FUNDAMENTAL STUDIES
OF THE
CATALYTIC IGNITION PROCESS

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This project supported development of catalytic igniters for environmentally friendly alternative fuels such as aqueous ethanol. This report describes the installation, calibration and preliminary testing of a catalytic plug-flow reactor after the new laboratory's electrical and plumbing upgrades were completed. The reactor was moved from Moscow, Idaho, to the new laboratories in Boise, Idaho. We calibrated a hot wire anemometer, used the anemometer to remeasure the plug-flow region of the reactor, and began testing and modeling of a platinum (Pt) wire catalyst exposed to a lean propane-oxygen-nitrogen mixtures. The methods used for the ALGOR modeling yield fairly accurate results. It is interesting to see the model slightly over predict temperature at lower flow and slightly under predict temperature at higher flow. The maximum difference between the results is less than 12 degrees, which gives them an accuracy rate within 2.6 percent.</td></tr>
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INTRODUCTION

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CONSTRUCTION OF A HOT-WIRE ANEMOMETER CALIBRATION APPARATUS

A hot-wire anemometer is an instrument capable of reflecting small changes in voltage. From these voltage readings the velocity can be determined. However, prior to using a hot-wire anemometer it is necessary to establish a base line value of voltage vs. velocity. Thus for a given voltage the velocity is known.

Figure 1 Hot-wire calibration apparatus

Procedure

To do this, it was necessary to construct a device with a known pressure and velocity. As can be seen in Figure 1, a two-liter bottle was used with a nozzle attached to the top with a precise shape and known exit diameter. Straws were inserted into the pop bottle to straighten the flow ensuring that the flow was laminar and the velocity constant for a given pressure. The nozzle was designed in SolidWorks and built at the University of Idaho in Moscow specifically for this application. The nozzle functions as a flow conditioner. It increases the flow velocity so that the hot-wire anemometer can detect changes in the velocity or voltage and it smoothes the flow to allow for an even more constant velocity profile for calibration. From Figure 2 you can see the smoothing shape of the nozzle as designed in SolidWorks and the actual part. The port on the side of the nozzle is where the hot-wire probe will be inserted and the diameter at that point is known. It is the diameter of the spout of the pop bottle.

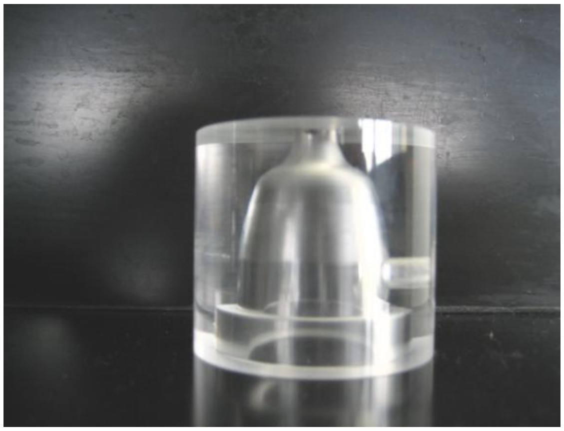

Figure 2 Nozzle as created in SolidWorks on the left and the actual part on the right

Compressed air was used to calibrate the hot-wire anemometer. However, prior to running the compressed air through the nozzle it was necessary to clean the air. Figure 1 shows two filters. The first is an air filter that purifies the compressed air down to 5-microns and the second is a coalescing filter that eliminates oil from the air to 0.5-microns. Prior to the air filter is a needle valve for more precise control over the flow of air.

Because the nozzle was designed with a known exit diameter the velocity of the air for a given pressure could be determined from the Bernoulli and the continuity equations. By taking a point at the air entrance and the air exit where diameters are known and the pressure difference can be measured by a manometer, the velocities can be calculated. Given the Bernoulli equation

$$\upsilon(P_2 - P_1) + \frac{(V_2^2 - V_1^2)}{2} + g(z_2 - z_1) = 0 \tag{1}$$

and the continuity equation

$$
\begin{gathered}
Q_1 = Q_2 \\
or \\
\rho_1 A_1 V_1 = \rho_2 A_2 V_2
\end{gathered}
\tag{2}
$$

There are two equations and two unknowns. The two unknowns are V_1 and V_2, which can easily be solved. From this pressure vs. velocity information you can obtain a direct correlation between the velocity and the voltage of the hot-wire anemometer. For a given voltage the velocity is known as a function of pressure. This is described in further detail in the next section on calibrating the hot-wire anemometer.

HOT-WIRE ANEMOMETER CALIBRATION

A hot-wire anemometer uses wire resistance data to display a voltage output. A 0.5-micron diameter tungsten wire was used for this calibration. At room temperature the resistance of the wire is known. The anemometer then heats the wire to a predetermined temperature, which corresponds to the value set on the anemometer resistance decades, at which temperature the resistance can be calculated. The anemometer then controls any fluctuation in the temperature of the wire such that a corresponding change in voltage is displayed to keep the temperature of the wire constant.

Figure 3 Anemometer settings

Procedure

Calibration of the wire and anemometer is essentially as follows:

1.
2. Set-up anemometer with the settings as shown in Figure 3, ensuring that the probe resistance decades are set to ≈ 12Ω. Signal Conditioner decades are not important for this test.
3. Turn on power to the anemometer and connect a voltage meter to the 'bridge output' connector on the anemometer and allow ≈ 1 hour for warm-up.
4. Set-up manometer, ensuring that it is level and has sufficient fluid. Hook up the manometer rubber tubing as shown in Figure 4 to the left port on the manometer and the other end to the pop bottle tube fitting.
5. Secure the hot-wire probe in a ring stand and insert the other end through the fitting on the nozzle as shown in Figure 4. Once the probe is in position, turn the white knob on the probe to release it and extend the wire into the nozzle flow such that it is in the center of the flow and the wire is horizontal.

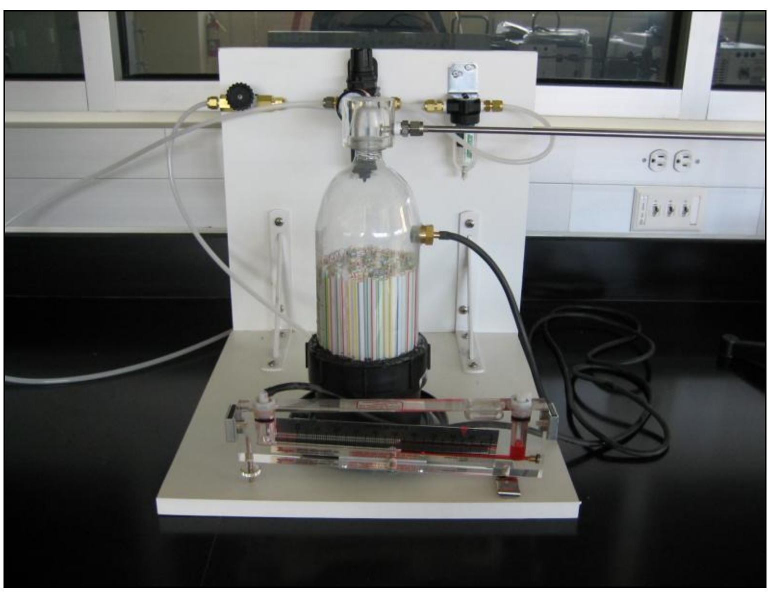

Figure 4 Hot-wire anemometer calibration test stand

6. Hook up the cable to the probe and the other end to the 'probe' connector on the anemometer.

7. Close the needle valve on the test stand and turn the compressed air on.
8. Set the air regulator on the air filter to ≈ 10psi.
9. Turn the anemometer on 'run' and record the voltage at zero pressure.
10. Randomly adjust the needle valve to change the pressure (careful not to increase the pressure beyond the manometer range, creating air bubbles in the fluid which will give inaccurate pressure readings) and record ≈ 15 voltage/pressure data points.

Now that this is done the correlation between pressure, voltage, and velocity can be made with Bernoulli, continuity, and the experimental pressure vs. voltage data to create a curve of velocity vs. voltage as seen in Figure 5.

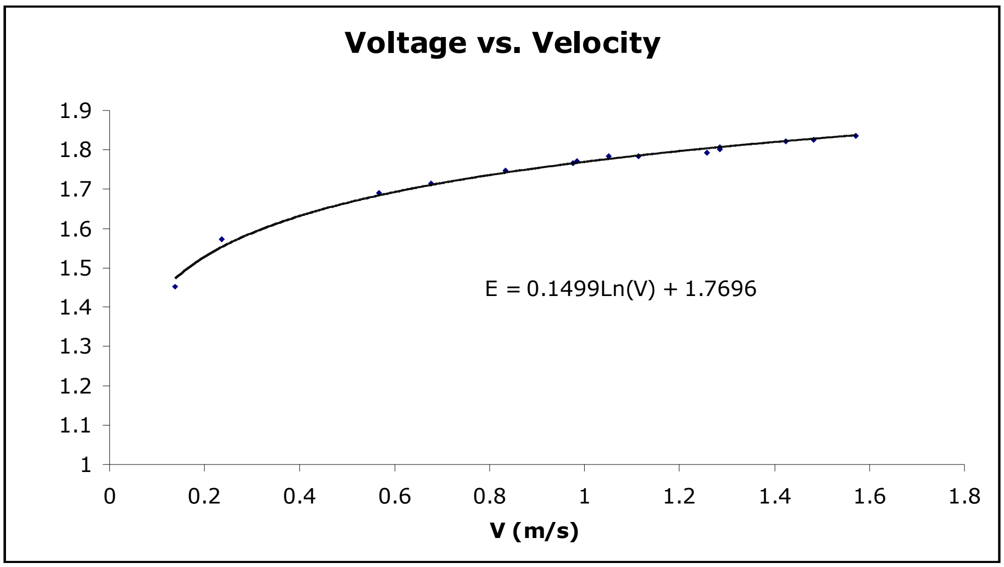

Figure 5 Voltage vs. Velocity

However, here voltage data is approximately a function of the natural log of velocity or velocity would be a function of the exponential of voltage. It would be more accurate to obtain a straight-line approximation for velocity as a function of voltage. To determine the velocity of the air as a function of hot-wire voltage it is necessary to calibrate the wire. This is done by application of King's Law analyzing the heat-transfer rate from the wire, which simplifies to

$$E^2 = A + BV^n \tag{3}$$

where A & B are the calibration constants and n is a variable that can be set to decrease uncertainty in calibration, initially set to 0.5, with a value of 0.38 found to give the lowest standard error. Using the data collected in Figure 5 a plot as in Figure 6 can be obtained and the constants A & B determined.

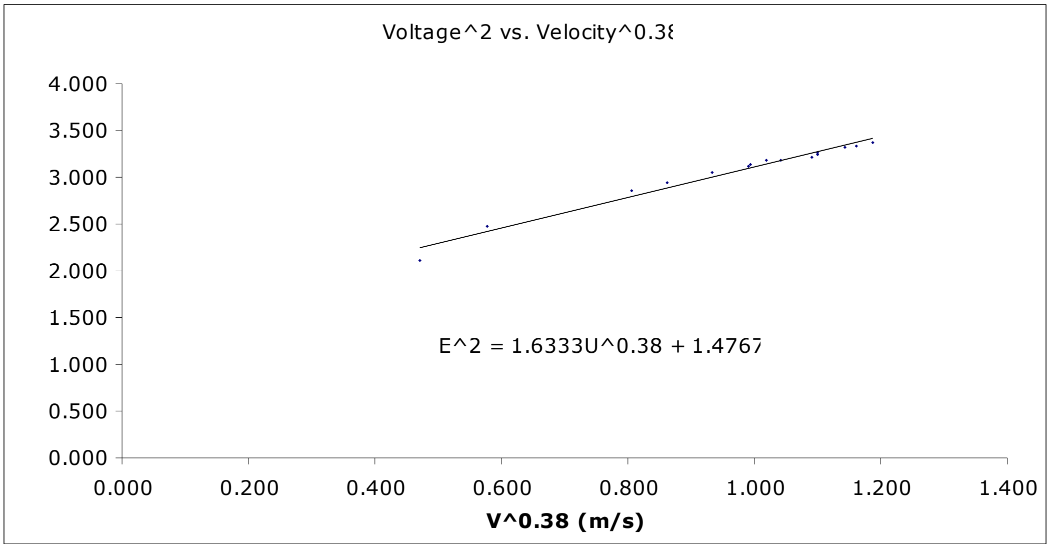

Figure 6 Voltage vs. Velocity calibration data

It is also necessary to calculate the uncertainty in this calibration data by the definition of the standard error, SE

$$SE = \sqrt{\frac{1}{n-2}\sum_i r_i^2} \tag{4}$$

where n is varied to minimize the standard error and r_i is the horizontal residual or horizontal distance from point i to the trend-line found in Figure 5.

USING THE HOT-WIRE ANEMOMETER TO DETERMINE THE PLUG-FLOW REGION IN THE REACTOR

The hot-wire probe is now calibrated and a velocity vs. voltage function curve generated for use in the reactor. The next step is to use the hot-wire anemometer in the reactor and record voltage readings for various flow conditions to determine where a constant velocity profile is obtained. This region of constant velocity is the plug-flow region for the reactor.

Procedure

The apparatus was setup as in Figure 7 so that data points were taken in 2mm increments radially and in numbers of diameters axially from the beginning to the end of the quartz reactor tube in increments of 1. At each location the voltage data was recorded from the oscilloscope and then plotted against velocity. Since the quartz tube is open to the atmosphere, the pressure is constant and was recorded for each experiment for use in the calculations.

Figure 7 Setup for plug-flow testing with hot-wire anemometer

It can be seen from Figure 8 that at approximately three diameters downstream the velocity is constant and continues to be constant to the end of the tube. These tests were performed for higher and lower flow regimes, through a range of Reynolds numbers between (150-2500), and it was determined that the same region of the quartz tube reactor achieved plug-flow conditions under these regimes.

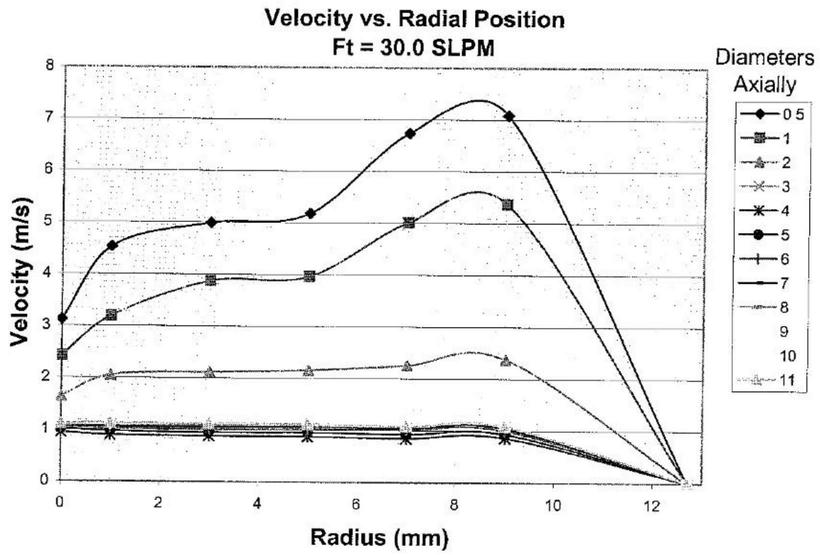

Figure 8 Velocity vs. Position in the quartz tube

HEAT TRANSFER MODELING IN ALGOR OF A PLATINUM WIRE CATALYST.

The objective of modeling the platinum catalyst wire was to generate surface temperature results that were comparable to the data obtained through experimentation. By using the ALGOR modeling program the average surface temperature that is expected from heat transfer through conduction, convection and radiation could be found. This temperature could then be compared to the temperature expected from the recorded resistance of the wire and the temperature coefficient of resistance equation.

Procedure

The approach to complete this modeling was to start by gathering data, and then use the ALGOR program to model the results with the same initial parameters. Figure 9 shows the equipment setup used to obtain the resistance of the wire while changing variables such as air flow rate over the wire and power to the wire.

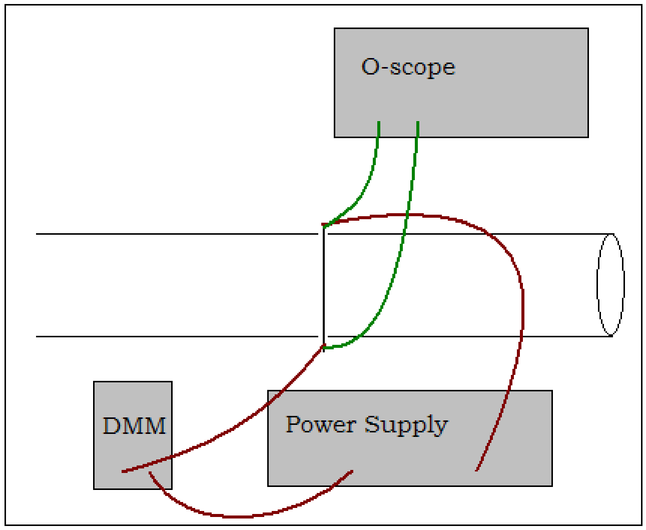

Figure 9: Setup for Recording Wire Resistance

By recording the voltage reading across the wire from the oscilloscope and the current reading from the digital multi-meter, it was possible to find the resistance using Ohm's Law. The surface temperature can be found from these resistances using Equation 5,

$$R = Ro\left[1 + \alpha\left(T - To\right)\right] \tag{5}$$

where α is the temperature coefficient of resistance which is 0.00385 for platinum, and Ro and To were 0.023 and 22°C respectively.

During the experiments it is also important to record the total flow that is going through the reactor, this way the convection coefficient over the wire can be found. By knowing the total flow, the velocity can be obtained from a previous calibration. Then the convection coefficient (h) was found using the Gosse equation from Harnett [1975]. Figure 10 shows a screenshot from the MathCad program used to find h for each Reynolds number that was obtained experimentally. Once h is known, the convection heat loss can be added to certain surfaces in ALGOR after the radiation is input. An emissivity of 0.9 was used on all surfaces of the wire for the modeling. An applied temperature of 22°C was also added to the end surfaces of the wire. To complete the modeling, platinum must be chosen as the material, and then the heat generation must be added to the part. To determine the heat generation, the voltage and current must be multiplied to get power which must then be divided by the volume of the wire. The screen shots from the ALGOR process can be seen in Appendix A.

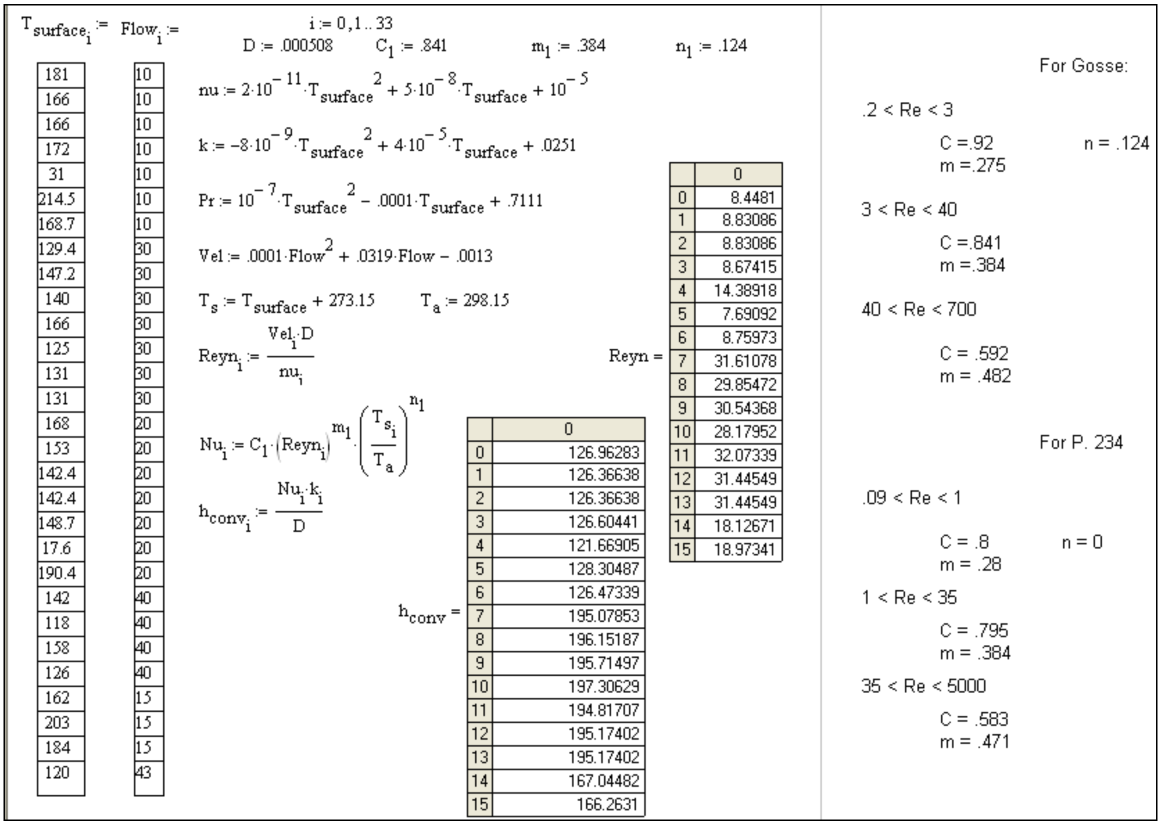

Figure 10: MathCad Program Used to Find Convection Coefficient, h

Results

The flow, current and voltage that were recorded from the experiments can be seen in Table 1. The velocity, resistance, power, surface temperature, and heat generations were all calculated using the equations mentioned above, and these values can also be seen in Table 1. A temperature vs. power and flow plot of this data can be seen in Figure 11. ALGOR modeling was done using these same velocity and heat generation values. These results can be seen in Table 2 along with the differences in temperature between the experimental values and the ALGOR results. Lastly, Figure 12 shows the ALGOR results as well as the experimental values; some of the points from experimental values cannot be seen due to the ALGOR points being directly on top of them.

Table 1: Experimental Results

Flow Total (SLPM)	Velocity Out (m/s)	Current (amps)	Voltage (V)	Resistance (Ω)	Power (W)	Temp from resistance (C)	Heat Generation (erg/mm^3-s)
10	0.3277	8.43	0.314	0.037247924	2.6470	180.90259	3264975.49
10	0.3277	7.94	0.2853	0.03593199	2.2652	166.04167	2794119.504
10	0.3277	8.01	0.2879	0.035942572	2.3060	166.16117	2844440.697
10	0.3277	8.17	0.298	0.036474908	2.4346	172.17288	3003039.353
10	0.3277	0.56	0.01345	0.024017857	0.0075	31.494716	9290.370074
10	0.3277	8.85	0.356	0.040225989	3.1506	214.53403	3886117.891
10	0.3277	8.1	0.293	0.03617284	2.3733	168.7616	2927354.66
30	1.0457	8.25	0.2697	0.032690909	2.2250	129.43997	2744464.375
30	1.0457	8.65	0.2964	0.034265896	2.5638	147.22638	3162401.516
30	1.0457	8.57	0.288	0.033605601	2.4681	139.76963	3044360.037
30	1.0457	9.12	0.3276	0.035921053	2.9877	165.91816	3685203.154
30	1.0457	8.15	0.2632	0.032294479	2.1450	124.96306	2645855.953
30	1.0457	8.05	0.2642	0.032819876	2.1268	130.89639	2623320.762
30	1.0457	8.3	0.2731	0.032903614	2.2667	131.84206	2795905.544
20	0.6767	8.7	0.3141	0.036103448	2.7326	167.97796	3370620.763
20	0.6767	8.52	0.2962	0.034765258	2.5236	152.86571	3112772.29
20	0.6767	8.02	0.2714	0.033840399	2.1766	142.42122	2684768.937
20	0.6767	8.08	0.2734	0.033836634	2.2090	142.3787	2724787.095
20	0.6767	8.27	0.2845	0.034401451	2.3528	148.75721	2902087.369
20	0.6767	0.56	0.01276	0.022785714	0.0071	17.58006	8813.763728
20	0.6767	9.13	0.3478	0.038094195	3.1754	190.45957	3916724.801
40	1.4347	8.88	0.2999	0.033772523	2.6631	141.65469	3284824.22
40	1.4347	8.16	0.2588	0.031715686	2.1118	118.42672	2604816.496
40	1.4347	9.33	0.3284	0.035198285	3.0639	157.7559	3779266.301
40	1.4347	8.45	0.2737	0.032390533	2.3127	126.0478	2852687.566
15	0.4997	8.3	0.2955	0.03560241	2.4526	162.3197	3025229.177
15	0.4997	9.09	0.3562	0.039185919	3.2378	202.78847	3993746.557
15	0.4997	8.69	0.3261	0.037525892	2.8338	184.04169	3495370.994

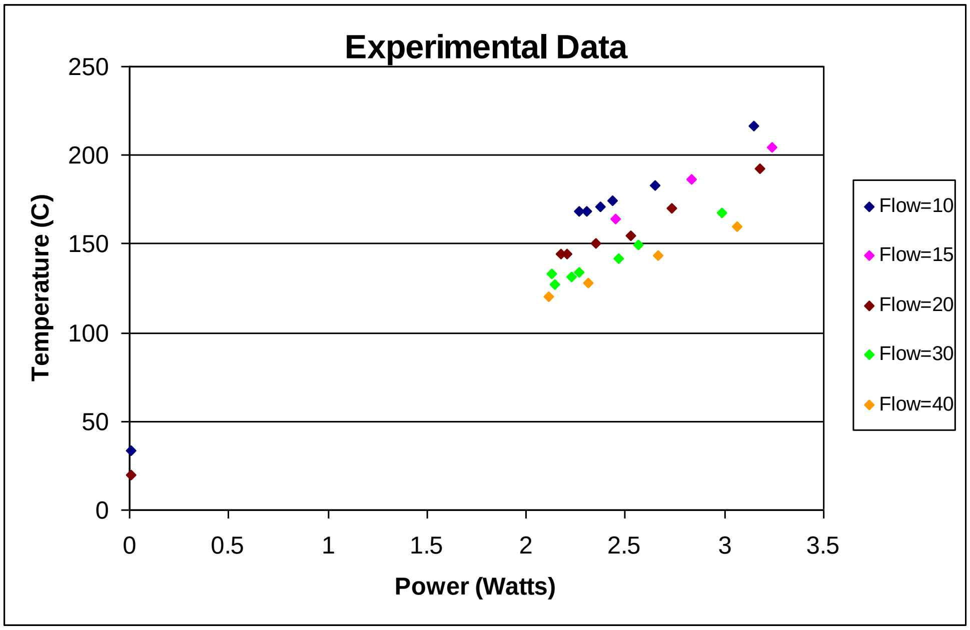

Figure 11: Temperature from Experimental Resistances

Table 2: ALGOR Results

Power (W)	Temp from resist (C)	ALGOR Temp. (C)	Difference in Temp.	Power (W)	Temp from resist (C)	ALGOR Temp. (C)	Difference in Temp.
2.64702	182.9025	194.6	11.697413	2.73267	169.978	168.7	-1.27796
2.265282	168.0416	170.3	2.2583295	2.52362	154.8657	158	3.134295
2.306079	168.1611	173	4.8388279	2.17662	144.4212	139.7	-4.72122
2.43466	174.1728	181.1	6.9271237	2.20907	144.3787	141.4	-2.9787
0.007532	33.49471	22.5	-10.99472	2.35281	150.7572	149	-1.75721
3.1506	216.5340	221	4.4659661	0.00714	19.58006	22.4	2.81994
2.3733	170.7616	177.2	6.438402	3.17541	192.4596	191.5	-0.95957
2.225025	131.4399	128.7	-2.739967	2.66311	143.6547	138.1	-5.55469
2.56386	149.2263	144.3	-4.92638	2.11180	120.4267	114.6	-5.82672
2.46816	141.7696	140	-1.769632	3.06397	159.7559	154.9	-4.8559
2.987712	167.9181	163.8	-4.118155	2.31276	128.0478	123.3	-4.7478
2.14508	126.9630	125	-1.963055	2.45265	164.3197	165.5	1.180298
2.12681	132.8963	123.9	-8.996395	3.23785	204.7885	209.4	4.611535
2.26673	133.8420	130.6	-3.242061	2.83380	186.0417	186.8	0.758308

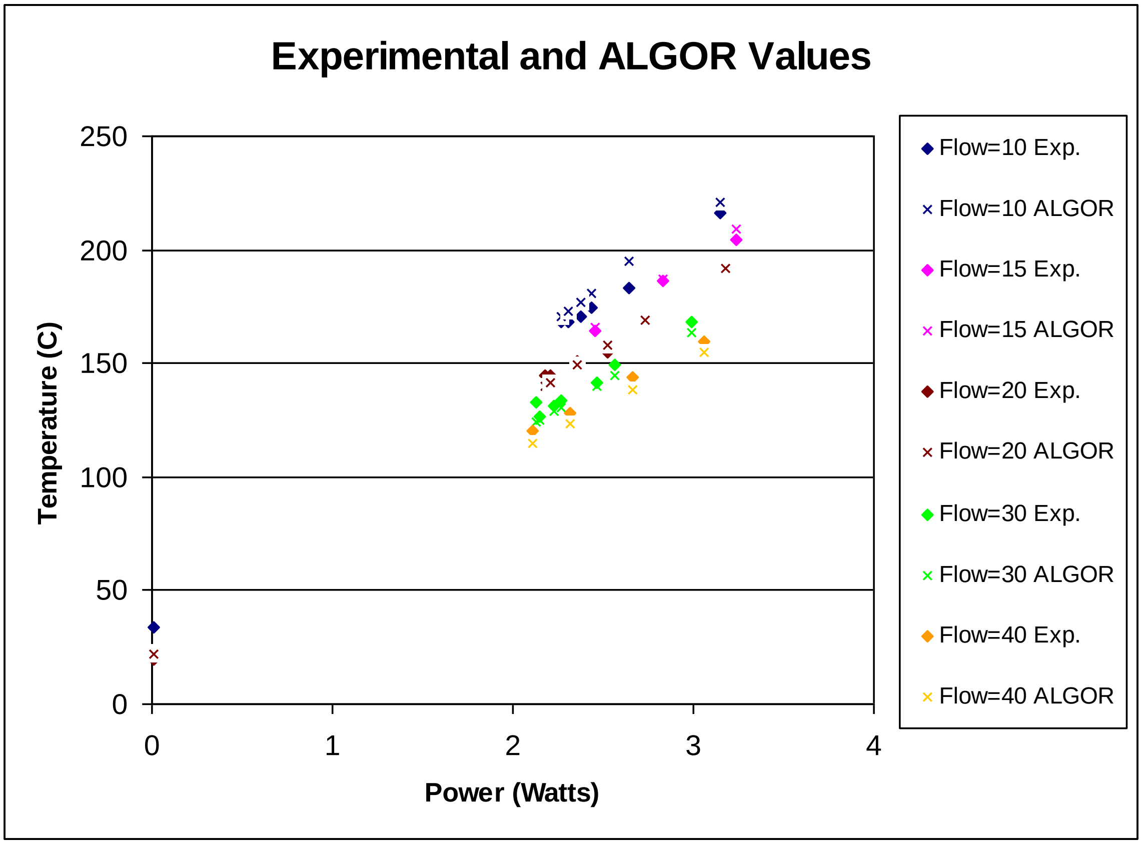

Figure 12: Plot of Experimental and ALGOR Results

CONCLUSIONS

It can be seen from Table 2 and Figure 12 that the methods used for the ALGOR modeling yield fairly accurate results. It is interesting to see the model slightly over predict temperature at lower flow and slightly under predict temperature at higher flow. The maximum difference between the results is less than 12 degrees, which gives them an accuracy rate within 2.6 percent. However, there are some obvious improvements that could be made to this data.

One suggestion for future experiments would be to get more accurate and precise equipment. Due to the power supply, the data taken experimentally was limited to below 0.5 watts. If the power supply had more precise displays, the digital multi-meter would not be needed, and depending on the cables used, it might also be possible to eliminate the oscilloscope from the system. Another limitation was the flow going through the reactor. During these experiments, the air was coming from the in-house compressor, so 40 SLPM was near the maximum that could be achieved. With the flow coming from compressed gas tanks, it should be possible to reach 100 SLPM.

REFERENCE

Hartnett, J. P. “The Overall Convective Heat Transfer from Smooth Circular Cylinders,” *Advances in Heat Transfer* Vol. 11 (1975): 222-223.