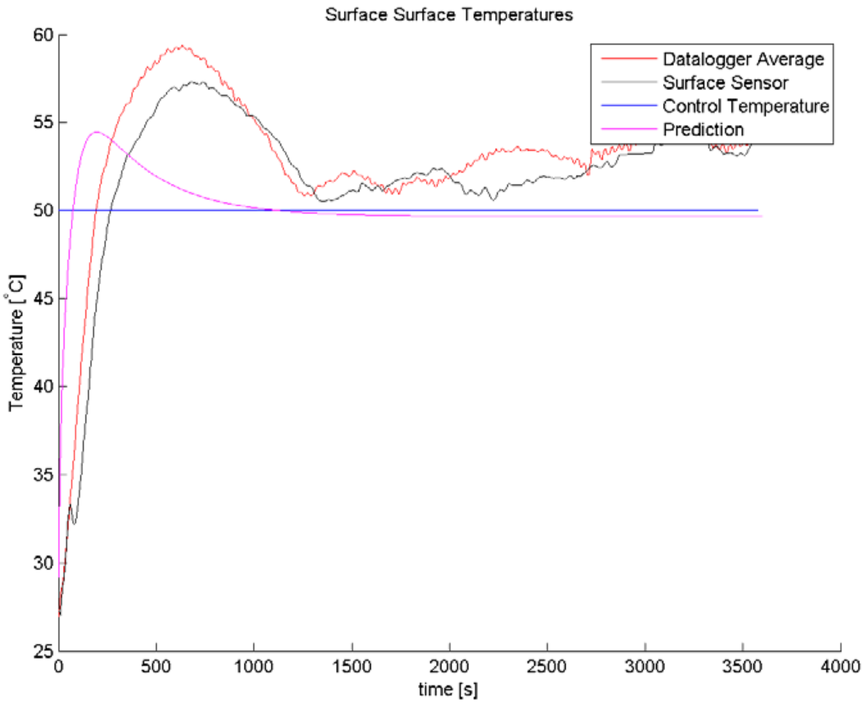

Figure 6.14 Temperature Response for 50°C

The figure above shows the temperature response with respect to time of the system with a control temperature of 50°C. The system responds slower than predicted by the transient model and overshoots about 5°C above what is predicted. Even though the result is more stable than at 35°C it is still quite unstable. It is expected that at this temperature the system will eventually stabilize given a long period of time.

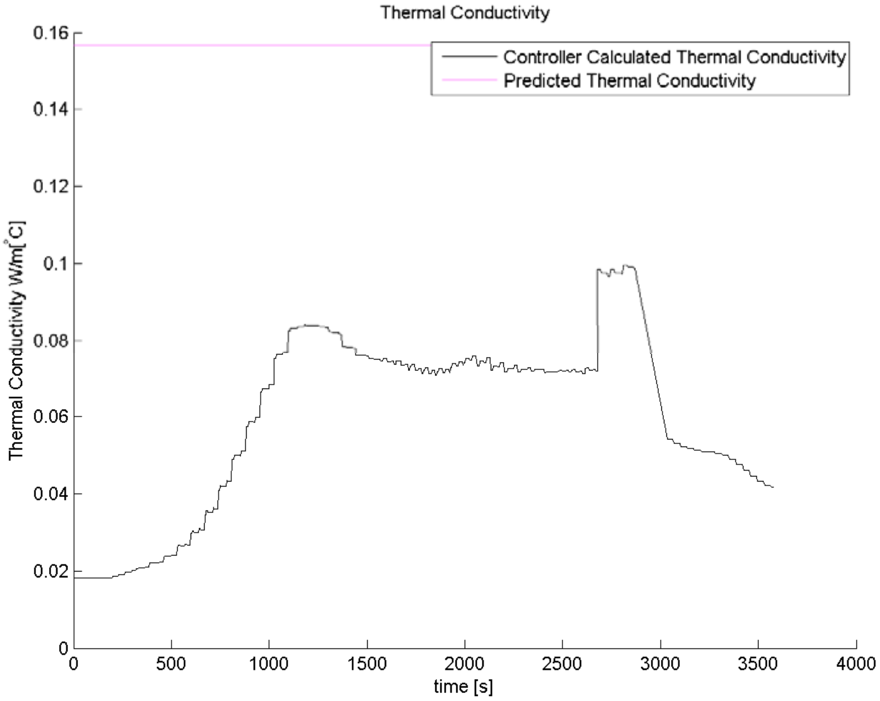

Figure 6.15 System Calculated and Estimated Thermal Conductivities vs Time for 50°C

Again the thermal conductivity is significantly lower than predicted for the same heat input, but less fluctuation is observed than with the 35°C test. The spike at approximately 2700 seconds shows the system adjusting the thermal conductivity for an increased heat input and then decreasing the thermal conductivity for a decrease in heat input.

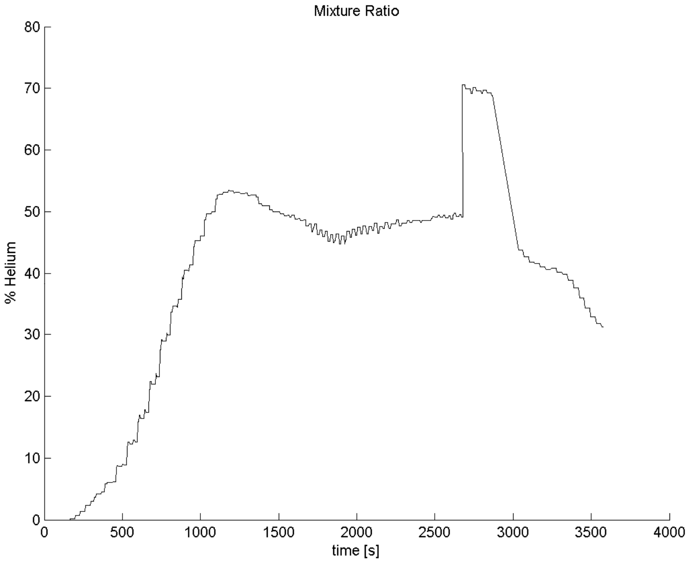

Figure 6.16 Gas Mixture Ratio vs Time for 50°C

The mixture ratio reacts in the same manner as the thermal conductivity since the thermal conductivity is used to determine the ratio.

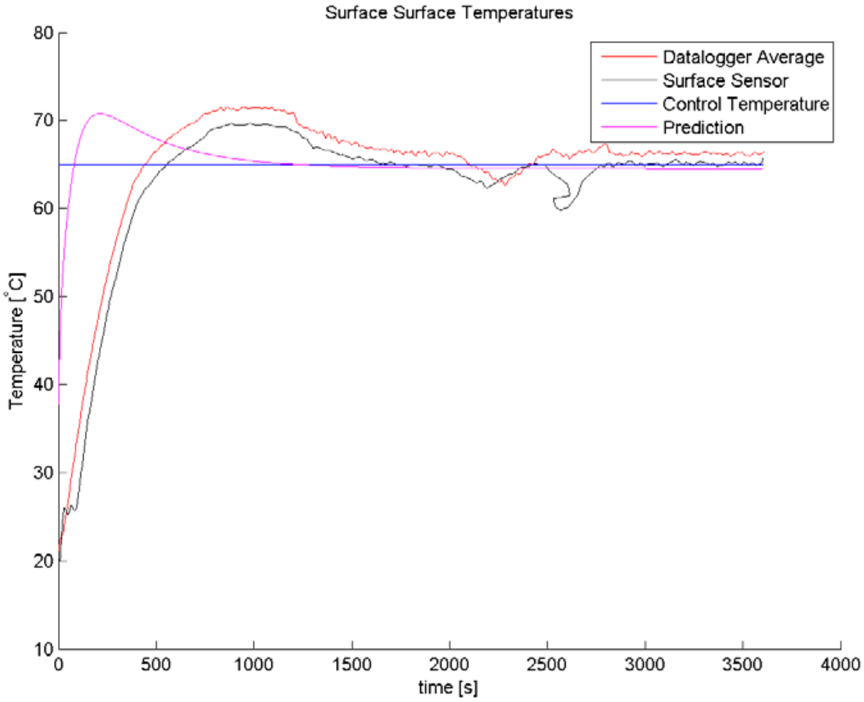

Figure 6.17 Temperature Response for 65°C

The figure above shows the temperature response with respect to time for a control temperature of 65°C as well as the response predicted by the numerical transient model. The system overshoot is approximately the same as the prediction but the temperature decreases from the overshoot slower and the system responds slower than predicted. At this temperature the system stabilizes faster than with the previous two control temperatures.

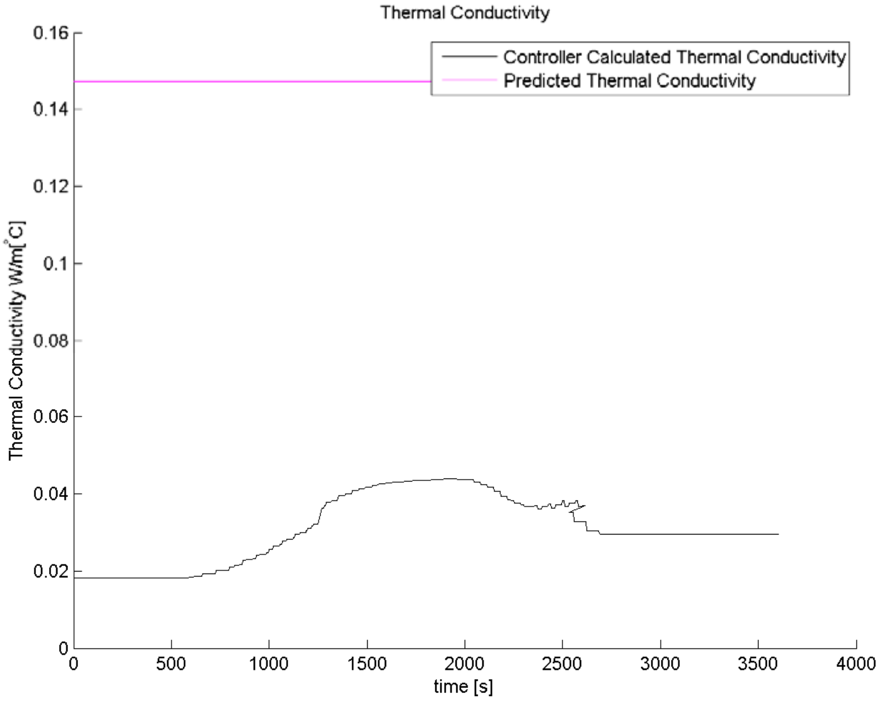

Figure 6.18 System Calculated and Estimated Thermal Conductivities vs Time for 65°C

The thermal conductivity of the gas mixture is significantly lower than what is predicted for the specific heat input. It would appear as if the thermal conductivity is unaffected by a increase in heat input, this is due to the slower response of the system observed at higher temperatures. The thermal conductivity does decrease with a decrease in heater power, and the temperature remains relatively unaffected.

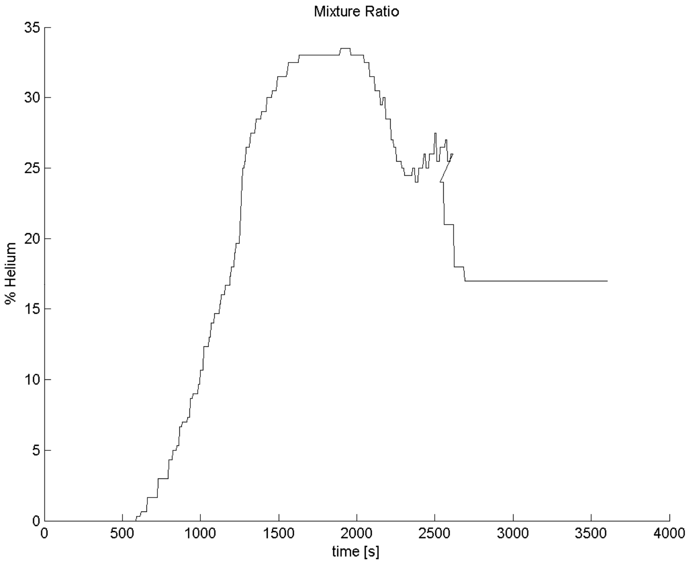

Figure 6.19 Gas Mixture Ratio vs Time for 65°C

Due to the ideal gas assumption and the method by which the mixture ratio is calculated the response is the same as the thermal conductivity. A lower percentage of helium is used at 65°C than with the previous two temperatures.

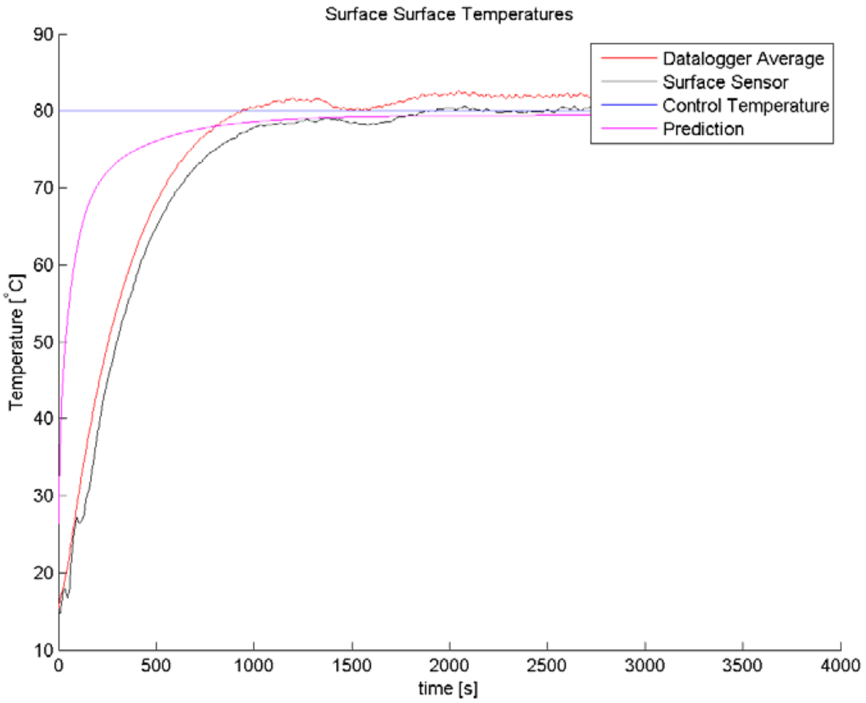

Figure 6.20 Temperature Response for 80°C

At 80°C the system responds almost exactly as predicted only slower. At this temperature the system stabilizes the fastest of all four control temperatures.

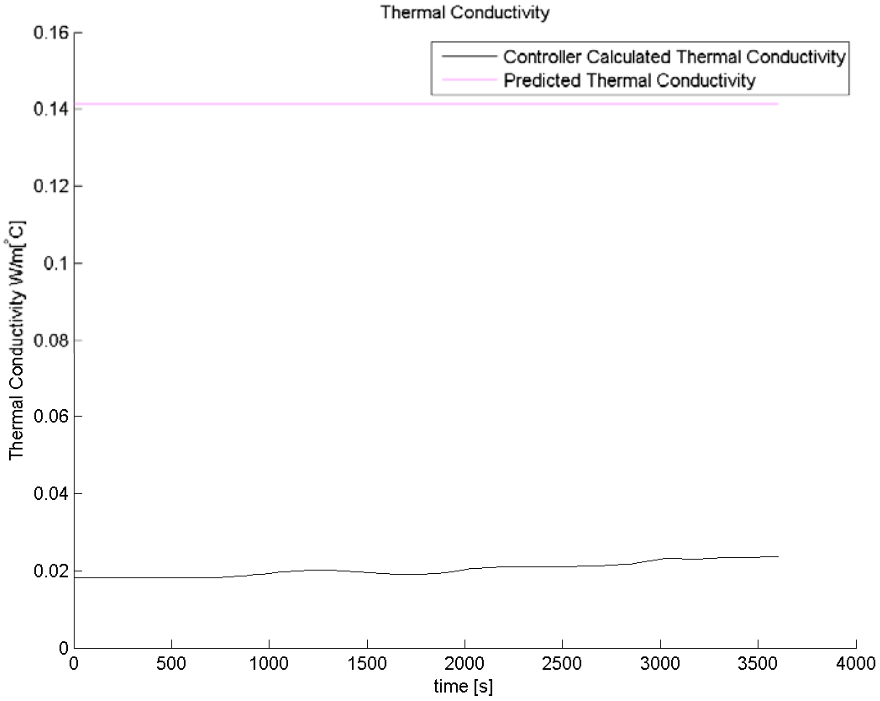

Figure 6.21 System Calculated and Estimated Thermal Conductivities vs Time for 80°C

At this temperature the thermal conductivity almost remains constant and is barely affected by any change in heat input, but this may be due to the system operating close to its upper limit in terms of temperature.

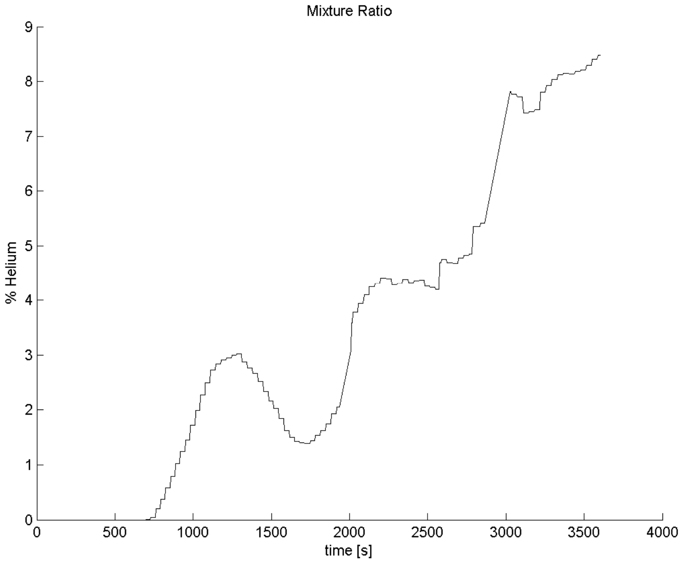

Figure 6.22 Gas Mixture Ratio vs Time for 80°C

The maximum mixture ratio at this temperature is below 10% helium, indicating the system is operating close to its limits.

7. Discussion

Based on the literature consulted and the theoretical analysis done the system is feasible with a relatively wide range of control. The insulator gas selected for the system is argon since it has a low thermal conductivity and is readily available as opposed to neon which is much more expensive and has to be imported. The conductor gas selected for the system is helium since it has a relatively high thermal conductivity and is inert.

The thermodynamic and transport properties of a helium-argon gas mixture have been determined based on the ideal assumption since the operating pressure and temperatures are both relatively low, the properties such as thermal conductivity is assumed to remain constant at a given temperature and the fluid properties are evaluated at the average temperature of the gas annulus. Theoretically the range of the thermal conductivity is 0.0182-0.1596 W/mK.

The thermodynamic analysis was done assuming pure heat conduction through the gas gap, and steady state conditions. Theoretically the controllable heat flux range of the system varies depending on the selected control temperature, the higher the control temperature the higher the allowable heat flux. Since there is very little in literature on internal natural convection in vertical concentric cylinderdrical geometries a CFD analysis was done in order to estimate the effects of convection and the results showed that natural convection will have a very small influence.

The numerical transient solution of the pure conduction problem suggests that the system will take a significant amount of time to reach steady state conditions, but the time required to reach steady state reduces as the helium content of the mixture increases. The transient model suggests that once steady state conditions have been reached the system is unaffected by a change in the heat flux if the thermal conductivity and thus the gas mixture is adjusted accordingly. The transient model did not take the gas exchange process into account.

The experiments conducted on the heating element showed that the temperature distribution on the heater surface is not uniform with the top section of the heater being significantly colder than the rest of the heater. The temperatures measured by the control system correlate very well with the average heater surface temperature and the heater internal thermocouple measurements were close to the average measured by the data logger with a relatively constant difference when the heater is heating up and a larger difference when it is cooling down which is due to the surface loosing heat faster than the interior since the outer surface looses heat by convection and radiation as well.

At all of the selected control temperatures the system performance correlates fairly well with the theoretical predictions with regard to temperature, in all of the tests the surface temperature rises slower than the theoretical prediction. This is due to the fact the transient model considers ideal conditions such as constant and uniform heat flux on the interior boundary, which was not the case as shown by the results of the first test. From the results it is observed that the system is much more stable at higher temperatures than the lower temperatures which is due to the fact that the system can not react fast enough for the rise in temperature. It is expected that at lower temperatures the temperature will eventually stabilise. In all of the main tests the system was run for one hour, during which time the higher temperatures did stabilise but the lower temperatures still oscillated. A 2 hour test was conducted using 50°C during which time the temperature did stabilize significantly. Unfortunately due to the strain the regular gas exchanges placed on the electronic components longer tests were not possible.

The thermal conductivities at which the temperatures stabilized were all significantly lower than predicted by the theoretical calculations which are an indication that natural convection did have a larger effect on the heat transfer than expected. This means that the assumption of heat transfer occurring only due to conduction is invalid. The incoming gas during a gas exchange is at a lower temperature than the internal capsule temperature which likely affected the heat transfer and the momentum from the incoming gasses most likely aided the convection heat transfer.

At the lower temperatures the system is very sensitive to changes in the heat input and takes a significant amount of time to recover from the change, at higher temperatures the system is much less sensitive to changes in the heat flux.

Upon further consideration the mixing process was changed from the original concept of using a volume based mixing process to using a pressure based mixing process since the pressure based process would be more accurate. The ideal gas assumption could not be fully validated by observations made during the tests and a gas analysis could not be done on the mixtures created by the system due to circumstances beyond the control of the student and in order to conduct an analysis of the concentrations of each gas in a mixture requires very specialised equipment. Standard gas chromatography would not have yielded useful results since helium is used as a carrier gas in most GC machines.

Some inaccuracies are expected since the controller is unable to compute complex equations or decimal numbers accurately and as a result some of the values such as natural logerithms had to be calculated beforehand and added into the programming as constants.

8. Project Costing

Even though this project did not have a fixed budget to which the student had to comply it is still important to keep track of costs for future reference or reproduction. The suppliers of the components are also noted in case that a component needs to be replaced. The table below summarises the costs of the project as well as the supplier of the components.

Table 8.1 Project Cost Summary

Item Nr	Part	Description	Category	Qty	Cost EA (Excl VAT)	Total	Supplier	Paid By	Notes
1	Helium	Helium5 Gas	Gas	1	R 1200.00	R 1200.00	Afrox	UP	
2	Argon	Argon5 Gas	Gas	1	R 329.28	R 329.28	Afrox	UP	
3	Regulator	Afrox Saffire Flow Regulator	Gas	2	R 895.84	R 1791.68	Afrox	UP	
4	Regulator	Pressure Reduction Valve	Gas	2	R 620.00	R 1240.00	DLM	Student	Less 15%
5	Gauge	Dry Gas Pressure Gauge	Gas	3	R 130.00	R 390.00	DLM	Student	Less 15%
6	Heater	1500W/m2 Cartridge heater	Capsule	1	R 582.00	R 582.00	PowerTherm CC	Student	
7	Capsule	Capsule Bottom Lid	Capsule	1	R 9.97	R 9.97	Lazerwise	Student	
8	Capsule	Capsule Top Flange	Capsule	1	R 36.73	R 36.73	Lazerwise	Student	
9	Capsule	Capsule Tube 76.2x2mm S/S	Capsule	0.2	R 0.00	R 0.00	UP	-	
10	Capsule	Capsule Lid	Capsule	1	R 94.47	R 94.47	Lazerwise	Student	
11	Screws	M5 S/S Cap Screw	Capsule	15	R 1.49	R 22.37	Acorn Fasteners	Student	
12	Nuts	M5 S/S Nut	Capsule	15	R 0.26	R 3.95	Acorn Fasteners	Student	
13	Screws	M3 S/S Cap Screw	Capsule	10	R 0.53	R 5.26	Acorn Fasteners	Student	
14	Screws	M3 S/S Nut	Capsule	10	R 0.75	R 7.46	Acorn Fasteners	Student	
15	Mounting	Pressure Reduction Valve Plate	Support	2	R 20.11	R 40.22	Lazerwise	Student	
16	Mounting	Square Tubing 25x25x1.6	Support	9	R 52.77	R 474.93	Chamberlain	Student	
17	Valve	2/3 230V AC Solenoid Valve	Plumbing	3	R 0.00	R 0.00	Logica Micro Systems	-	Borrowed (Approx R750 EA)
18	Pipe	8mm Air Hose	Plumbing	10	R 17.54	R 175.40	Builders Warehouse	Student	
19	Fitting	Hose Tail 1/4" Male	Plumbing	16	R 17.54	R 280.64	Builders Warehouse	Student	
20	Fitting	3/8-3/8 Pipe Adaptor	Plumbing	2	R 23.32	R 46.64	Builders Warehouse	Student	
21	Fitting	Hose Clamp	Plumbing	14	R 0.39	R 5.46	Builders Warehouse	Student	
22	Fitting	Hose Tail 3/8" Male	Plumbing	2	R 26.32	R 52.63	Builders Warehouse	Student	
23	Fitting	Elbow 1/4" M/F	Plumbing	2	R 43.86	R 87.72	Builders Warehouse	Student	
24	Tape	PTFE Tape	Plumbing	4	R 2.00	R 8.00	Builders Warehouse	Student	

Item Nr	Part	Description	Category	Qty	Cost EA (Excl VAT)	Total	Supplier	Paid By	Notes
25	Bucket	Bucket 25lt	Temp Bath	1	R 35.04	R 35.04	Plastic Land	Student	
26	Bucket	Bucket 10 lt	Temp Bath	1	R 24.52	R 24.52	Plastic Land	Student	
27	Sealing	Silicone	Temp Bath	1	R 16.42	R 16.42	Builders Warehouse	Student	
28	Insulation	Expanding Foam	Temp Bath	2	R 103.89	R 207.78	Builders Warehouse	Student	
29	Button	Push Button	Electronics	2	R 24.00	R 48.00	Communica	Student	
30	PCB	Main PCB Manufacturing	Electronics	1	R 570.18	R 570.18	ElectronicsFG	Student	
31	Enclosure	Enclosure 150x90x52	Electronics	1	R 80.61	R 80.61	ElectronicsFG	Student	
32	Enclosure	enclosure 195x110x90	Electronics	1	R 98.86	R 98.86	ElectronicsFG	Student	
33	Connector	Kettle Plug Socket	Electronics	5	R 13.07	R 65.35	ElectronicsFG	Student	
34	Connector	Chassis kettle socket fused	Electronics	1	R 40.44	R 40.44	ElectronicsFG	Student	
35	Connector	Kettle Plug	Electronics	5	R 13.95	R 69.75	ElectronicsFG	Student	
36	Wire	Cabtyre 1.5mm 3 Core	Electronics	10	R 12.28	R 122.81	Builders Warehouse	Student	
37	Wire	8 Core Signal Cable	Electronics	2	R 8.42	R 16.84	ElectronicsFG	Student	
38	Cap	Polyester Capacitor 100nF	Electronics	6	R 1.93	R 11.57	ElectronicsFG	Student	
39	Cap	Polyester Capacitor 47nF	Electronics	6	R 1.93	R 11.57	ElectronicsFG	Student	
40	LED	LED Red	Electronics	6	R 0.79	R 4.74	ElectronicsFG	Student	
41	LED	LED Holder	Electronics	6	R 3.68	R 22.11	ElectronicsFG	Student	
42	Wire	2 Core 1.5mm Cabtyre	Electronics	5	R 7.49	R 37.45	ElectronicsFG	Student	
43	Connector	2 Pin Panel Mount Connector	Electronics	1	R 12.72	R 12.72	ElectronicsFG	Student	
44	Connector	DC Plug 2.1mm	Electronics	1	R 9.30	R 9.30	ElectronicsFG	Student	
45	PSU	12V 25W Switching Power Supply	Electronics	1	R 198.42	R 198.42	ElectronicsFG	Student	
46	Switch	6 Position Rotary Switch	Electronics	1	R 7.56	R 7.56	Mantech	Student	
47	Controller	Arduino Uno	Electronics	1	R 395.81	R 395.81	Mantech	Student	
48	Sensor	Pressure Transducer	Electronics	1	R 165.00	R 165.00	Mantech	Student	
49	IC	Optocoupler	Electronics	6	R 2.80	R 16.80	Mantech	Student	
50	IC	BT136	Electronics	6	R 4.14	R 24.84	Mantech	Student	
51	Connector	Connectors	Electronics	20	R 2.25	R 45.00	Mantech	Student	
52	Display	LCD	Electronics	1	R 0.00		-		Borrowed
53	Sensor	LM35	Electronics	1	R 21.70	R 21.70	Mantech	Student	
54		Misc Electronics		1	R 50.00	R 50.00	-	Student	
55		Misc Components		1	R 100.00	R 100.00	-	Student	

Total Excl VAT	**R 9416.00**
VAT	**R 1318.23**
Total Incl	**R 10734.23**

9. Conclusions & Recommendations

Based on the various analyses done the system is feasible, using a helium-argon gas mixture to control the temperature on the surface of a heated sample.

The theoretical results predicted promising performance of the system The transient heat conduction analysis predicts that initially the system will be very slow to reach steady state conditions but remains relatively unaffected by changes in the heat flux and gas mixture, but the model assumes instantantious mixture adjustments, which are not the case in reality. Theoretical investigations and numerical simulations suggested that heat transfer by convection inside the capsule will have a minimal effect on the system performance, but from the results obtained it is clear that additional factors influenced the heat transfer through the gas gap.

The experimental system succeeded in maintaining a constant temperature on the surface of the heater within reasonable limits. The system is not very stable at lower temperatures and deviates considerably from theoretical predictions but is quite stable at higher temperatures and correlates very well with theoretical predictions. At lower temperatures the system is much more sensitive to changes in the heat input than at the higher temperatures. The thermal conductivities at which the system operated and managed to control the temperatures are significantly lower than what was expected from the theoretical analysis which proves the assumption of heat transfer by conduction only is invalid.

The system showed slow response times especially when the initial temperature is close to or below ambient temperatures, but response time improves somewhat when the system temperature is at the control temperature.

Heat transfer by means of internal convection having an effect on the system is not necessarily a problem, since the presence of convection would allow temperature control at much larger heat flux ranges than initially calculated using the pure conduction assumption. It is recommended that further research is done on internal convection in vertical concentric cylindrical geometries if this project is to be developed further. If convection heat transfer is not desired steps should be taken in order to eliminate convection heat transfer such as reducing the size of the capsule but this will have significant effects on the capabilities of the system. Other steps that may be considered is to add baffles to the inside of the capsule or filling the capsule with a fine grain sand of similar substance with a low or known thermal conductivity, though the last mentioned method might not be practical in nuclear irradiation experiments since the sand could contaminate the test sample.

The gas exchange process affected the performance of the system since the incoming gas is at a lower temperature than the mixture being evacuated which increased the time the system required to reach the desired temperature and made it difficult to reach higher temperatures. A gas preheating system will reduce these effects and could increase the performance of the system. A constant flow of gas over the heated sample was not used since this would require a large amount of gas which was not possible due to financial restrictions. Separating gas mixtures into their components was not possible since this would require very specialised equipment and since this was not the main focus of the project not much attention was given to this matter. If a constant flow of gas over the sample can be implemented it would allow significantly higher temperatures due to the added effects of forced convection heat transfer.

The control system used in this project is quite simple and succeeded in proving the feasibility of such a system. This fairly inexpensive control system does have its limitations especially when it comes to large or complex calculations. A more sophisticated or specially designed control system will improve the system performance since more accurate measurements and calculations would be possible.

The ideal gas assumption could not be validated since a analysis of the composition of mixtures produced by the system could not be done since the analysis would require extremely specialised equipment and standard gas chromatography could not be used since helium is used as a carrier gas in most GC machines. Sampling equipment was also required which had to be purchased from overseas.

From the analysis and design it can be seen that the performance of the system can be influenced by many factors such as capsule size, desired control temperature and heat input range. It is suggested that optimisation techniques be implemented in future designs to ensure proper system performance at the desired values.

In conclusion the project succeeded in its main purpose and demonstrated that it is possible to control the surface temperature of a heated sample using a gas gap consisting of a mixture of two gasses. Several opportunities for improvement or further development have been identified which have the potential of resulting in a system which can accurately control the temperature with a wide range of control.

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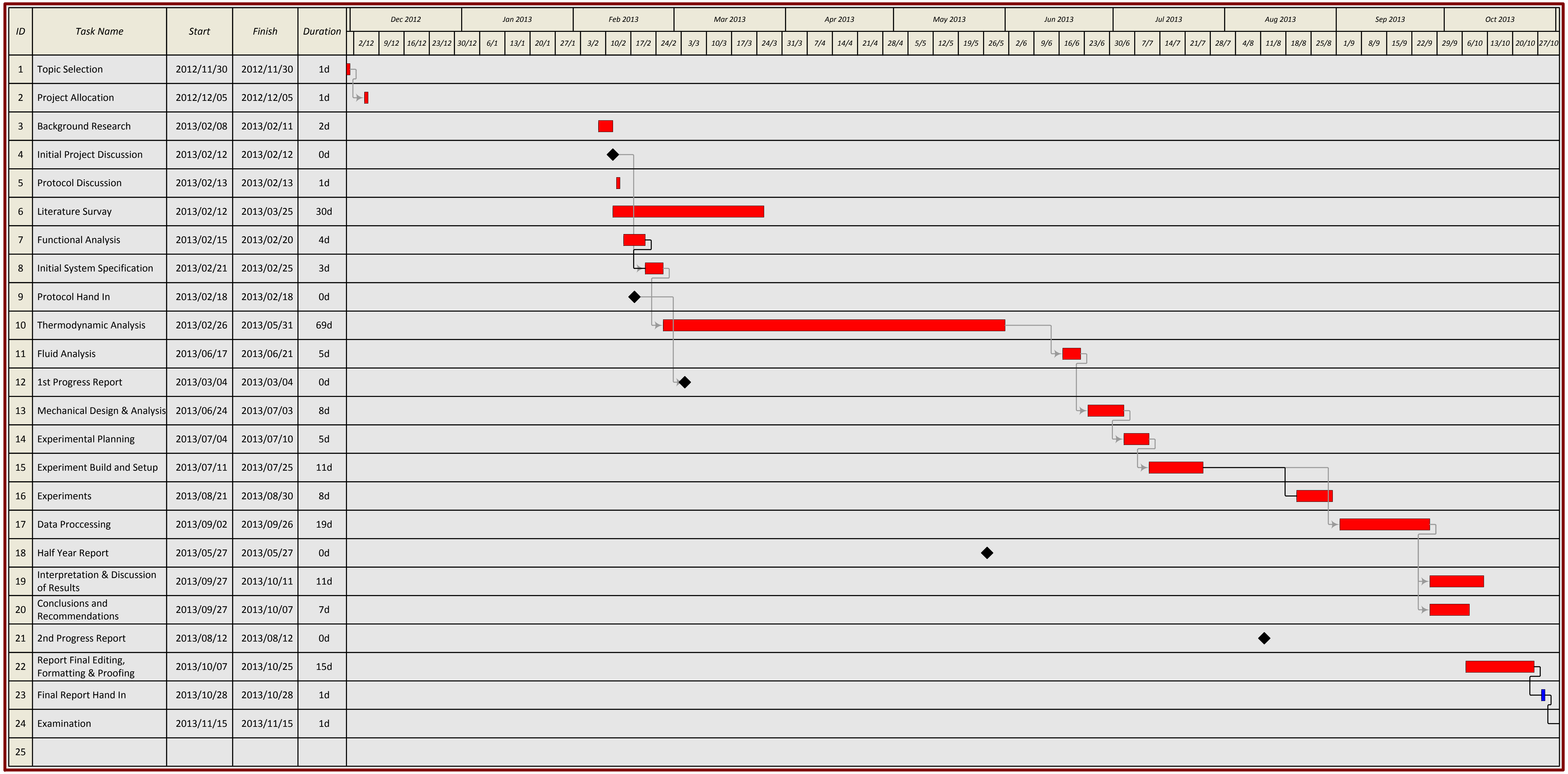
Appendices

Appendix A: Project Gantt Chart



ID	Task Name	Start	Finish	Duration
1	Topic Selection	2012/11/30	2012/11/30	1d
2	Project Allocation	2012/12/05	2012/12/05	1d
3	Background Research	2013/02/08	2013/02/11	2d
4	Initial Project Discussion	2013/02/12	2013/02/12	0d
5	Protocol Discussion	2013/02/13	2013/02/13	1d
6	Literature Survay	2013/02/12	2013/03/25	30d
7	Functional Analysis	2013/02/15	2013/02/20	4d
8	Initial System Specification	2013/02/21	2013/02/25	3d
9	Protocol Hand In	2013/02/18	2013/02/18	0d
10	Thermodynamic Analysis	2013/02/26	2013/05/31	69d
11	Fluid Analysis	2013/06/17	2013/06/21	5d
12	1st Progress Report	2013/03/04	2013/03/04	0d
13	Mechanical Design & Analysis	2013/06/24	2013/07/03	8d
14	Experimental Planning	2013/07/04	2013/07/10	5d
15	Experiment Build and Setup	2013/07/11	2013/07/25	11d
16	Experiments	2013/08/21	2013/08/30	8d
17	Data Proccessing	2013/09/02	2013/09/26	19d
18	Half Year Report	2013/05/27	2013/05/27	0d
19	Interpretation & Discussion of Results	2013/09/27	2013/10/11	11d
20	Conclusions and Recommendations	2013/09/27	2013/10/07	7d
21	2nd Progress Report	2013/08/12	2013/08/12	0d
22	Report Final Editing, Formatting & Proofing	2013/10/07	2013/10/25	15d
23	Final Report Hand In	2013/10/28	2013/10/28	1d
24	Examination	2013/11/15	2013/11/15	1d
25				

Appendix B: Project Meeting Log Cards

Appendix B

REPORT CARD FOR THESIS MSC 412 and 422 20013

Name J. A. KRUGER **Reg. no.** 29321299

Topic Temperature control using a gas gap

Supervisor Prof J. F. M. Slabber

Commencement date:

Date	Signature (Supervisor)	Signature (Student)	Comments
12 Feb 2013			Initial discussion
13 Feb 2013			Protocol
26 Feb 2013			Progress, Prelim Calculations
26 Maart '13			Calculations.
09 Apr. '13			Calculations & Progress update
15 Apr. '13			Control system discussion
15 Mei 2013			Half year report, progress discussion
22 Jun 2013			Progress update.
05 Aug 2013			

Registration for Thesis MSC 412 and 422 20.13

Name JOHAN KRUGER **Reg. no.** 29321299

Address

Topic Temperature control by means of a gas gap

Supervisor **Signature**

Appendix B

REPORT CARD FOR THESIS MSC 412 and 422 20.13.........

Name J.A. KRUGER .... Reg. no. 29321299

Topic Temperature Control by means of a gas gap

Supervisor Prof J.F.M. Slabber ....

Commencement date:

....

Date	Signature (Supervisor)	Signature (Student)	Comments
02-09-2013			Discussion of Results.

Registration for Thesis MSC 412 and 422 20.................

Name ....**Reg. no.**..........................

Address ....

Topic ....

Supervisor .... **Signature**..............................

Appendix C: Project Progress Reports

1st Progress Report

Temperature control by means of a gas gap

J.A. Kruger

29321299

MSC412/422 Research Project

March 2013

Supervisor: Prof J.F.M. Slabber

Signed: ________________ ________________

J.A. Kruger Prof J. Slabber

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Engineering, Built Environment and Information Technology

Summary

The objective of this project is to investigate the possibility of using a Helium and Neon gas mixture to control the temperature on the surface of a heated specimen. The investigation consists of two main components, a theoretical analysis to determine the feasibility of such a system as well as to estimate the temperature range and effectiveness of the system. The second component is the design and building of an experiment in order to practically test such a system and to verify and validate the theoretical results. According to research and calculations so far the system appears viable and a fairly wide range of temperature control is predicted. The project is currently ahead of schedule and every effort is being made to maintain this lead.

Contents

List of Tables

List of Figures

1. Introduction

The temperature of an electrically heated sample is to be controlled by varying the thermal conductivity of the gas mixture around the sample. The gas gap around the sample consists of a mix of two noble gasses namely Helium and Neon. The thermal conductivity of the gas mixture will depend on the ratio to which the two gasses are mixed.

This type of system is used in nuclear test reactor irradiation experiments in what is commonly referred to as lead experiments. This type of experiment is an actively controlled and monitored experiment where there is instrumentation such as thermocouples installed into the test capsule and the test specimen is surrounded with a blend of Helium and Neon or Helium and Argon. The ratio to which the gases are mixed determines the thermal conductivity which can be varied in order to maintain a constant temperature on the test specimen,

The objective of the project is design and test a temperature control system to control the temperature of an electrically heated sample by varying the thermal conductivity if the gas surrounding the sample.

The project includes a theoretical analysis of the temperature control system in order to determine the feasibility and estimate the performance of a gas temperature control system. As part of the experiment an experiment is to be designed and built in order to verify and validate the theoretical results.

2. Literature Study

The purpose of the literature study is to give the student a better understanding of the project topic and to gain insight into topics not covered during the course of the student's studies and to gain insight into how the principles of the topics are applied in practice. The literature study that will be included in the final project report serves two purposes, firstly to show the project supervisor the literature consulted during research and to give non technical readers the required information so that they can understand the project.

Several relevant topics have been identified for information regarding the project. These topics are being researched, sorted and filtered in order to identify the most important information relevant to the project. As the project progresses more topics might be identified and researched so that thorough research has been done and included in the project by the project completion.

3. Theoretical Analysis

The initial specifications of the system have been determined by according to the requirements, part availability and thermodynamic and other calculations. These specifications are listed in Table 3.1.

Table 3.1Initial System Specifications

Specification	
Capsule Material	Nylon6
Capsule Inner Diameter	100 mm
Capsule Outer Diameter	120 mm
Capsule Wall Thickness	10 mm
Temperature Range	$\pm 60 - 170$°C (for $500 W/m^2$ heat input)
Thermal Conductivity Range	$0.0461 - 0.1418\ W/m^2$
Sample Heat Input Range	$\pm 250 - 700\ W/m$^2 @ 80°C

These specifications are subject to change depending on the availability of components, further calculations and requests from project supervisor.

A functional analysis has been done based on the currently known information and specifications known on the system, the functional analysis will be updated as needed if functions are added or removed and as more information regarding functions and specifications become available.

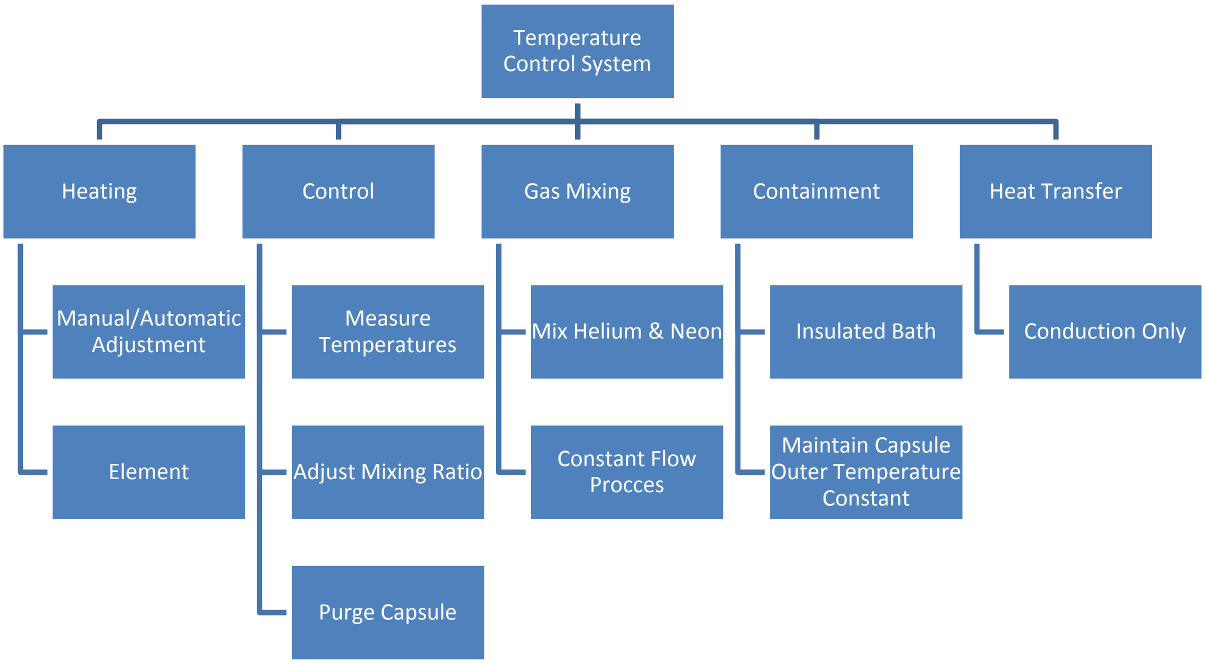


Figure 3.1 Functional Analysis based on current information

Based on the current planned functioning of the system, that the capsule will be filled with the appropriate gas blend and emptied and refilled when the specimen heat changes. It has been assumed that only conduction heat transfer will be present, other heat transfer mechanisms of heat transfer will be considered to be negligible.

Using the general heat conduction equation and the system boundary conditions an equation has been derived for the system that can be manipulated to determine the required unknown (heat flux or thermal conductivity).

A fluid analysis is currently in progress in order to determine the flow rates of the gases and required gas ejection and fill times so that the gas exchange process can happen as fast as possible and with as little as possible transient effects. This information will be used to determine the time each valve needs to remain open in order to achieve the desired gas blend, as well as in the design of the control system.

The mechanical strength analysis of the experimental capsule and the selected material is also underway to determine if the capsule will be able to handle the internal pressures. Research is still being done into methods of how the capsule can be sealed so that no gas leaks out during operation.

4. Experimental

The experimental setup is currently in the planning phase, the test capsule is to be immersed into a simple constant temperature bath to maintain a constant temperature on the outer surface of the capsule. The temperature bath will consist of two plastic containers with insulation in between.

The parts required for the experiment is being researched to check if they will meet the requirements of the project. Quotes for the manufacturing of the components have been requested from manufacturing companies. The parts will only be purchased when all of the specifications of the system are known and it has been determined that each component will be able to perform the required functions.

5. Project Schedule

The project is currently about one week ahead of schedule, it will be attempted to maintain this lead on the schedule as long as possible. The extra time will be used to verify and check the calculations.

Where possible it will be attempted to complete tasks earlier than the deadline so as to allow for unforeseen events.

6. Conclusions

The project is progressing well according to the project schedule and a there is a possibility of early completion given that no major problems or changes occur in the project.

The literature study has identified the relevant topics for discussion in order to give readers a better understanding of the principles of the system. The literature study is expected to be completed within the allowed time in the project schedule.

The theoretical analysis thus far predicts promising results for the performance of the system, the remaining components of the theoretical analysis is to determine the strength of the capsule so that it won't fail under pressure and to determine the fluid properties of the system so that the control system design can commence.

According to research and calculations done thus far the project appears viable and calculations predict a fairly wide range of temperature control for a capsule of the selected size. The parts required for experimental testing of the system are being designed or sourced and construction is expected to begin within the month.

2nd Progress Report

Temperature control by means of a gas gap

J.A. Kruger

29321299

MSC412/422 Research Project

Augustus 2013

Supervisor: Prof J.F.M. Slabber

Signed: ________________ ________________

J.A. Kruger Prof J. Slabber

UNIVERSITEIT VAN PRETORIA
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Faculty of Engineering, Built Environment and
Information Technology

Summary

The objective of this project is to investigate the possibility of using a Helium and Argon gas mixture to control the temperature on the surface of a heated specimen. The application of this type of system is in nuclear test reactor irradiation experiments where the temperature of the test specimen is to be controlled. The investigation consists of two main components, a theoretical analysis to determine the feasibility of such a system as well as to estimate the temperature range and effectiveness of the system. The second component is the design and building of an experiment in order to practically test such a system and to verify and validate the theoretical results. This report describes the progress of the project thus far with regards to the schedule and any problems faced during the project. The experiments have been designed and all of the components have been acquired. At this point all of the mechanical components are completed and by the time this report is submitted all of the electronic systems will have been built and assembled. The project is currently behind schedule due to problems with the electronics, but this point time is not a large concern since there is extra time availible in the schedule.

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1. Introduction

The temperature of an electrically heated sample is to be controlled by varying the thermal conductivity of the gas mixture around the sample. The gas gap around the sample consists of a mix of two noble gasses namely Helium and Argon. The thermal conductivity of the gas mixture will depend on the ratio to which the two gasses are mixed.

This type of system is used in nuclear test reactor irradiation experiments in what is commonly referred to as lead experiments. This type of experiment is an actively controlled and monitored experiment where there is instrumentation such as thermocouples installed into the test capsule and the test specimen is surrounded with a blend of Helium and Neon or Helium and Argon. The ratio to which the gases are mixed determines the thermal conductivity which can be varied in order to maintain a constant temperature on the test specimen,

The objective of the project is design and test a temperature control system to control the temperature of an electrically heated sample by varying the thermal conductivity if the gas surrounding the sample.

The purpose of this report is to describe the progress of the project to date and to describe any changes or deviations from the original project protocol and the reasons for any such changes.

2. Theoretical Analysis & Design

The thermodynamic analysis has been completed with the half year report along with the structural design and analysis. A basic fluid analysis has been done in order to estimate the exit velocities and the time required to fill and purge the gas capsule.

The transient model of the system still needs to be improved in order to better simulate and estimate the system's performance.

All of the electronic circuits that are required for the control system have been designed along with the basic parameters of the control system.

3. System Construction

The final system specifications as described in the half year report are shown in Table 3.1 below:

Table 3.1 System Specifications

Specification	
Capsule Material	Stainless Steel
Capsule Inner Diameter	72mm
Capsule Outer Diameter	76 mm
Capsule Wall Thickness	2 mm
Temperature Range	$\pm 30 - 270$°C (for $500 W/m^2$ heat input)
Thermal Conductivity Range	$0.0461 - 0.1418\ W/m^2$
Sample Heat Input Range	$\pm 110 - 960\ W/m$^2 @ 60°C

The specifications for the temperature range and the heat input range are estimated from theoretical calculations, these specifications will be confirmed by testing.

All of the required hardware components have been acquired and all of the subcomponents have been assembled. The system consists of the gas capsule that holds the gases, the element and measurement devices. The capsule has two gas inlets at the top along with an attachment point for a pressure gauge, a cable gland for the measurement devices and an outlet at the bottom.

Figure 3.1 Test Capsule With Heater Installed

The capsule and the valves are mounted on a frame in order to keep the components in place during testing and keep the capsule in place in the ice bath.

Figure 3.2 Main Frame With Valves Installed

The system also includes an electronic distribution box which connects the valves to the microcontroller that is used to control the system. Since the valves operate on 240V AC and the controller only outputs a 5V signal an electronic circuit was designed in order to connect the two.

Some problems have been encountered with the electronics such as resistors failing out due to high current spikes but a suitable solution to this problem has been found and is being implemented.

The programming of the microcontroller is still in progress, the controller has several functions, the first of which is to measure the temperature on the heating element and from the temperature readings determine the appropriate gas mixture. Safety features will also be included in the programming to ensure that temperatures and pressures do not exceed the capabilities of the system. The controller will also have manual buttons to add gas to the system and to immediately stop the system.

4. Experimental

The experiments that will be done have been decided on and the final experimental procedures will be completed once the system has been completed and preliminary tests has been completed.

Three experiments will be done, the first is a fairly simple experiment which will be done in order to determine the uniformity of the heat provided by the heater and the time required for the heater to reach certain temperatures.

The second experiment is to test the accuracy of the gas mixing system. Several problems arised in the planning of this experiment, first of which is that in order to analyse the gas mixture, a gas mass spectrometer had to be located, the student has made arrangements with the department of chemical engineering to analyse the mixture. The second problem is that the gas mass spectrometer uses helium as its carrier gas for the sample that is being analysed and since the gas mixture consists of helium and argon this would present problems. A suggestion was made to use single ion monitoring in order to determine the amount of argon in a mixture, and from there determine the ratio.

The experiments are planned to commence in the next few weeks.

5. Project Schedule

The project is currently about two weeks behind of schedule, this is due to the problems with the electronics of the system. All attempts will be made to get the project back on schedule. When the project schedule was created additional time was allocated to allow for unforeseen events and problems.

A copy of the project schedule is attached to this report in Appendix A, the items indicated in red are complete, the items in yellow are in progress and the items in blue has not been started.

6. Conclusions

The project is progressing well even though the project is behind schedule but at this time it is not a major cause for concern since extra time to allow for unforeseen events was allocated in the original project schedule.

With the theoretical analysis and design complete all of the hardware components were acquired and construction of the system has commenced and is progressing well. Problems did arise with some of the electronic circuits but solutions are being implemented.

Most of the experimental planning and arrangements are complete and the remaining work will be completed once the system construction is complete.

The project is estimated to be completed early September and at this stage no large concerns have arisen thus expectations are high for the project.

Appendix D: Properties of a Helium Argon Mixture at 310 K and 200 kPa

%He	$p_{He}\ [kPa]$	$n_{he}\ [mole]$	$m_{He}\ [kg]$	$p_{Ar}\ [kPa]$	$n_{Ar}\ [mole]$	$m_{Ar}[kg]$	$n_{tot}\ [mole]$	y_{He}	y_{Ar}	$\rho_{mix}\ [\frac{kg}{m^3}]$	$k_{mix}[\frac{W}{mK}]$	$\mu \times 10^{-7}[\frac{kg}{ms}]$	$C_p\ [\frac{J}{kgK}]$	Pr	$\alpha\ [\frac{m^2}{s}]$
0.00	0	0.00E+00	0.00E+00	150	4.82E-05	1.93E-03	4.82E-05	0.000	1.000	2.30	0.01820	220.89	520.00	0.6311	1.52E-05
5.00	7.5	2.41E-06	9.64E-06	142.5	4.58E-05	1.83E-03	4.82E-05	0.005	0.995	2.20	0.02138	221.92	544.48	0.5651	1.79E-05
10.00	15	4.82E-06	1.93E-05	135	4.34E-05	1.74E-03	4.82E-05	0.011	0.989	2.10	0.02476	222.96	571.38	0.5146	2.07E-05
15.00	22.5	7.23E-06	2.89E-05	127.5	4.10E-05	1.64E-03	4.82E-05	0.017	0.983	1.99	0.02834	224.00	601.07	0.4751	2.37E-05
20.00	30	9.64E-06	3.86E-05	120	3.86E-05	1.54E-03	4.82E-05	0.024	0.976	1.89	0.03215	225.04	634.03	0.4438	2.69E-05
25.00	37.5	1.21E-05	4.82E-05	112.5	3.62E-05	1.45E-03	4.82E-05	0.032	0.968	1.79	0.03622	226.07	670.81	0.4187	3.02E-05
30.00	45	1.45E-05	5.79E-05	105	3.38E-05	1.35E-03	4.82E-05	0.041	0.959	1.68	0.04056	227.08	712.13	0.3986	3.39E-05
35.00	52.5	1.69E-05	6.75E-05	97.5	3.13E-05	1.25E-03	4.82E-05	0.051	0.949	1.58	0.04522	228.04	758.88	0.3827	3.78E-05
40.00	60	1.93E-05	7.72E-05	90	2.89E-05	1.16E-03	4.82E-05	0.063	0.937	1.47	0.05021	228.94	812.20	0.3703	4.19E-05
45.00	67.5	2.17E-05	8.68E-05	82.5	2.65E-05	1.06E-03	4.82E-05	0.076	0.924	1.37	0.05558	229.75	873.58	0.3611	4.64E-05
50.00	75	2.41E-05	9.64E-05	75	2.41E-05	9.64E-04	4.82E-05	0.091	0.909	1.27	0.06138	230.42	945.01	0.3547	5.13E-05
55.00	82.5	2.65E-05	1.06E-04	67.5	2.17E-05	8.68E-04	4.82E-05	0.109	0.891	1.16	0.06765	230.89	1029.17	0.3512	5.65E-05
60.00	90	2.89E-05	1.16E-04	60	1.93E-05	7.71E-04	4.82E-05	0.130	0.870	1.06	0.07446	231.09	1129.79	0.3506	6.22E-05
65.00	97.5	3.13E-05	1.25E-04	52.5	1.69E-05	6.75E-04	4.82E-05	0.157	0.843	0.96	0.08187	230.92	1252.22	0.3532	6.84E-05
70.00	105	3.38E-05	1.35E-04	45	1.45E-05	5.78E-04	4.82E-05	0.189	0.811	0.85	0.08997	230.23	1404.44	0.3594	7.52E-05
75.00	112.5	3.62E-05	1.45E-04	37.5	1.21E-05	4.82E-04	4.82E-05	0.231	0.769	0.75	0.09884	228.81	1598.80	0.3701	8.26E-05
80.00	120	3.86E-05	1.54E-04	30	9.64E-06	3.86E-04	4.82E-05	0.286	0.714	0.65	0.10861	226.35	1855.62	0.3867	9.07E-05
85.00	127.5	4.10E-05	1.64E-04	22.5	7.23E-06	2.89E-04	4.82E-05	0.362	0.638	0.54	0.11940	222.43	2210.77	0.4118	9.98E-05
90.00	135	4.34E-05	1.74E-04	15	4.82E-06	1.93E-04	4.82E-05	0.474	0.526	0.44	0.13138	216.37	2734.11	0.4503	1.10E-04
95.00	142.5	4.58E-05	1.83E-04	7.5	2.41E-06	9.64E-05	4.82E-05	0.655	0.345	0.33	0.14471	207.14	3582.15	0.5128	1.21E-04
100.00	150	4.82E-05	1.93E-04	0	0.00E+00	0.00E+00	4.82E-05	1.000	0.000	0.23	0.15960	193.06	5193.00	0.6282	1.33E-04

Appendix E: Control System Programming Code

```
// Main Gas/Temp Control System
// J Kruger 2013

// Additional Libraries
  #include <Wire.h>
  #include <LiquidCrystal.h>
  #include <TimerOne.h>
  LiquidCrystal lcd(0);

// Map pins
  int ZCP  =  2;//Zero Crossing Detection
  int PRG = 3;// E-Stop/Purge
  int EO = 5;// Element
  int IV1 = 6;// Argon
  int IV2 = 7;//Helium
  int OV1 = 8;// Outlet Valve

// Constants
  // define volume
    float vol = 0.000627808 +0.000103044;//Total Gass volume + hose volume
    float pTot = 150;//Total system pressure in kPa
  // define flow rates
    float ArFr = 30.0 / 60000.0;//Argon Flow Rate
    float HeFr = 30.0 / 60000.0;//Helium Flow Rate
  //define atmosperic pressure
    float PAtm = 83.0;
  // Control Temperature
    int Tctrl = 55;
    const float kHe = 0.1596;
    const float kAr = 0.0182;
    const float D11 = 1;
    const float D12 = 2.38921910926554;
    const float D21 = 0.273499572036382;
    const float D22 = 1;
    const int Tmaxdev = 8;
    const float ri = 0.005;
    const float ro = 0.0365;
    float tss = 0;

// input variables

  int TC = A0;// Internal Thermocouple
  int Elsw = A1;// Element Control Switch
  int LM35 = A2;// LM35 Temperature Sensor
  int Psnsr = A3;// Pressure Sensor
```

```
// Zero Crossing/Element Control Variables

   volatileint i = 0;
   volatileboolean zc = 0;
  int dim = 0;
  int freqStep = 80;
  int swi = 1023;

// Calculation Variables

  int  TempTol  =  3;// Temperature Tolerance
  float ArVol  =  0;// Argon Volume
  float HeVol  =  0;// Helium Volume
  float Ratio  =  0;// Mixture Ratio
  float q  =  0;// Heat flux
  float keff  =  0;// thermal conductivity
  float xHe = 0;
  float xAr = 0;
  float pHe = 0;
  float pAr = 0;
  float heaterA = 0.00255;
  float tfi = 0;
  float iT1 = 0;
  float iT2 = 0;
  float iT3 = 0;
  float iTf = 0;
  float iTrange[5] = {0, 0, 0, 0, 0};
  int rangecnt = 0;
  int preheat = 1;
  int cyclenr = 0;
  float iTcf = 6.39;
  float cftime = 0;
  float cfnr = 6;
  float tstart = 0;
  float Pctrl = 150;
  float As  =  0;

// Start Up Sequence
void setup() {
  Serial.begin(9600);
  lcd.begin(16,2);
  lcd.print("Starting UP..");
  lcd.setCursor(0, 1);
  lcd.print("Please Wait");

  // Element
```

```
 pinMode(EO,OUTPUT);
 attachInterrupt(0,  zero_cross_detect,RISING);
Timer1.initialize(freqStep);
 Timer1.attachInterrupt(dim_check, freqStep);

 // Inlet Valves
 pinMode(IV1,OUTPUT);
 pinMode(IV2,OUTPUT);
 digitalWrite(IV1,LOW);
 digitalWrite(IV2,LOW);

 //Outlet Valves Close
 pinMode(OV1,OUTPUT);
 digitalWrite(OV1,HIGH);

delay(3000);
 //Ambient Pressure
int pra  =analogRead(A3);
float voltage3a = (pra / 1023.0) - 0.04;
PAtm = (voltage3a) / 0.0012858 ;
 // Fill Capsule With Argon to Purge Air
 tfi = ((vol / ArFr) * 1000) + 50;// default time??
 ArVol = tfi * ArFr;
 float timei  =millis();
 while (millis() < (timei + tfi)) {
   digitalWrite(IV1,HIGH);
   digitalWrite(OV1,LOW);
   if (measurepres() > Pctrl) {
     digitalWrite(IV1,LOW);
     digitalWrite(OV1,LOW);
   }

   digitalWrite(IV1,LOW);
   digitalWrite(OV1,HIGH);
 }
 if (measurepres() < 100) {
   while (measurepres()  <  100)  {
     digitalWrite(IV1,HIGH);
     digitalWrite(OV1,HIGH);
   }
   //  failsafe1();
   }
   digitalWrite(IV1,LOW);
   digitalWrite(OV1,HIGH);
 iTrange[0] = measureinttemp();
 iTrange[1] = measureinttemp();
```

```
 iTrange[2] = measureinttemp();
 iTrange[3] = measureinttemp();
 iTrange[4] = measureinttemp();

 float timef = (millis() - timei) / 1000;
 Ratio = HeVol / vol;
 xHe = Ratio;
 xAr = 1 - xHe;
 keff  = kAr;
 As = 0.003141592;
 q = (pow(225,2)/8800) / As;
 digitalWrite(IV1,LOW);
 digitalWrite(OV1,HIGH);
 lcd.clear();
 lcd.setCursor(0, 0);
 lcd.print("Ready!");
 delay(2000);
 lcd.clear();
 lcd.setCursor(0, 0);
 lcd.print(timef);
 lcd.setCursor(0, 1);
 lcd.print("Mix: ");
 lcd.print(Ratio);
 lcd.print(" %");
OutputData(0,measureinttemp(),measureexttemp(),measurepres(),q,keff,Ratio,Tctr
  tstart =millis()/1000;

 }
void zero_cross_detect() {
  zc =true;
 i = 0;
 digitalWrite(EO, LOW);
}
void dim_check() {
 if(zc == true) {
  if(i>=dim) {
   digitalWrite(EO, HIGH);
   i = 0;
    zc =false;
  }
  else {
   i++;
  }
 }
}
void OutputData(float  tme,float  iT,float  eT,float iP,float iq,float ik,float
```

```
  Serial.print(tme);
  Serial.print(",");
    Serial.print(iT);
  Serial.print(",");
    Serial.print(eT);
  Serial.print(",");
    Serial.print(iP);
  Serial.print(",");
    Serial.print(iq);
  Serial.print(",");
    Serial.print(ik,4);
  Serial.print(",");
    Serial.print(iRatio,4);
  Serial.print(",");
    Serial.print(iTctrl);
  Serial.print(",");
  Serial.println(hA,4);
}
float calcK(float k1,float k2,float qx1,float qx2,float qD12,float qD21) {
float k = ((qx1*k1)/(qx1 + qx2*qD12))+((qx2*k2)/(qx1*qD21 + qx2));
  return  k;
}
float measureinttemp() {
  // internal thermocouple
    int t =analogRead(TC);
    float vad = (t * 5.0) / 1024.0;
    float tad = (vad) * 100.0;
    return tad;
}
float measureexttemp() {
    //lm35
    int reading =analogRead(LM35);
    float voltage = (reading * 5.0) / 1024.0;
    float temperatureC = (voltage) * 100.0 ;
    return temperatureC;
}
float measurepres() {
   //Pressure sensor
    int pr =analogRead(Psnsr);
    float voltage3 = (pr / 1023.0) - 0.04;
    float pressure = (voltage3) / 0.0012858 ;
    float PGauge = pressure - PAtm;
    return PGauge;
}
void failsafe1(float ftemp,float fpress)  {//overheating protection / failsafe
```

```
  if (ftemp > 120 || fpress > 400)
 {
  digitalWrite(EO,LOW);
  digitalWrite(OV1,LOW);
  digitalWrite(IV1,LOW);
  digitalWrite(IV2,LOW);
  OutputData(23,23,23,23,23,23,23,23,23);//Overheat Error Code
  lcd.clear();
  lcd.print("Overheating");
   }
 else {
  digitalWrite(OV1,HIGH);
 }
}
void purgesys() {
  digitalWrite(EO,LOW);
  digitalWrite(IV1,LOW);
  digitalWrite(IV2,LOW);
  digitalWrite(OV1,LOW);
  //failsafe1();
  lcd.clear();
  lcd.print("Purge");
  delay(100000);

}
void MixGas(float mRatio,float mtemp,float mpres,int refill) {
//Ratio is the percentage Helium
lcd.clear();
lcd.print(mRatio);
float mHeVol = mRatio*vol;
float mArVol = (1-mRatio)*vol;
float mHeP = mRatio*Pctrl;
float mArP = (1-mRatio)*Pctrl;
float mtHe = (mHeVol / HeFr) *1000;
float mtAr = (mArVol / ArFr) *1000;
lcd.clear();
lcd.print(mRatio);
lcd.print(" ");
lcd.print(mHeP);
lcd.setCursor(0, 1);
lcd.print(mArP);

if (refill == 1) {
  float pcurrent = measurepres();
  float pAdd = Pctrl - pcurrent;
  if (pAdd > 10) {
```

```
    mArP = (1-mRatio)*pAdd;
    mHeP = mRatio*pAdd;
    float pp1 = pcurrent;
    while (measurepres() < (pp1 + mArP)) {
      digitalWrite(IV1,HIGH);
    }
    digitalWrite(IV1,LOW);
    float pp2 = measurepres();
    while (measurepres() < (pp2 + mHeP)) {
      digitalWrite(IV2,HIGH);
    }
    digitalWrite(IV2,LOW);
  }
  }
if (refill == 0) {
float itime  =millis();
while (millis() < (itime + tfi)) {
  digitalWrite(IV1,HIGH);
  digitalWrite(OV1,LOW);
}
digitalWrite(IV1,LOW);
digitalWrite(OV1,HIGH);

while (measurepres() > mArP) {
  digitalWrite(OV1,LOW);
}
digitalWrite(OV1,HIGH);
while (measurepres() < (mArP)) {
  digitalWrite(IV1,HIGH);
}
  digitalWrite(IV1,LOW);
float pP1 = measurepres();
while (measurepres() < (pP1 + mHeP)) {
  digitalWrite(IV2,HIGH);
}
digitalWrite(IV2,LOW);
}
 }
float filterTemp(float fRange[5]) {
  float f = (fRange[0] + fRange[1] + fRange[2] + fRange[3] + fRange[4])/5;
  return f;
}
// Main Program Loop

void loop() {
  cyclenr = cyclenr + 1;
```

```
 float exttemp = measureinttemp();
 float PGauge = measurepres();

 // Inputs:

  iT2 = iT1;
  cftime = (millis()/1000) - tstart;
  iT1 = measureexttemp();
  if (cyclenr > 2) {
  if (abs(iT1 - iT2) > Tmaxdev) {
    iT1 = iT2;
  }
  }
  if (rangecnt == 5) {
    rangecnt = 0;
  }

  iTrange[rangecnt] = iT1;
  rangecnt = rangecnt + 1;

  if (cyclenr < 5) {
    iTf = iT1;
    iTrange[0] = iT1;
    iTrange[1] = iT1;
    iTrange[2] = iT1;
    iTrange[3] = iT1;
    iTrange[4] = iT1;
  }
  if (cyclenr >= 5) {

  iTf = filterTemp(iTrange);
  }
failsafe1(iTf,PGauge);
if (PGauge < Pctrl) {
MixGas(Ratio,iTf,PGauge,1);
}


 // Element Control

  int  sw  =analogRead(Elsw);
  if (swi != sw) {
      if (sw == 0) {
         dim = 128;
         heaterA = 0;
         cfnr = 1;
```

```
       }
       if ((sw > 185) && (sw < 220)) {
      heaterA = (0.5*0.00255);
       cfnr = 2;
         dim = (1-0.32) * 128;
       }
       if ((sw > 395) && (sw < 425)) {
       dim = (1-0.4) * 128;
      heaterA = 0.65*(0.00255);
       cfnr = 3;
       }
       if ((sw > 585) && (sw < 625)) {
         dim = (1-0.5) * 128;
         heaterA = 0.8*(0.00255);
         cfnr = 4;
       }
       if ((sw > 790) && (sw < 835)) {
         heaterA = 0.95*(0.00255);
         cfnr = 5;
         dim = (1-0.6) * 128;

       }
       if (sw > 990) {
         dim = 0 * 128;
         heaterA = 0.00255;
         cfnr = 6;
       }
       swi = sw;
      failsafe1(iTf,PGauge);
  }

 OutputData((millis() / 1000),iTf,exttemp,PGauge,q,keff,Ratio,Tctrl,heaterA);

lcd.clear();
lcd.setCursor(0, 0);
lcd.setBacklight(HIGH);
lcd.print("T=");
lcd.print(iTf);
lcd.print(" ");
lcd.print("P= ");
lcd.print(PGauge);
lcd.setCursor(0, 1);
lcd.print("R= ");
lcd.print(Ratio);
lcd.print(" k=");
lcd.print(" ");
```

```
 lcd.print(keff,4);
 //
 if (preheat == 1) {
   if (iTf > (Tctrl - 3)) {
     preheat = 0;
     sw = 0;
   }
 }
 if (preheat == 0) {
  if ((millis()/1000) > tss) {
 lcd.clear();
 lcd.setCursor(0, 0);
 lcd.setBacklight(HIGH);
 lcd.print("Temp Change");

if ((iTf + TempTol) > Tctrl || (iTf - TempTol) < Tctrl) {
  q = (iTf*keff)/(ri*1.987874348154346);//log(ro/ri));
  keff = ((q*ri)/Tctrl)* 1.987874348154346;//log(ro/ri);
  if (keff < kAr) {
    lcd.clear();
    lcd.print("Of of Range");
    keff = kAr;
  }
  if (keff > kHe) {
    lcd.clear();
    lcd.print("Of of Range");
    keff = kHe;
  }
  xHe = (-sqrt(0.1200966*pow(keff,2) - 0.123233*keff + 0.02402048)+3.1249878*kef
   xAr  = 1  -  xHe;// calculate required ratio
  Ratio = xHe;
   MixGas(Ratio,iTf,PGauge,0);// calculate required valve open times/pressures
  lcd.print("Waiting");
  float currenttime  =millis()/1000;
  tss = (currenttime + ((0.5*60)));
   }
  }
  }
  delay(2000);
}
  //
 // 23
```