Abstract

Masters of Engineering Degree (Mechanical)

Project Title:

Biomass Insertion System for Pyrolysis Experiments

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Abstract:

Biochar, a solid byproduct of heating organic materials in the absence of oxygen, has many benefits for agriculture and energy. Researchers at Cornell University use a pyrolysis flow reactor to study the production of biochar. These experiments depend on biomass samples undergoing a sudden rise in temperature, and the samples should not be near oxygen once this heating has begun. The way in which biomass samples are inserted in this reactor is difficult and fails to keep oxygen outside. This report deals with the design and analysis of an improved insertion system.

The improved system allows samples to be placed in a part of the reactor where they are not heated until the oxygen is removed. Two design concepts are modeled as networks of thermal resistors. Computational fluid dynamics software and correlations for conduction and free, forced, laminar, and turbulent convection are used to predict the relevant resistances. This model allows the dimensions of the new insertion system to be predicted. This model is shown to accurately predict the temperatures inside a flow reactor.

It is concluded that a duct hose should be added to the reactor in order to allow the samples to be held far away from the heat while the air is sealed outside. Also adding a solid cylinder to the current particle holder may improve the flow properties without affecting the thermal requirements.

Biomass Insertion System for Pyrolysis Experiments

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Master of Engineering Project, 2013–2014
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Introduction

Biochar and Its Uses

Biochar is a solid carbon-rich byproduct of the heating of organic materials. It benefits agriculture by helping soil maintain its nutrients and reducing the need for artificial fertilizers.[1] Researchers at Cornell University are designing and improving stoves that can cook food and produce biochar at the same time. Large-scale equipment is also being studied to produce char and liquid fuels for electricity. Both of these projects require an understanding of the physical and chemical processes that favor the production of biochar.

Current Experiments

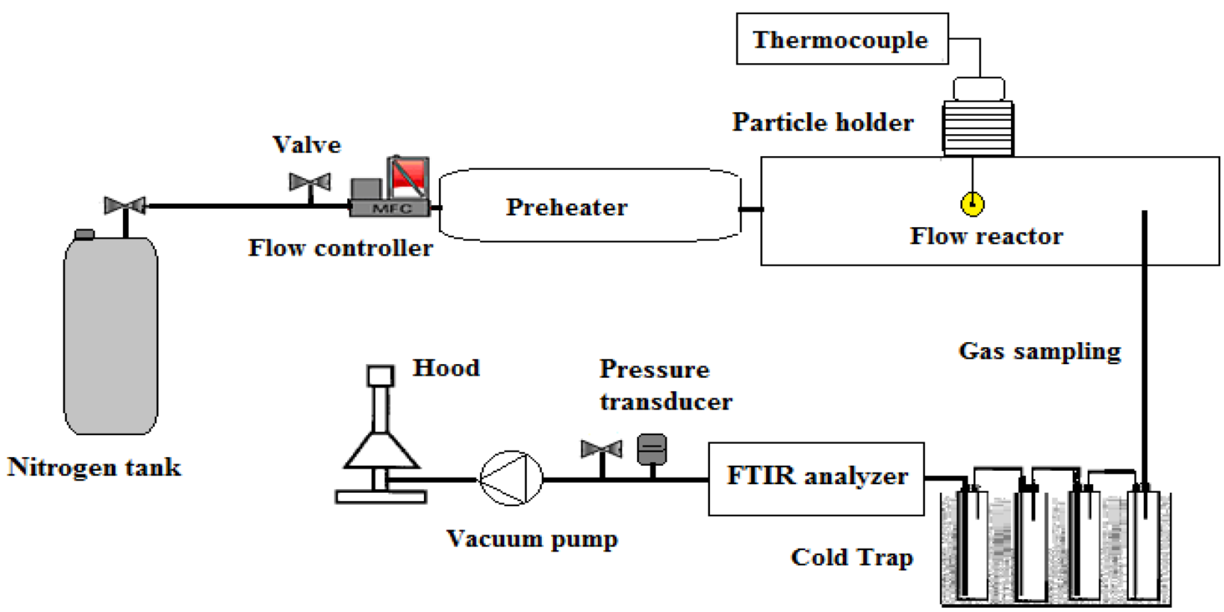

Figure 1: Current experimental setup. Image from Bennadji, H., Smith, K., Shabangu, S., Fisher, E. M. (March 2013). "Low-Temperature Pyrolysis of Woody Biomass in the Thermally Thick Regime".

Experiments are being carried out to analyze the production of biochar. The current setup is shown in Figure 1. A sample of biomass, such as wood, is inserted into a heated flow of nitrogen gas in the flow reactor. The temperature and gaseous products of this reaction are measured. It is important that the sample's surroundings be free of oxygen once the heating has started so that the desired reactions will happen. The presence of oxygen would cause oxidation and combustion rather than pyrolysis.

[1] "Frequently Asked Questions about Biochar". International Biochar Initiative. n.d. http://www.biochar-international.org/biochar/faqs

The Insertion System

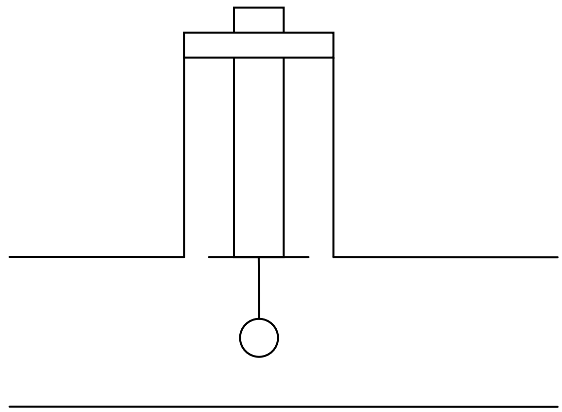

Figure 2: The particle holder in the flow reactor during an experiment

Redesigning the insertion system is the goal of this project. The insertion system is the part of the reactor where biomass is placed before the experiment begins. Hot nitrogen flows through a horizontal metal tube which is attached to a vertical side-arm or T-section, which is drawn in Figure 2. While the reactor is heating up and nitrogen is replacing the air, the top of the side-arm is covered by a thin sheet of metal. After the sample is attached to the bottom of a particle holder, the metal sheet is removed and the holder is inserted through the side-arm into the reactor. The holder and the top of the side-arm are then connected by an airtight seal. Later, the sample can be raised, cooled in the side-arm, and then lowered for a second time into the horizontal part of the reactor.

Figure 3: The current particle holder

The particle holder, photographed in Figure 3, measures the sample's temperature while keeping it in place in the flow reactor. Three thermocouples go through the holder's hollow rod and come into contact with the biomass sample. An adjustable disc with an O-ring seals the holder to the side-arm. Originally, the holder would be raised back into the side-arm after a time of heating to be cooled and then re-lowered. The adjustable disc allowed this to happen while keeping the system sealed. This was discontinued because the temperatures and temperature gradients in the side-arm were too high, even when an active water-cooled system was added to the side-arm and cool nitrogen was blown through the holder.

The accuracy of the experiments is threatened by small amounts of air that enter the reactor through the insertion system. The apparatus is somewhat difficult to use, and it suffers from some gases and heat moving from the horizontal part of the reactor into the side-arm, leading to more complicated flow patterns. The current design project seeks to further improve the holder and insertion system to make the experiments more accurate and simpler to carry out.

Design Problem

Primary Design Requirements

The goal of this project is to design an improved insertion system. The primary design requirements are to hold the sample and the thermocouples in place, to minimize the amount of oxygen that enters the reactor while maintaining a step change in temperature and to make the flow of nitrogen inside the reactor more unidirectional.

The main purpose of the particle holder is to keep the biomass sample in the flow of heated nitrogen. It should do this while allowing the thermocouples to touch the sample and be connected to the measurement device.

Oxygen currently enters the reactor during the insertion process. The current version of the insertion system requires two people to work very quickly to insert the sample. After the nitrogen in the reactor reaches the high temperature, one person removes a cover from the side-arm while the other person puts the holder into the side-arm. A small amount of air enters the reactor during this time.

The sample must remain in gases that are cool with a known initial temperature (less than 105 °C) before insertion and then go through a sudden temperature rise when inserted.

Unidirectional flow in the second version of the holder is intended to be maintained by a curved plate rigidly attached near the bottom of the holder. This plate is intended to keep the hot nitrogen from escaping into the side-arm during the experiment. This seal is not perfect; this adds to the vertical component of the flow in the area of the sample. The calculations and numerical modeling in the experiments are simpler if flow in a single direction can be assumed.

Secondary and Other Design Requirements

Once the above requirements are satisfied, the following criteria are used to evaluate and compare the different options:

- a repeatable positioning of the sample within the reactor
- low cost
- ease of use

Approach

The design process began with generating several initial concepts and considering their potential to meet the requirements. Two main concepts were selected for in-depth modeling

Initial Design Concepts

After identifying the criteria and constraints listed in "Design Problem", some initial design concepts were generated. Each concept involved enclosing the sample inside of the reactor before the gases start to heat up. The entire system then remains sealed until after the experiment. This requires a thermal barrier to be added between the sample and the heating gases. Three main types of barriers were considered: attachments within the reactor, solid attachments to the holder, and gaseous material under the holder.

Attachments within the reactor are solid barriers added where the horizontal and vertical parts come together. This barrier could look like a gate valve or like the shutter on a camera. Figure 4 demonstrates how the opening in such a shutter can change size. This barrier would be in the closed position when the gas is heating up and would be opened to allow the sample to be lowered. This process is shown in Figure 5; the shaded regions represent the shutter.

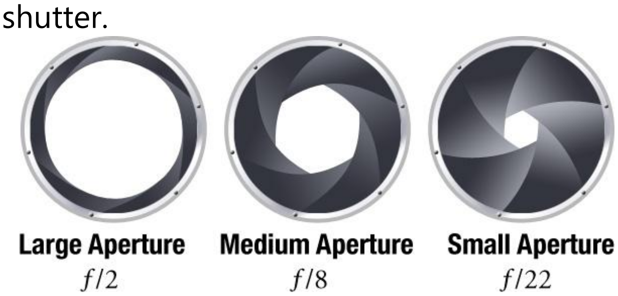

Figure 4: Illustration of a camera's shutter from Arbabi, S. (Dec. 27, 2011). "What is aperture, and how does it affect my photos?". Engadget. http://www.engadget.com/2011/12/27/engadget-primed-what-is-aperture-and-how-does-it-affect-my-pho/

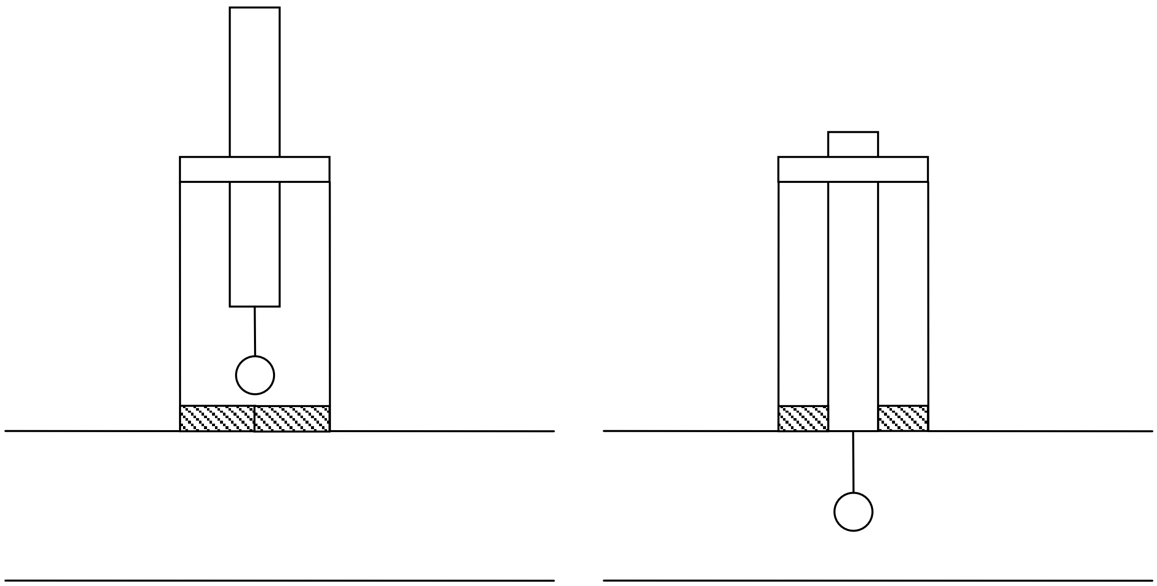

Figure 5: The shutter-style system during the heat-up phase (left) and during the experiment (right)

Solid attachments to the holder take the place of the existing curved plate and extend this barrier all the way around the sample. This could take the form of a pipe with a uniform thickness or a piston-like object where the bottom is thicker than the top. These two shapes are modeled in Figure 6.

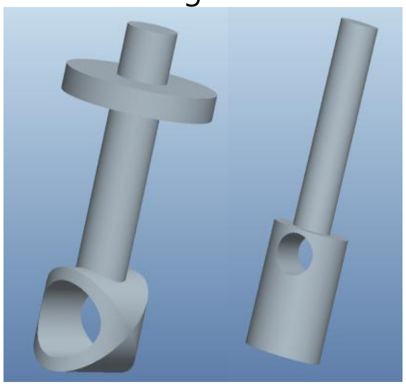

Figure 6: The pipe concept (left) and the piston concept (right)

Gaseous material under the holder can be added using the bellows or accordion concept illustrated in Figure 7. This involves extending the side arm with a compressible hose. By holding the sample inside this hose at a sufficient height, the column of gas under the sample should be enough to insulate it from the reactor.

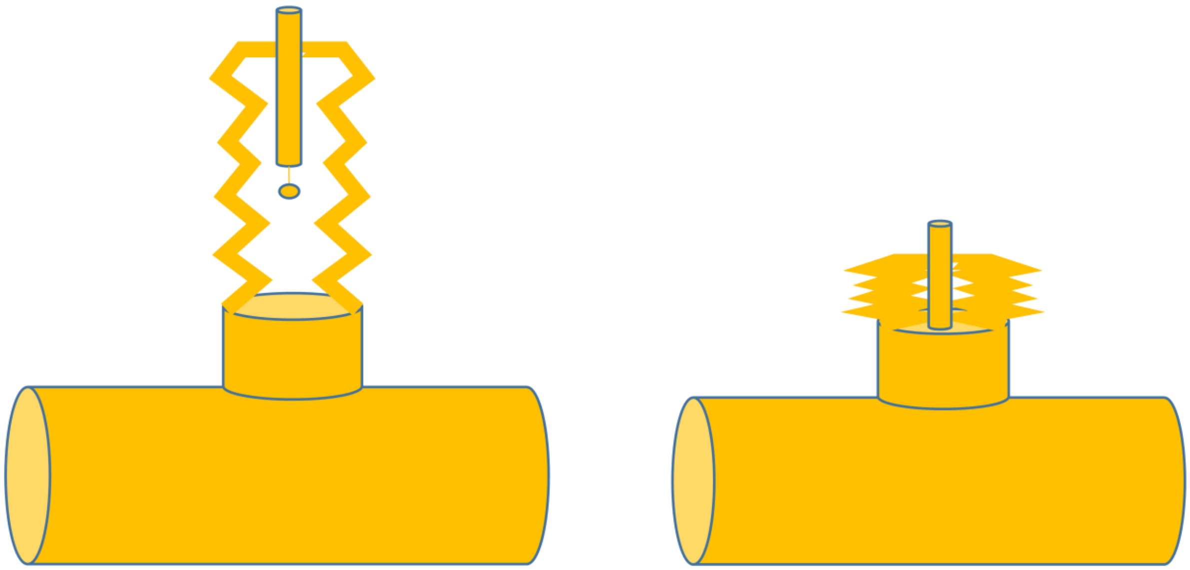

Figure 7: The bellows concept before (left) and during (right) the experiment

Exploring Possibilities

The concept of a solid on-reactor attachment was rejected due to manufacturability and usability concerns. These ideas require several small moving parts that could be expensive and difficult to produce. Because they would be installed inside of a sealed reactor, it would be difficult to design a way for the experimenter to open and close them. The experimenter would need to complete two actions (opening the valve or shutter and lowering the sample) in a short amount of time. This would not be significantly easier to do than the current method of opening the upper seal and lowering the sample. Each of these moving parts would need to be designed to withstand the high temperatures of the nitrogen flow and would need to be thick or resistive enough to stop enough heat from escaping into the side-arm.

The pipe, piston, and bellows systems are all relatively easy to manufacture, repair, and use. They each require only a single motion (lowering the sample) for the experimenter, making them more usable. The bellows would be the most compatible with the existing reactor, whereas the pipe and piston would require that the inner diameter of the reactor be increased. An added benefit of the pipe or piston is that they allow for more repeatable positioning of the sample within the reactor. The researcher would simply push the holder down until the bottom surface of the pipe or piston comes into contact with the bottom of the reactor. The complete cylindrical surrounding of the pipe and piston also helps to maintain unidirectional flow.

The solid holder attachment and bellows concepts were selected as the two most promising concepts based on the above explanations. To decide between these ideas an in-depth heat analysis was completed, as described in “Modeling”. It was also decided that any of the concepts could be combined with an active cooling system if necessary.

Modeling

A heat transfer model of the bellows system was used to determine the temperature of the gas near the sample as a function of the height of the side-arm. The piston system is discussed in the section “Refining the Design.” The bellows system was modeled as a network of eleven thermal resistances connected to a well-stirred reactor, as shown in Figure 8 and Figure 9. According to this model, some hot nitrogen enters the well-stirred region from the horizontal reactor and an equal amount of nitrogen reenters the horizontal reactor at an equal mass flow rate. The nitrogen in the mixture zone reaches a single temperature, T_{mix}. The energy from this mixture zone is then carried up through the eleven-resistor network and out to the ambient room air.

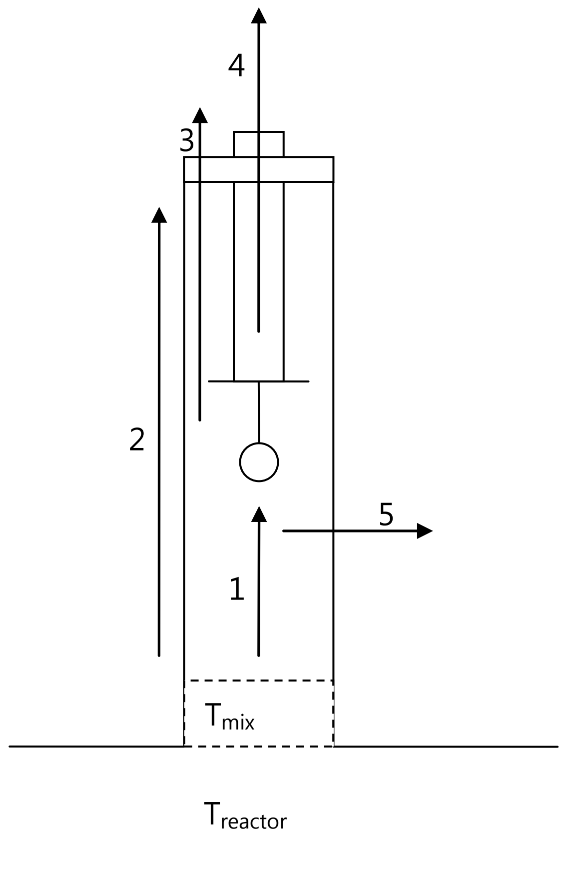

Figure 8: The principal paths of heat transfer in the bellows insertion system.

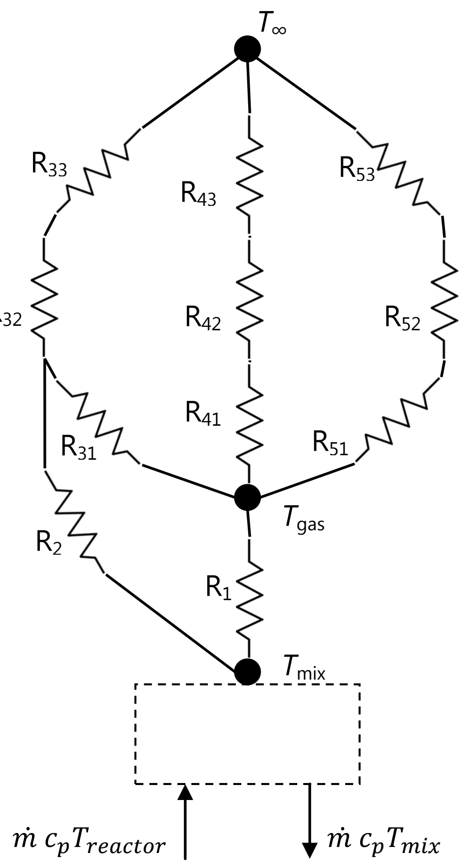

Figure 9: The heat transfer model. The mixture zone is represented by the dashed box. R_2 was treated as open in the final model.

The main goal of this model is to determine T_{gas}. The experimental biomass sample is surrounded by gases of this temperature. If it were a transient system, it would be possible for the sample to have a different temperature from T_{gas}. Because this is being modeled as a one-dimensional and steady state system, the sample will act as a lumped capacitance and will be equal to T_{gas}.

Process

Determining the temperatures required a four-step process:

1.) Find the values of each of the eleven resistances.
2.) Find the temperature of the mixture region, T_{mix}.
3.) Determine the energy and heat flux out of the mixture region and through the resistor network.
4.) Calculate the temperature of the gases near the sample, T_{gas}.

Resistances

Eleven resistances were considered as either conduction or convection. The general forms of these resistances are given by the following equations.

$$R_{conduction} = \frac{L}{kA} \quad (1)$$

$$R_{convection} = \frac{1}{hA} \quad (2)$$

L is the length in meters in the direction of heat transfer. *A* is the area in meters squared normal to this direction: a cross section of the material for conduction or a surface area for convection. The conductivity, *k*, is a property of the material in W/(m K). The convective heat transfer coefficient, *h*, is measured in units of W/(m^2 K) and is a function of the Nusselt number. The Nusselt number in turn depends on the geometry and flow properties. The flow may be either forced or free convection. Forced convection can either be laminar or turbulent. The resistors are labeled in Figure 9 as follows:

- Resistance 1 represents the heat transfer through the column of nitrogen from the mixture region (T_{mix}) to the region near the sample (T_{gas}).
- Resistance 2, which was ultimately removed from the model, represents the heat transfer from the bottom of the hose wall to the top. Unlike R_{52}, the length is the height of the side-arm, and the area is the product of the hose thickness and its circumference.
- Branch 3, including resistances R_{31}, R_{32}, and R_{33}, represents the heat flux through the lid at the top of the vertical chamber.
  - Resistance 3.1 is the convection through nitrogen gas from the area near the sample to the bottom of the lid.
  - Resistance 3.2 is conduction from the bottom of the lid to the top of the lid.
  - Resistance 3.3 is convection from the top of the lid to the ambient room temperature.
- Branch 4 includes resistances R_{41}, R_{42}, and R_{43}.
  - Resistance 4.1 is convection from the gas near the sample to the surface of the rod of the holder.
  - Resistance 4.2 is conduction through the rod. The length is the length of the rod and the area is the circular cross section of the rod.
  - Resistance 4.3 is convection from the surfaces of the rod that are outside of the reactor to the ambient.
- Branch 5 models the heat flow in the radial direction.
  - Resistance 5.1 is the convection through nitrogen gas from the region near the sample to the inner surface of the hose wall.
  - Resistance 5.2 is conduction through the hose wall. Unlike R_2, the relevant length is the wall's thickness, and the area is the product of the side-arm's height and circumference.

- Resistance 5.3 is the convection from the outer surface of the bellows to the ambient.

The Peclet number was used to determine whether R_1 should be modeled as conduction or convection. If the Peclet number (the product of the Reynolds and Prandtl numbers) is greater than 100, then Rohsenow and Hartnett recommend neglecting conduction.[2] The Peclet number for this region was calculated by the following equation.

$$Pe = Re\,Pr = \frac{VD}{\nu}\mathrm{Pr} = \frac{\left(1\,\frac{m}{s}\right)(0.0525\,m)}{66.32\times10^{-6} m/s}\cdot 0.72 = (791.62)(0.720) = 570 \qquad (3)$$

V is a representative velocity. A new post-processing of a previous CFD simulation showed that the nitrogen in most of the vertical side-arm had a velocity on the order of 1 m/s, while the nitrogen above the sample was close to 0.2 m/s. The predicted velocity contours are shown in Figure 10. D is the diameter of the column. The viscosity (ν) and Prandtl number were evaluated[3] for nitrogen gas at 700 K. Since the Peclet number is significantly higher than 100, the heat transfer through R_1 was modeled as pure convection.

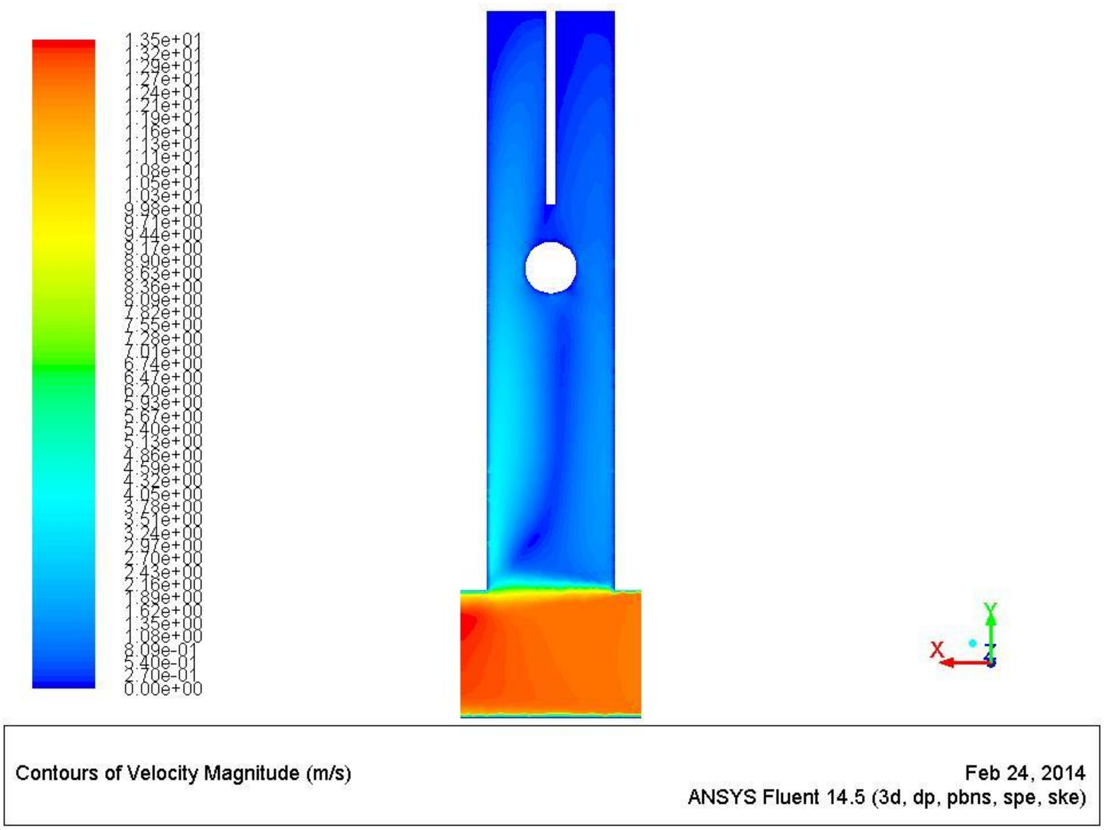

Figure 10: Velocities predicted by the CFD model. The nitrogen flows in the positive x-direction.

[2] Rohsenow, W. M.; Hartnett, J. P. (Eds.) (1973). *Handbook of Heat Transfer*. McGraw-Hill. pg. 7.25.

[3] Kays, W. M.; Crawford, M. E.; Weigand, B. (2005). *Convective Heat and Mass Transfer* (4^{th} Ed.). McGraw-Hill. pg. 459.

The Grashof and Reynolds numbers were compared in order to determine whether the convection in R_1 is forced or free. Incropera and DeWitt[4] recommend neglecting free convection if the ratio Gr_L/Re_L^2 is less than 1 and neglecting forced convection if the ratio is greater than 1. This ratio is calculated as follows:

$$\frac{Gr_L}{Re_L^2} = \frac{g\,\beta\,\Delta T\,L^3}{\nu^2}\left(\frac{\nu}{V\,L}\right)^2 \quad (4)$$

For properties of nitrogen evaluated at 700 K, a characteristic temperature difference of 400 K, and a characteristic length of 0.2 m, this gives a critical velocity of 0.2 m/s. Because the velocity in most of the nitrogen column is about 1 m/s, R_1 should be considered as forced convection.

Because the Reynolds number is lower than 5×10^5, R_1 is laminar convection. The top of the mixture region can be modeled as a flat plate. For forced and laminar convection from a flat plate, the Nusselt number is given by[5]:

$$\overline{Nu_x} = 0.664 Re_x^{1/2} Pr^{1/3} = 0.664\left(791.62^{\frac{1}{2}}\right)\left(0.72^{\frac{1}{3}}\right) = 16.744 \quad (5)$$

The "plate" is a circle with the same diameter as the side-arm, so *Re* and *Pr* are the same as in the Peclet calculation.

Resistance 2 is conduction through the length of the bellows hose. The hose is modeled as the Extreme Temperature Duct Hose for Fumes from McMaster-Carr. The manufacturer describes the material as "alumina-coated glass fabric with fine stainless steel wire woven in."[6] Its thermal conductivity was assumed to be similar to other ceramics, so a value of 1 W/(m K) was used. The resistance increases with the length of the hose. For a 40-centimeter height, this resistance is calculated to be over 9,000 K/W. The next highest resistance is about of 120 K/W. (See Figure 18.) Because R_2 is so much larger than any other resistance in the system, it was treated as an open circuit in the calculations.

The velocities above the sample are approximately 0.2 m/s. Therefore, R_{31} must be modeled as a combination of forced and free convection. These two modes of heat transfer can be combined by the equation.[7]

$$Nu^n = Nu_F^n + Nu_N^n \quad (6)$$

In the above equation, n is approximately 3, Nu_F is the Nusselt number for forced convection as estimated for R_1, and Nu_N is the Nusselt number for free or natural convection as estimated by a correlation from Incropera and DeWitt:[8]

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[4] Incropera, F. P.; DeWitt, D. P. (1996). *Fundamentals of Heat and Mass Transfer* (4th Ed.). pg. 487.

[5] Incropera & DeWitt. pg. 394.

[6] "Extreme-Temperature Duct Hose for Fumes". McMaster-Carr. http://www.mcmaster.com/#45825k71/.

[7] Incropera & DeWitt. pg. 515.

[8] Incropera & DeWitt. pg. 493.

$$\overline{Nu_L} = \left(0.825 + \frac{0.387 Ra_L^{\frac{1}{6}}}{\left(1 + \left(\frac{0.492}{\text{Pr}}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}} \right)^2 \quad (7)$$

where the Rayleigh number is given by:

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha} \quad (8)$$

The length scale used to convert this combined Nusselt number into a heat transfer coefficient is the diameter of the lid.

R_{32} is a conductive resistance. The conductivity used was 235 W/(m K), the conductivity of aluminum.[9]

R_{33} is free convection because there is no significant fluid flow in the room outside of the reactor. The Nusselt number for free convection is as estimated for R_{31}. The fluid properties were evaluated for air at 300 K. The temperature difference between the top of the metal plate and the ambient air was estimated to be 50 K. An iterative method can improve the accuracy of this model. Once a temperature is found, it could be plugged back in to this equation to find a more accurate temperature difference. This could be repeated until the Rayleigh number stops changing significantly.

R_{41} is a combination of free and forced convection like R_{31}. The relevant length and area are those of the rod rather than of the lid.

R_{42} is conduction through the length of the rod. The conductivity was taken as 235 W/(m K), the conductivity of aluminum.

R_{43} is free convection to the ambient. It is like R_{33}, except that the surface area is the sum of the area of the end of the rod and the sides of the rod above the lid.

R_{51} was modeled as laminar and forced convection through a tube with a constant surface temperature. The Nusselt number for this case is a constant[10] of 3.66. The resistance is a function of this Nusselt number and of the surface area of the wall.

R_{52} uses the length parameters given in the bullet list and the same conductivity as R_2.

R_{53} is the free convection from the surface of the bellows hose wall to the outside temperature. The relevant surface area is that of the outer wall of the hose.

The assumptions about the resistances are summarized in Table 1.

[9] Wolfram Alpha LLC (2013). Wolfram Alpha. http://www.wolframalpha.com/input/?i=aluminum+thermal+conductivity . Retrieved November 7, 2013.

[10] Incropera & DeWitt. pg. 460.

Table 1: Summary of Eleven Heat Transfer Models

Resistance	Mode of Heat Transfer	Function of Side-arm Height?
R_1	Laminar forced convection	No
R_2 (neglected)	Conduction	Yes
R_{31}	Combined free convection and laminar forced convection	No
R_{32}	Conduction	No
R_{33}	Free convection	No
R_{41}	Combined free convection and laminar forced convection	No
R_{42}	Conduction	No
R_{43}	Free convection	No
R_{51}	Laminar forced convection	Yes
R_{52}	Conduction	Yes
R_{53}	Free convection	Yes

If R_2 is removed from the model, then this system can be simplified into a two-resistor model as shown in Figure 11.

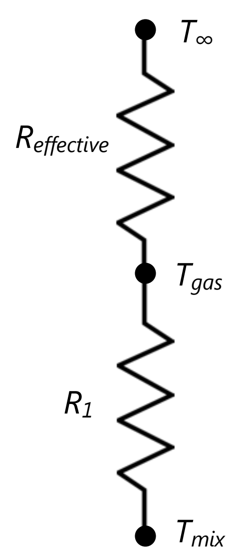

Figure 11: Simplified Resistance Model

$R_{effective}$ is the parallel combination of three resistor branches; each branch in turn is the series combination of three resistances. The equation below is used to transform the nine calculated resistances into $R_{effective}$.

$$\frac{1}{R_{eff}} = \frac{1}{R_{31} + R_{32} + R_{33}} + \frac{1}{R_{41} + R_{42} + R_{43}} + \frac{1}{R_{51} + R_{52} + R_{53}} \quad (9)$$

The goal of this design is to have T_{gas} approach T_∞. This requires that $R_{effective}$ be much smaller than R_1.

Mixture Temperature

Once the eleven resistances were determined, the mixture temperature was calculated. The mixture region is a control volume at steady state, with a general energy equation given by[11]

$$\dot{Q} - \dot{W} = \dot{m}\left[(h_o - h_i) + \frac{1}{2}(v_o^2 - v_i^2) + g(z_o - z_i)\right] \quad (10)$$

where $\dot{Q}$ is heat transfer, $\dot{W}$ is work, $\dot{m}$ is a mass flow rate, h is enthalpy, v is velocity, g is acceleration due to gravity, and z is an elevation. It is further simplified as a well-stirred reactor with a single chemical species (nitrogen gas). After neglecting work and kinetic and potential energies, the energy equation becomes[12]

$$\dot{Q} = \dot{m}\,(h_{out} - h_{in}) \quad (11)$$

Because the resistance network can be simplified as a one-directional system, the net energy entering the mixture zone can be set equal to the heat flux from this zone to the ambient using the equation

$$\dot{m}\,c_p\,(T_{reactor} - T_{mix}) = \frac{T_{mix} - T_\infty}{R_1 + R_{eff}} \quad (12)$$

where the nitrogen is assumed to be an ideal gas with a constant specific heat. $T_{reactor}$ was taken as 750 K, T_∞ was set to the room temperature of 300 K, and c_p was equal to a constant 1040 J/(kg K), the specific heat of nitrogen gas at 350 K and 1 atm.[13]

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[11] Turns, S. R. (2012). *An Introduction to Combustion: Concepts and Applications* (3rd Ed.). McGraw-Hill. pg. 28.
[12] Turns. pg. 196.
[13] Kays, Crawford & Weigand. pg. 459.

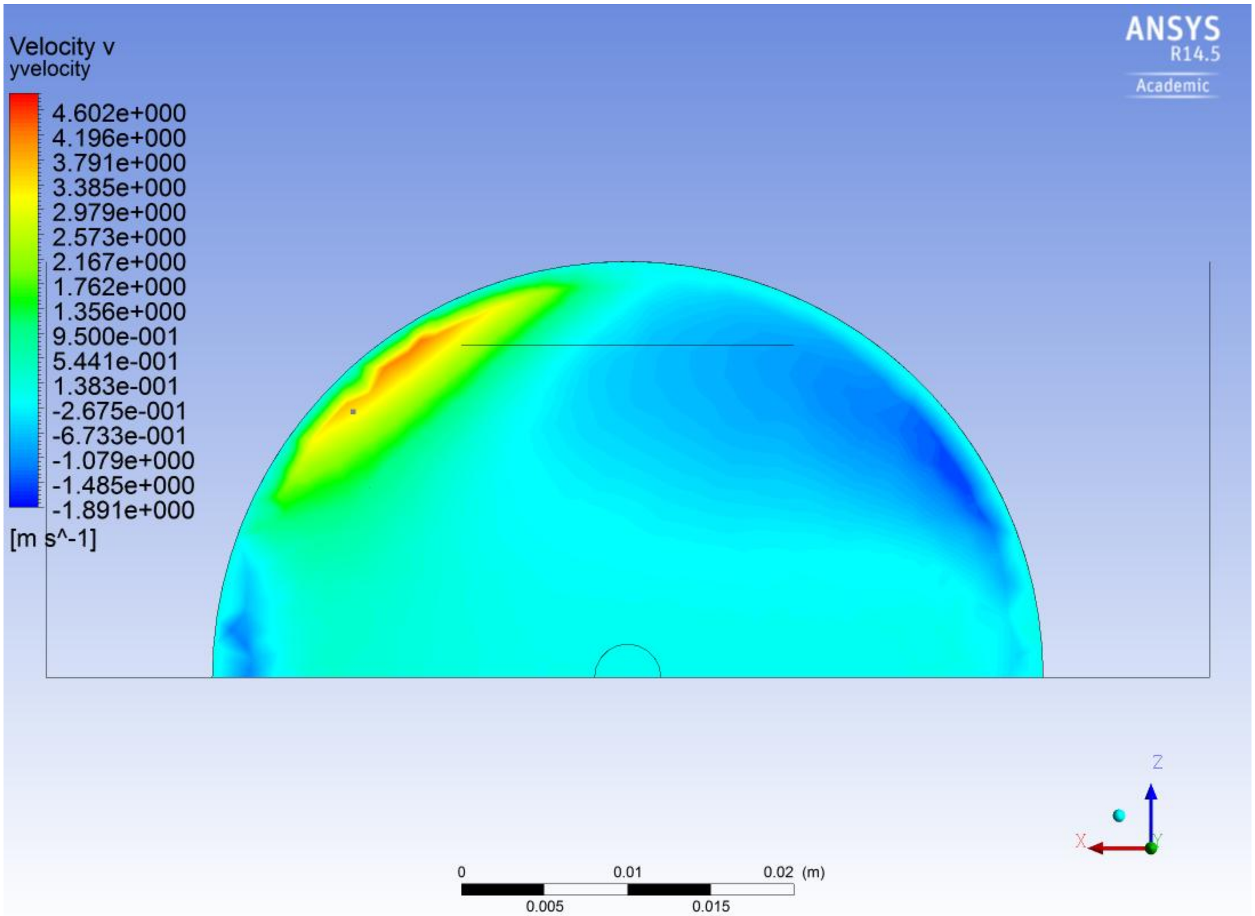

Figure 12: The y-component of velocity of half of a horizontal cross-section of the reactor near the intersection of the vertical and horizontal parts.

$\dot{m}$ in this equation is the mass flow rate into and out of the mixture zone; it was estimated as follows. A previous ANSYS Fluent simulation by post-doctoral researcher Shaka Shabangu assisted in making this estimate. A contour plot like the one in Figure 12 was produced of the vertical components of velocity at the boundary between the horizontal and vertical parts of the reactor. The approximate area of each contour band was multiplied by the density of nitrogen and by the average velocity in that band. This calculation was done once with the areas where the velocity components were positive and again with the areas where the velocity components were negative. Both mass flow estimates were close to 3.42×10^{-4} kg/s.

After rearranging Equation 12, T_{mix} was found to vary based on R_{eff}, which varies with the height of the bellows.

$$T_{mix} = \frac{(R_1 + R_{eff})\,\dot{m}\,c_p\,T_{reactor} + T_\infty}{(R_1 + R_{eff})\,\dot{m}\,c_p + 1} \tag{13}$$

Energy Flux

This value of T_{mix} was used to determine the energy flux, which was equal to the heat flux. These are shown by the following equation.

$$\dot{Q} = \dot{m}\, c_p \left(T_{reactor} - T_{mix}\right) \quad (14)$$

Gas Temperature

Finally, the heat flux across the entire resistance network was set equal to the heat flux across the R_{eff} resistor to find the temperature of the gas near the sample.

$$\dot{Q} = \frac{T_{gas} - T_{\infty}}{R_{eff}} \quad (15)$$

T_{gas} will be discussed in the "Results" section of this report.

Limitations

The concept of thermal resistance circuits is typically used to analyze steady-state and one-dimensional systems, but is being used here to predict temperatures in a more complex geometry with heat being added.

The biomass sample and the materials close to it are approximately at room temperature when the sample is first placed into the side-arm. This would not reach steady state until later. Therefore, the temperatures predicted in this model are likely to be higher than what would actually occur during the heat-up process.

Using a one-dimensional model for a two-dimensional "composite wall" is "often reasonable" if additional assumptions are made.[14] It is necessary to assume that the surfaces represented by nodes are each isothermal. For example, T_{gas} represents an average of temperatures in the side-arm, and the junction of R_2, R_{31}, and R_{32} represents the single average temperature across the entire bottom surface of the lid at the top of the side-arm. If the temperature varies across the lid, then this model might not be as accurate. The full eleven-resistor model also has two independent resistors (R_2 and R_{52}) representing the wall of the bellows. If the conduction represented by R_2 were significant, it would be preferred to combine these two resistors into a two-dimensional control volume.

Accuracy is also affected by the use of Nusselt number correlations that were derived for different purposes. The correlation used to find the Nusselt number for R_1 is intended to be used for flat plates in a parallel flow. The equation used for combined free and forced convection is said to be only "a first approximation."[15] Mixed convection can often include complicated vortices, oscillations, and asymmetries. The correlation used for free convection is intended for isothermal and vertical plates and cylinders, but there is most likely a temperature difference between the bottom and top of the bellows

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[14] Incropera & DeWitt. pg. 79.

[15] Incropera & DeWitt. pg. 515.

wall. The correlation used for R_{51} (the constant Nu = 3.66) was derived for fully developed conditions in a pipe flow with a constant surface temperature. Here it is not being used in a typical pipe flow situation since the pipe (side-arm) is closed at the top.

Refining the Design

A similar model was made to analyze the effects of combining the bellows and piston design concepts. The considered combination is illustrated in Figure 13 and Figure 14.

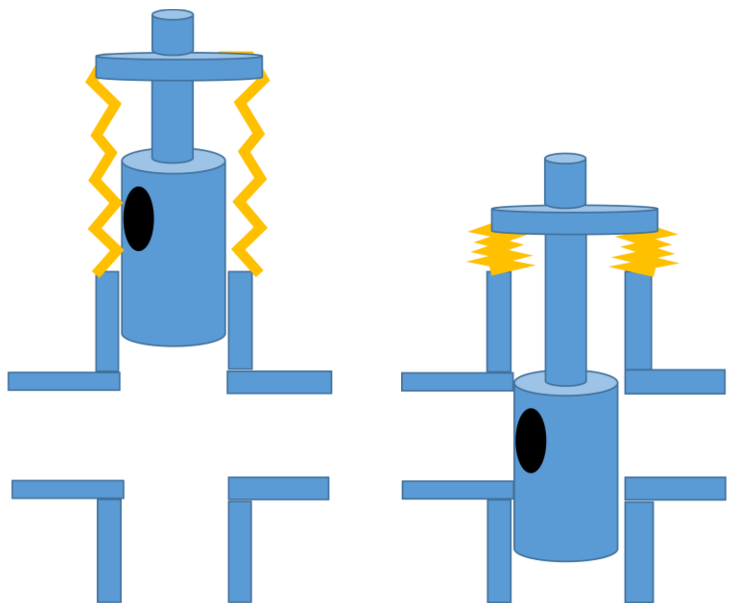

Figure 13: Bellows and piston concepts combined

R_1, $R_{effective}$, T_{mix}, and T_∞ in Figure 14 are analogous to the resistances and temperatures with these names in the bellows-only model. R_{ins} represents the conduction through the insulation at the bottom of the piston. T_{floor} is the temperature at the top of this insulation and at the bottom of the chamber that contains the sample. $R_{chamber}$ is the convection through this chamber and is equal to R_1. R_{wall} accounts for the amount of heat that is conducted through the wall from the floor to the ceiling of the chamber; it is similar to R_2 of the bellows-only model. The temperature at the top of the chamber is $T_{ceiling}$ and the conduction through the top of the chamber is R_{roof}. The T_{gas} in this model is the average of T_{floor} and $T_{ceiling}$.

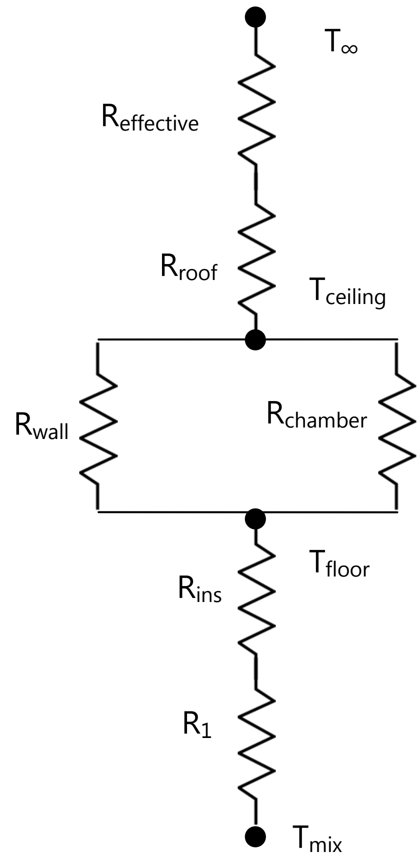

Figure 14: Thermal resistance model of combined bellows and piston

Verification

To verify the model, the parameters were modified to replicate the existing insertion system. The results from this modified model were then compared to measurements and are plotted in Figure 15.

The dots in Figure 15 are measured values of the temperature in the existing reactor. Measurements were taken at half-inch increments starting from the bottom of the reactor's horizontal part.

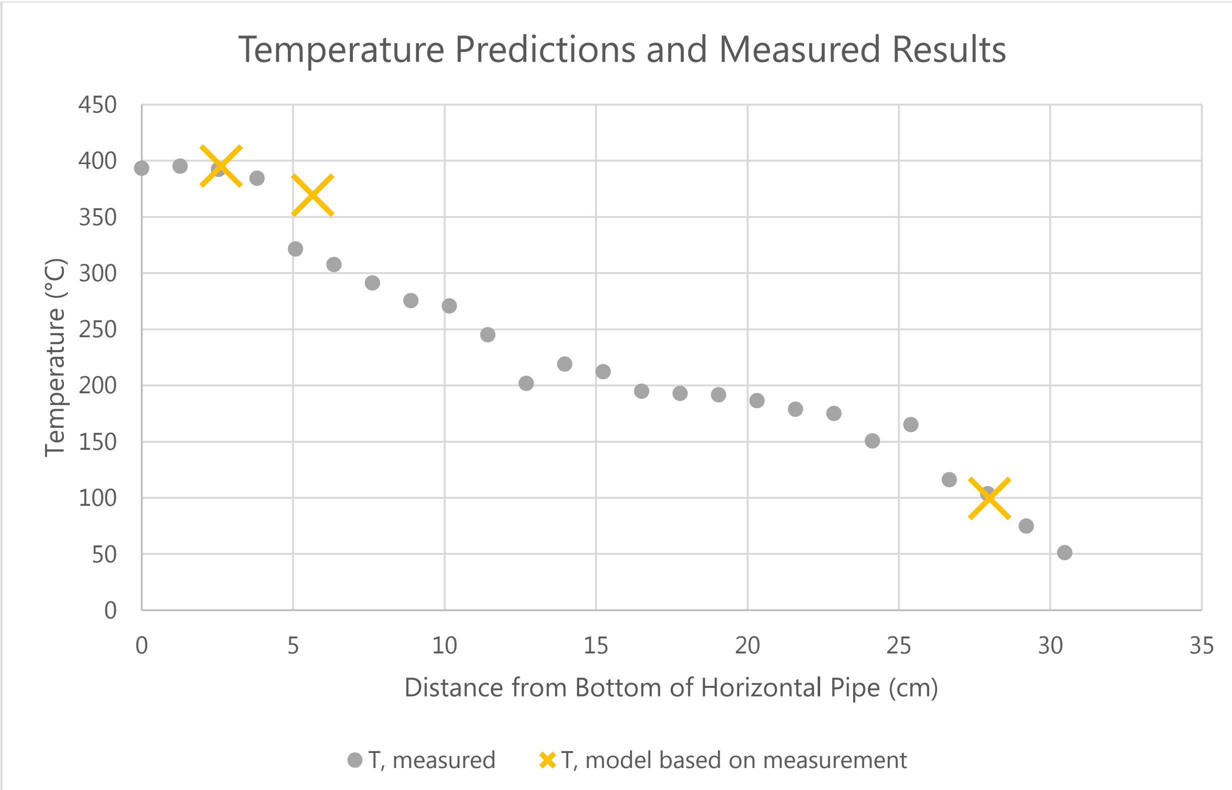

Figure 15: Comparison of measured and calculated temperatures in the existing insertion system

The X's in Figure 15 are the results predicted by the modified model. The leftmost X is $T_{reactor}$. The middle X is the calculated T_{mix} and is shown in its approximate location where the horizontal and vertical reactor sections come together. The rightmost X is T_{gas}, the calculated average temperature of the gas near the sample. $T_{reactor}$ was set to 395.2274 °C in order to match the observed reactor temperature. The height of the vertical section was set to 25.23 cm, so that the total height from the bottom of the horizontal section to the top of the vertical section was 12 inches (30.48 cm) as in the measurements. The wall thickness was changed from 5.08×10^{-4} m (0.02 in.) to 0.015 m.

In Figure 16, the parameters are again modified to match the conditions of the CFD simulation. The solid lines are two temperature profiles from a new post-processing of a previous ANSYS Fluent simulation. The curve that is mostly at a higher temperature is the profile along a vertical line just upstream of the sample, and the other curve is from a vertical line just downstream of the sample. The locations of these profiles are indicated on the temperature contours in Figure 17. The simulation assumes that there is a constant 300-kelvin device at the top, walls of constant 473 K, and a heat flux at the sample of -660 W/m^2. The simulation predicts that the change in temperature where the two sections come together should be much more sudden than what is observed.

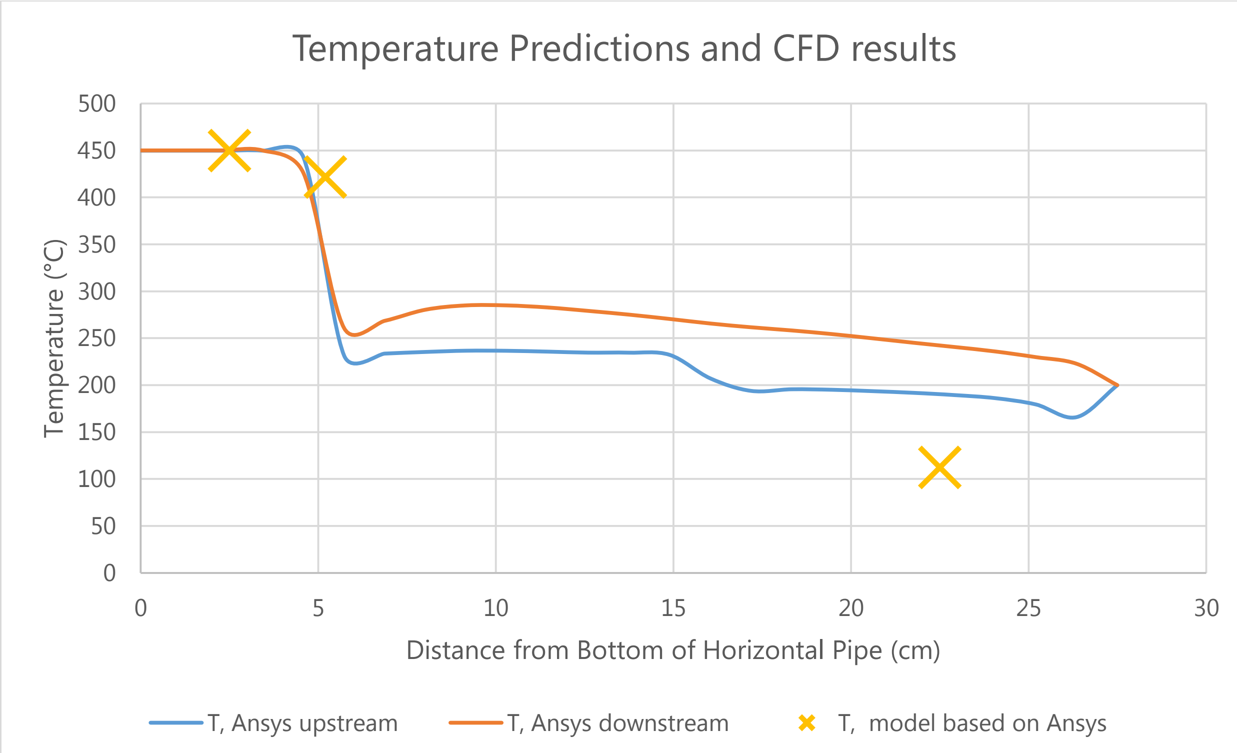

Figure 16: Comparison of simulated and calculated temperatures in the existing insertion system

The X's in Figure 16 are the $T_{reactor}$, T_{mix}, and T_{gas} from the model as modified to match the conditions of the CFD simulation. The diameters of both the horizontal and the vertical pipes were changed from 5.25 cm to 5 cm. $T_{reactor}$ was set to 723 K, and the height of the vertical section was set to 22.5 cm. The modeled T_{mix} agrees closely with the CFD result, although the T_{gas} in this model is significantly lower than the temperature from the CFD.

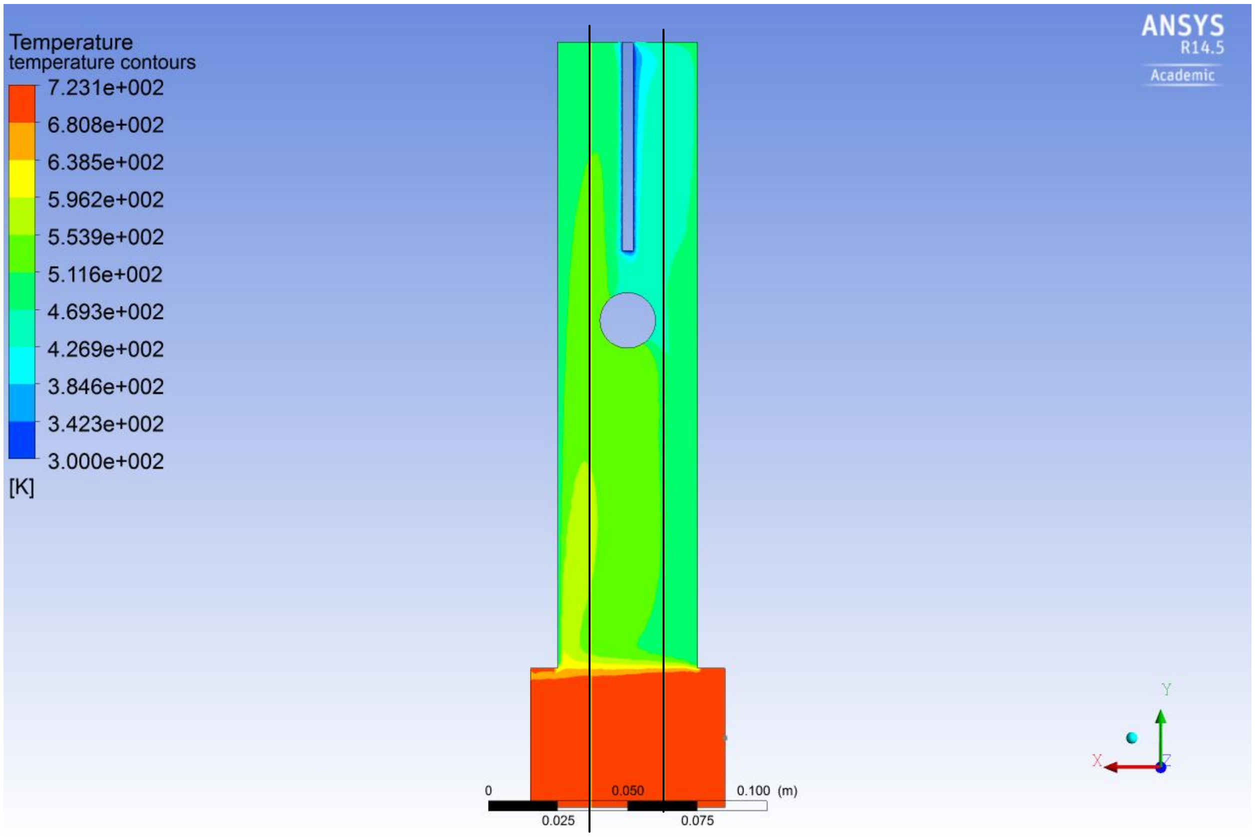

Figure 17: Temperature contours from CFD simulation of existing insertion system. The nitrogen flows in the positive x-direction.

The verification process shows that the described heat transfer model accurately predicts the observed temperature of the gas near the top of the existing reactor. Since this is the same basic shape as the proposed design concept, the same equations can be used for both designs. Only the input parameters of height, reactor temperature, wall thickness, and wall material need to be changed

Results

The model was solved using the original parameters to find the resistances and temperatures of the bellows design and of the combined bellows–piston design. These parameters are then modified to show the sensitivity of the model.

Resistances

The predicted resistances of the major branches are shown in Figure 18 for a side-arm height of 40 cm. R_2 would have a resistance of 9,502.1 K/W for this height and is not included in the bar chart. Among the parallel branches, most of the heat will go through the one with the least resistance. The least resistive branch is Branch 5, the radial branch, which is also the only one other than R_2 that depends on the height of the side-arm. As the height increases, the cross section of the conductive path (R_{52}) is larger and allows for easier conduction. There is also more surface area, which improves the convection (R_{51} and R_{53}). For shorter side-arm designs, such as 15 cm, the resistance along Branch 5 is 18.4 K/W, which is comparable to Branch 4.

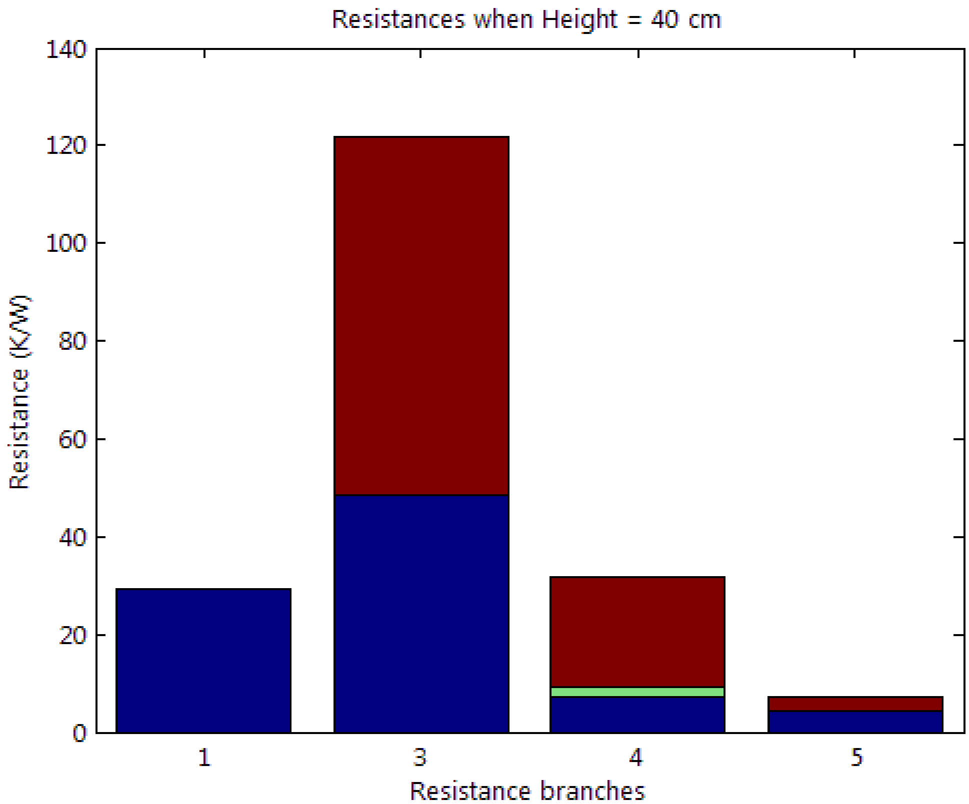

Figure 18: Resistances of the major branches

Figure 18 also shows the contribution of each thermal resistor to the total resistance of its branch. As each bar represents a series summation of resistances, the smallest resistance in each branch will have the smallest effect on the branch's total. The lower segments of columns 3, 4, and 5 show the convective resistances nearest the sample (R_{31}, R_{41}, and R_{51}). The top segments of these bars show the convection to the ambient (R_{33}, R_{43}, and R_{53}). In between these segments, invisible at this scale for all but Branch 4, are the conductive resistances (R_{32}, R_{42}, and R_{52}). This suggests that changing the material of the rod, lid, or bellows hose is unlikely to have a significant influence on the system.

Temperatures

The thermal resistance model of the bellows insertion system was solved in MATLAB to produce plots of the various temperatures as a function of the height of the extended side-arm. Figure 19 shows how this height affects the temperature of the mixture region, of the outer surface of the rod, and of the gas near the sample. The model predicts that increasing the distance of the vertical part to 30.7 cm will meet the requirement of keeping the gas near the sample below 105 °C. The surface of the rod that is outside of the bellows would have a temperature of 82.39 °C. This could cause safety concerns, and it would be recommended to wear gloves when carrying out the experiment. The following equations show how to determine the temperature at the top of the rod:

$$\dot{Q}_4 = \frac{\dot{Q}\,R_{eff}}{R_4} \tag{16}$$

$$T_{rodtop} = \dot{Q}_4\,R_{43} + T_\infty \tag{17}$$

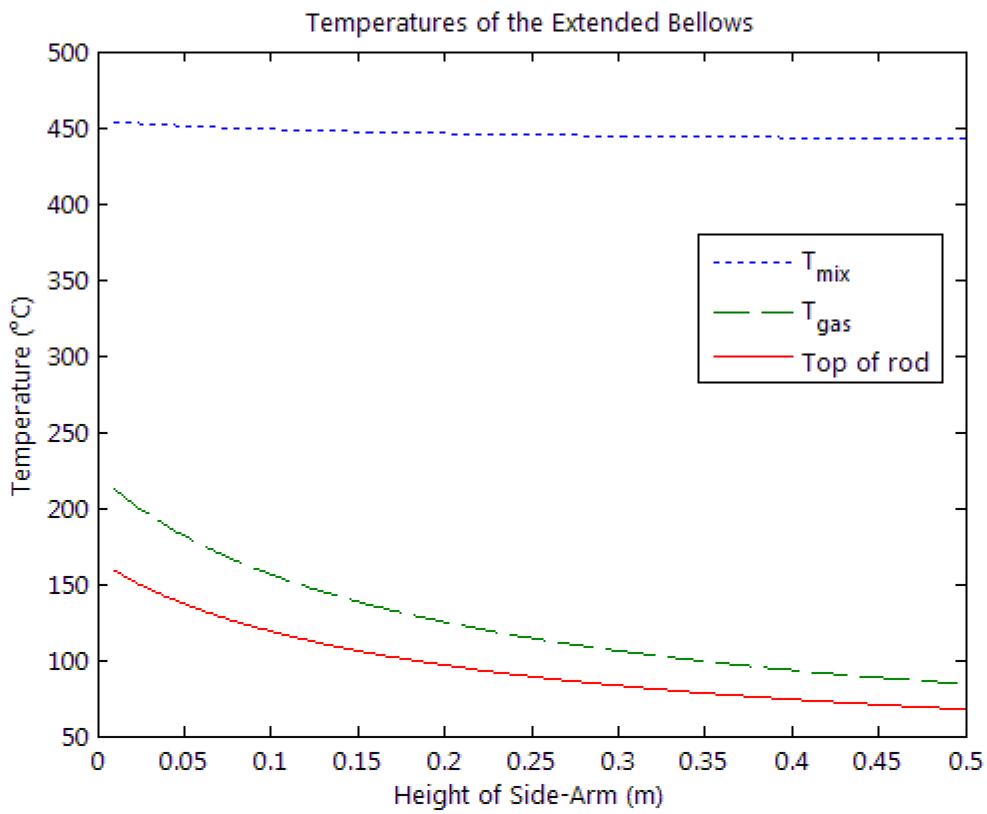

Figure 19: Temperatures at three locations on the bellows insertion system

Figure 20 shows the temperature of the gas near the sample for the combined system described in "Refining the Design". The side-arm height was set to 40 cm. The temperatures here are a function of the material and the thickness of the insulation at the bottom of the piston. The materials considered are glass[16] (k = 0.8 W/[m K]), steel[17]

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[16] Nave, C. R. (n.d.) "Thermal Conductivity". *HyperPhysics*. http://hyperphysics.phy-astr.gsu.edu/hbase/tables/thrcn.html . Retrieved on November 21, 2013.

[17] Wolfram Alpha LLC (2013). Wolfram Alpha. http://www.wolframalpha.com/input/?i=steel+thermal+conductivity . Retrieved November 7, 2013.

(*k* = 46.6 W/[m K]), and aluminum (*k* = 235 W/[m K]). If the piston is made of glass, then the temperature of the gas near the sample is strongly dependent on the glass's thickness. If metals are used, then changing their thickness does not significantly alter the temperatures near the sample, although all of these thicknesses satisfy the requirement of 105 °C.

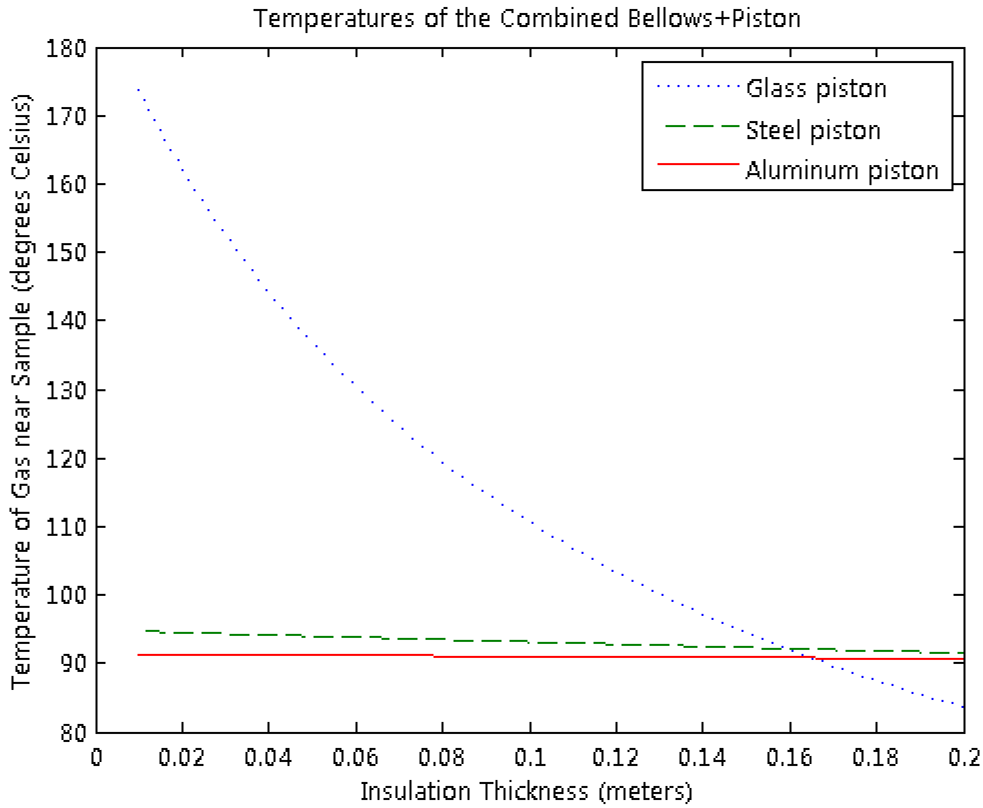

Figure 20: Combined bellows and piston system with three materials

In Figure 21 the temperatures at three locations of the combined system are shown. This is using steel for the insulation and the height of the side-arm is 40 cm. None of these temperatures are strongly dependent on the thickness of the steel. The requirement for the temperature near the gas is satisfied for all of these thicknesses. The temperature on the surface of the rod is approximately the same as it is in the model for the bellows alone.

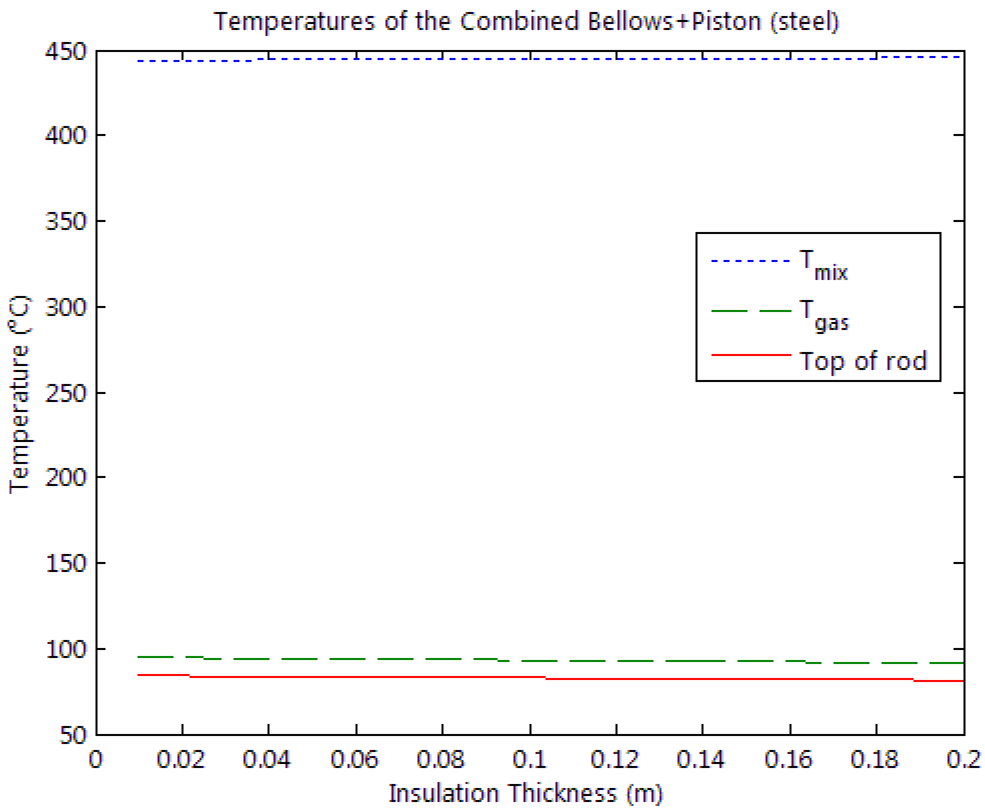

Figure 21: Temperatures at three locations of the combined insertion system

Although there is not a significant difference in this temperature between the two designs, it is likely that the piston could help maintain a uniform and unidirectional flow near the sample. Both the bellows alone and the combination of the bellows with the piston satisfy the requirement of keeping the gas near the sample below 105 °C. While the holder is in the side-arm before the experiment, enclosing the sample within the piston's chamber could help to reduce the temperature gradients in this region. During the experiment, this full enclosure could help to maintain unidirectional flow by not allowing gas from the reactor to escape into the side-arm.

Sensitivities

After obtaining these results, a sensitivity analysis was completed by varying several of the parameters, one at a time. Table 2 shows the results from this analysis.

Table 2: Sensitivity Analysis

Conditions	Predicted T_{gas} (°C)
Extended bellows, 40 cm length (the original model)	93.3201
k of bellows changed from 1 to 1000 W/(m K)	93.2729
k of bellows changed from 1 to 0.01 W/(m K)	97.8393
ΔT in Rayleigh numbers of air and nitrogen changed from 50 K to 5K	115.4587
ΔT in Rayleigh numbers of air and nitrogen changed from 50 K to 100K	88.2097
Mass flow rate changed from 3.42×10^{-4} to 3.42×10^{-3} kg/s	92.6787
Mass flow rate changed from 3.42×10^{-4} to 3.42×10^{-5} kg/s	63.3980
Bellows diameter changed from 5.25 to 10.5 cm	106.7506
Bellows diameter changed from 5.25 to 3 cm	74.5665
Specific heat of nitrogen changed from 1040 to 800 J/(kg K)	86.8519
Specific heat of nitrogen changed from 1040 to 1200 J/(kg K)	88.8331

Each row of Table 2 differs from the described model by only one parameter. As predicted from the Figure 18, changing things related to conduction do not have a significant effect. The convection-related parameters can change the predicted T_{gas} by tens of degrees Celsius.

Design

Figure 22 shows the proposed design in its pre-experiment configuration, and Figure 23 shows the hose compressed as it will be during the experiment. The existing side-arm is to be extended vertically using the Extreme-Temperature Duct Hose for Fumes from McMaster-Carr, shown at the left of Figure 24. This hose is designed to withstand temperatures from -200 to 1000 °F (-128.89 to 537.78 °C). It costs $55.21 per foot for a four-inch inner diameter. It compresses 75% of its length. The total height from the top of the horizontal flow reactor to the top of the vertical side-arm should be no less than 40 cm.

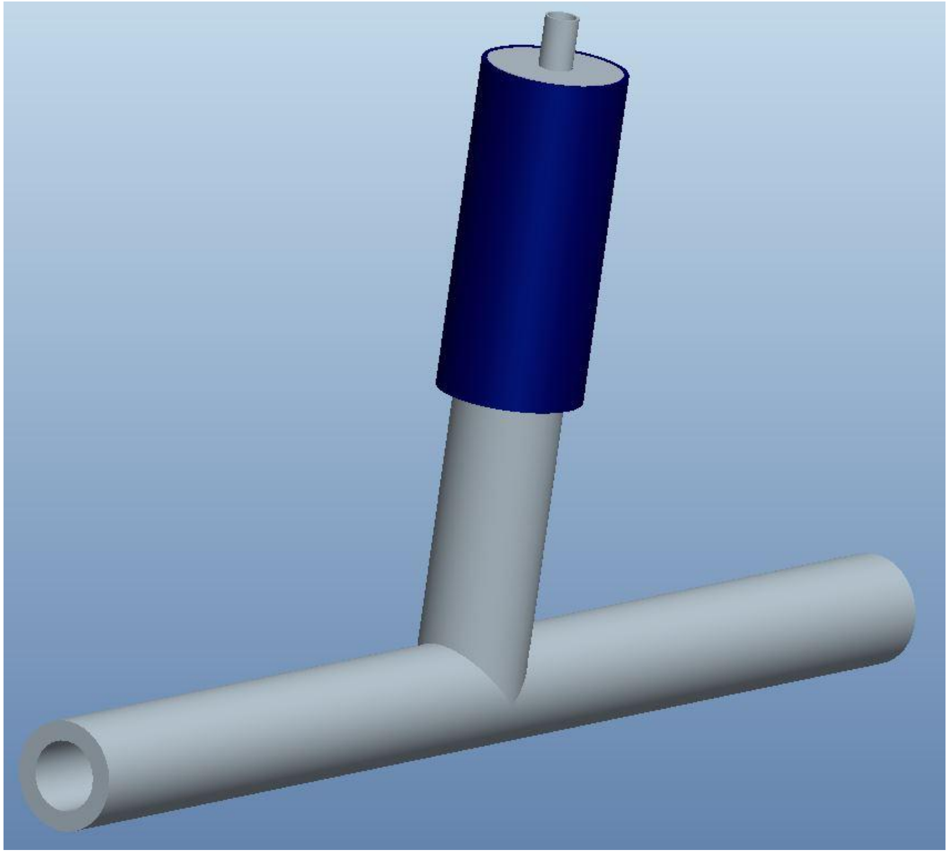

Figure 22: The 25 cm bellows attached to the 20 cm side-arm

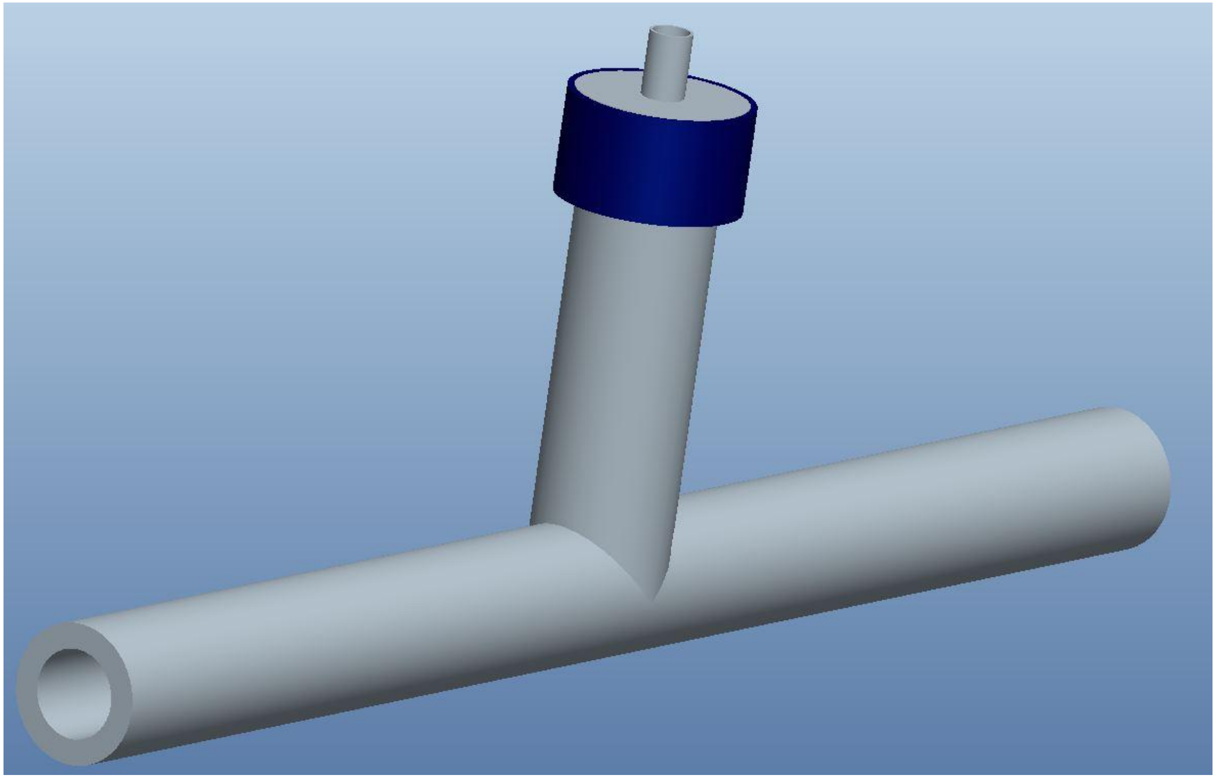

Figure 23: The bellows compressed to 6.25 cm.

Because the duct hose is only available with inner diameters that are whole numbers of inches, the flow reactor's side-arm will need to be modified slightly with a disk-shaped adapter. The inner diameter of this disk will be rigidly attached to the side-arm. The outer diameter will fit inside the 4-inch hose.

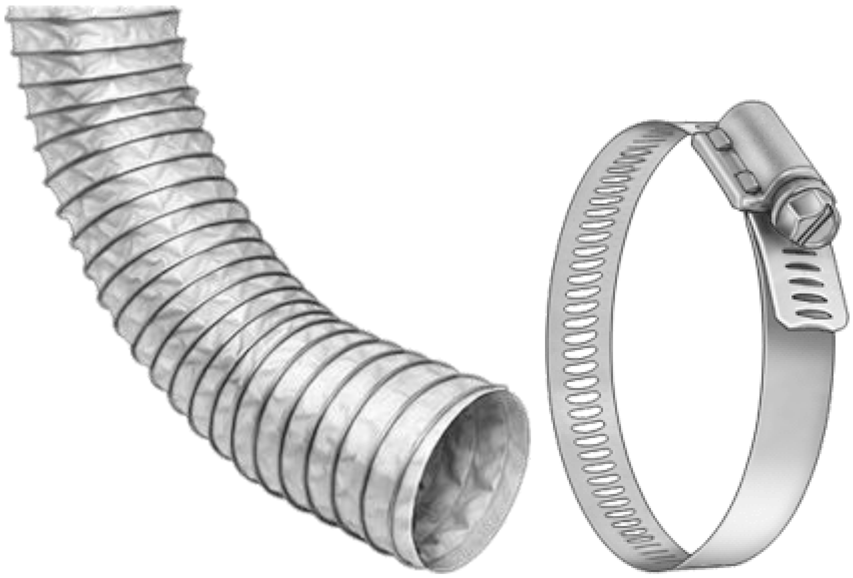

Figure 24: The bellows hose (left) and hose clamp (right). Image source: McMaster-Carr. http://www.mcmaster.com/#45825k71/ and http://www.mcmaster.com/#5415k42/

The lid or flange plate of the current particle holder will be replaced with a larger disk. The current part has an inner diameter of 1.0080 inches and an outer diameter of 3.7335 inches. The outer diameter will need to be increased to 4 inches in order to form a seal with the duct hose.

Each end of the hose is to be attached to a disk-shaped adapter using reusable hose-clamps like the one at the right of Figure 24. A Worm-Drive Hose Clamp with Zinc-Plated Steel Screw is available from the same supplier for $11.05 for a pack of ten clamps.[18]

The existing particle holder can be used with this improved design. The current holder is capable of blowing cool nitrogen on the sample, but this will not be necessary if this design is implemented.

Either of the concepts described under "Results" (extending the side-arm or both extending the side-arm and adding a pipe around the sample) will meet the main thermal requirements. Further analysis is necessary in order to conclude that fully enclosing the sample as in the combined system will help to maintain uniform flow.

[18] "Worm-Drive Hose Clamp with Zinc-Plated Steel Screw". McMaster-Carr. http://www.mcmaster.com/#5415k42/

Relation to Design Goals

The described design is likely to satisfy the requirements set forth in "Design Problem." The part of the system that holds the biomass particle is not affected, so it will still be able to hold the sample and the thermocouples. The analysis has shown that a system using these specifications will keep the temperature of the biomass below 105 °C before the experiment begins. Unidirectional flow is likely to be improved by the combined bellows–piston design, but further analysis is needed to be sure of this. The piston will help with repeatable positioning, and the modifications will be inexpensive. The experimental method is also simplified and should be able to be accomplished by a single person.

Future Work

Although the approach described in this report has been shown to match the measured values, the accuracy of the model could be improved. The Rayleigh and Grashof numbers both contain a term related to the temperature difference. This difference had to be estimated, as finding the temperatures was the primary goal of the model. An improved method could include an iterative process. The temperatures given in this report could be used as a first estimate and plugged back in to the Rayleigh and Grashof numbers, which would yield slightly different results. This could be repeated until the final temperature estimates do not change significantly.

Future improvements to the design could include allowing visual observation of the experiments and making it easier to replace the thermocouples. Researchers have noticed that the samples occasionally split during the experiments. The researchers would like to be able to see inside the reactor so that they can tell when these splits occur. Replacing the thermocouples has been described as a difficult and time-consuming process because of the need to push the wires through the long tube.

This report focused on a thermal analysis of the design, and further work could include a fluid mechanic analysis. This could provide insight about the flow profile near the sample and how unidirectional or uniform it is.