Development of FrED Run Condition Models.

Regression analysis of FrED run condition data to develop operational models for process optimization.

Uses auto porcessed run condition data - "Run Condition Data Summary.csv"

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In [1]:
```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from sklearn.linear_model import LinearRegression
from sklearn.svm import SVR
from sklearn.preprocessing import PolynomialFeatures
from sklearn.preprocessing import StandardScaler
from sklearn.pipeline import Pipeline
import seaborn as sn
from mpl_toolkits.mplot3d import Axes3D
import pickle
```

In [2]:
```
# load run condition data into dataframe
# current file - 050820 11:06pm
path_local = 'C:/Users/cuiff/Dropbox/Python Common Library/python-fred/data/Reports/'
data = pd.read_csv(path_local + 'Run Condition Data Summary.csv')
data.head()
```

Out[2]:

	Run File	Feed Rate Ave (RPS)	Spool Wind Rate Set (RPS)	Spool Rate Ave (RPS)	Wind BF Rate Ave (PPS)	Heater Set (C)	Heater Temp Ave (C)	Filament Diamter Ave (mm)	Filament Std Dev (mm)	System Power Ave (W)	System Power Std Dev (W)	Cu
0	log_Manual Control__2020-04-12_12-13-50.csv	0.001000	1.00	1.000132	127.730719	90.0	90.009313	0.213487	0.016746	29.041052	1.000198	17
1	log_Manual Control__2020-04-12_17-26-48.csv	0.000312	0.25	0.250982	20.426288	90.0	90.068162	0.228383	0.044286	30.064674	1.123981	19
2	log_Manual Control__2020-04-12_17-26-48.csv	0.000312	0.50	0.499899	28.561457	90.0	90.080434	0.172805	0.012332	29.126951	1.001411	18
3	log_Manual Control__2020-04-12_17-49-04.csv	0.000500	0.25	0.254232	45.159629	90.0	89.850642	0.302968	0.022932	28.685025	1.093912	18
4	log_Manual Control__2020-04-12_17-49-04.csv	0.000500	0.50	0.499777	63.865360	90.0	90.043857	0.217002	0.014405	28.366543	0.931641	17

In [3]:
```python
# add a dataframe column that includes sqrt(feed speed / spool speed) as shown in our basic model
data['Sqrt Feed/Spool'] = np.sqrt(data['Feed Rate Ave (RPS)'] / data['Spool Rate Ave (RPS)'])
data.head()
```

Out[3]:

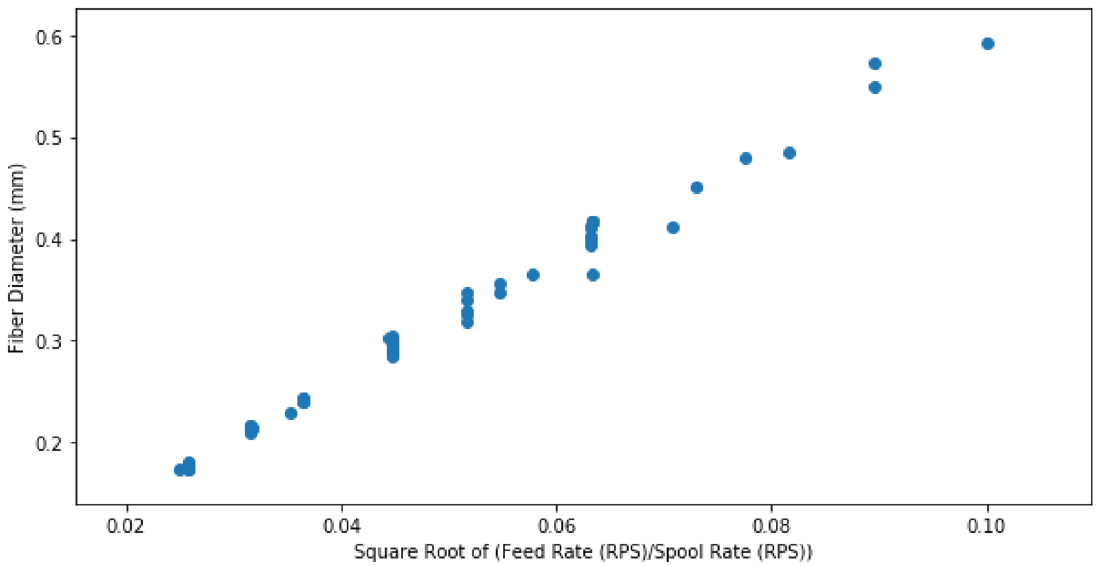
	Run File	Feed Rate Ave (RPS)	Spool Wind Rate Set (RPS)	Spool Rate Ave (RPS)	Wind BF Rate Ave (PPS)	Heater Set (C)	Heater Temp Ave (C)	Filament Diamter Ave (mm)	Filament Std Dev (mm)	System Power Ave (W)	System Power Std Dev (W)	Cu
0	log_Manual Control__2020-04-12_12-13-50.csv	0.001000	1.00	1.000132	127.730719	90.0	90.009313	0.213487	0.016746	29.041052	1.000198	17
1	log_Manual Control__2020-04-12_17-26-48.csv	0.000312	0.25	0.250982	20.426288	90.0	90.068162	0.228383	0.044286	30.064674	1.123981	19
2	log_Manual Control__2020-04-12_17-26-48.csv	0.000312	0.50	0.499899	28.561457	90.0	90.080434	0.172805	0.012332	29.126951	1.001411	18
3	log_Manual Control__2020-04-12_17-49-04.csv	0.000500	0.25	0.254232	45.159629	90.0	89.850642	0.302968	0.022932	28.685025	1.093912	18
4	log_Manual Control__2020-04-12_17-49-04.csv	0.000500	0.50	0.499777	63.865360	90.0	90.043857	0.217002	0.014405	28.366543	0.931641	17

Fiber Diameter Modeling

Explore regression machine learning to develop a model for fiber diameter.

In [4]:
```
# plot filament diameter versus sqrt(feed/spool)
%matplotlib inline
fig, ax1 = plt.subplots()
fig.set_size_inches(10,5)
ax1.scatter(data['Sqrt Feed/Spool'],data['Filament Diamter Ave (mm)'])
ax1.set_xlabel('Square Root of (Feed Rate (RPS)/Spool Rate (RPS))')
ax1.set_ylabel('Fiber Diameter (mm)')
print('Fiber Diameter versus Sqrt(Feed/Spool)')
```

```
Fiber Diameter versus Sqrt(Feed/Spool)
```

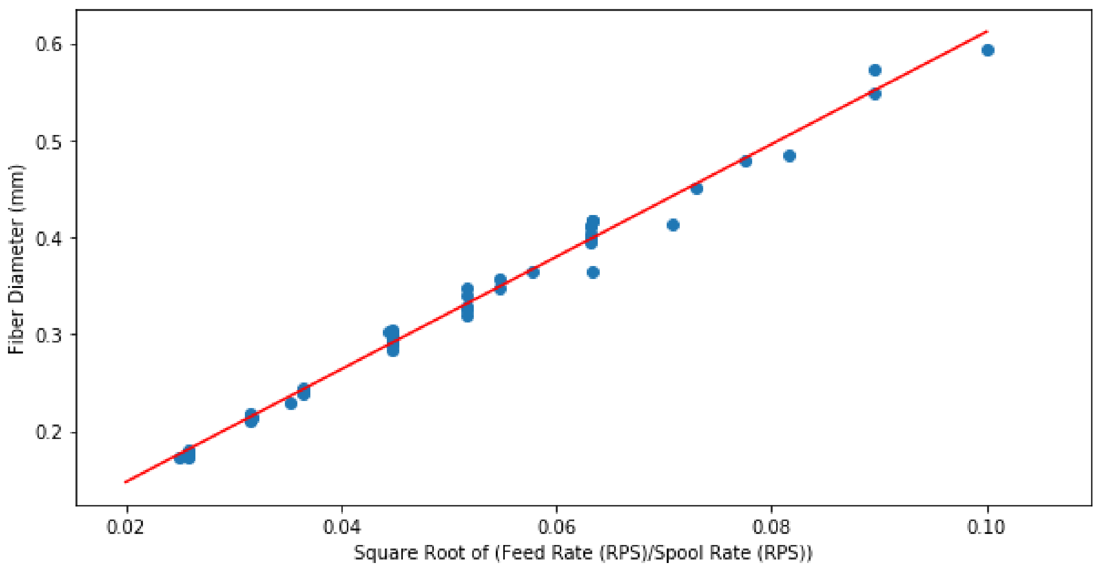


In [5]:
```
# perform a simple linear regression to develop a model for fiber diameter
# input data - reshaped to be a column vector
X = data['Sqrt Feed/Spool'].to_numpy().reshape(-1,1)
# target data - row vector
Y = data['Filament Diamter Ave (mm)'].to_numpy()
# create model, fit data, report coefficients
model = LinearRegression()
model.fit(X,Y)
print('Slope = ', model.coef_[0])
print('Intercept = ', model.intercept_)
print('Score (R^2) = ', model.score(X,Y))
```

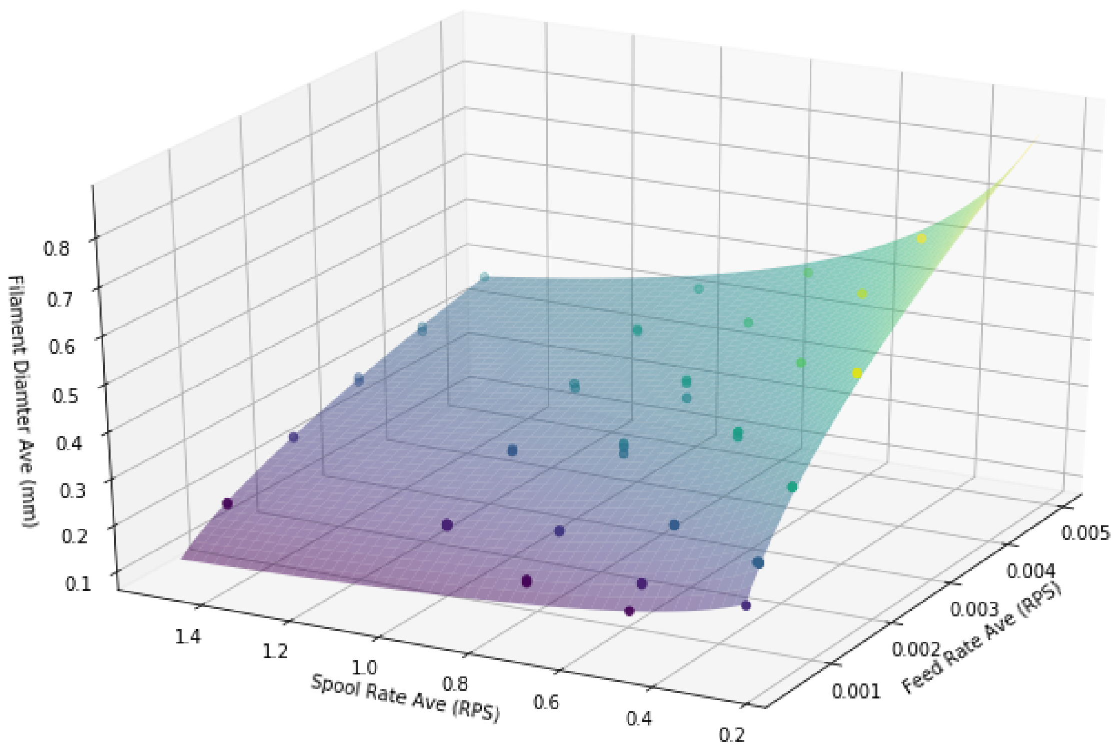
```
Slope =  5.802830190291016
Intercept =  0.03145952131840202
Score (R^2) =  0.9905204454820381
```

In [6]:
```
# plot model versus actual
# create prediction
X = np.linspace(.02,.1).reshape(-1,1)
Y = model.predict(X)
# plot together
fig, ax1 = plt.subplots()
fig.set_size_inches(10,5)
ax1.scatter(data['Sqrt Feed/Spool'],data['Filament Diamter Ave (mm)'])
ax1.plot(X,Y,c='red')
ax1.set_xlabel('Square Root of (Feed Rate (RPS)/Spool Rate (RPS))')
ax1.set_ylabel('Fiber Diameter (mm)')
print('Predicted Fiber Diameter versus Sqrt(Feed/Spool)')
```

```
Predicted Fiber Diameter versus Sqrt(Feed/Spool)
```



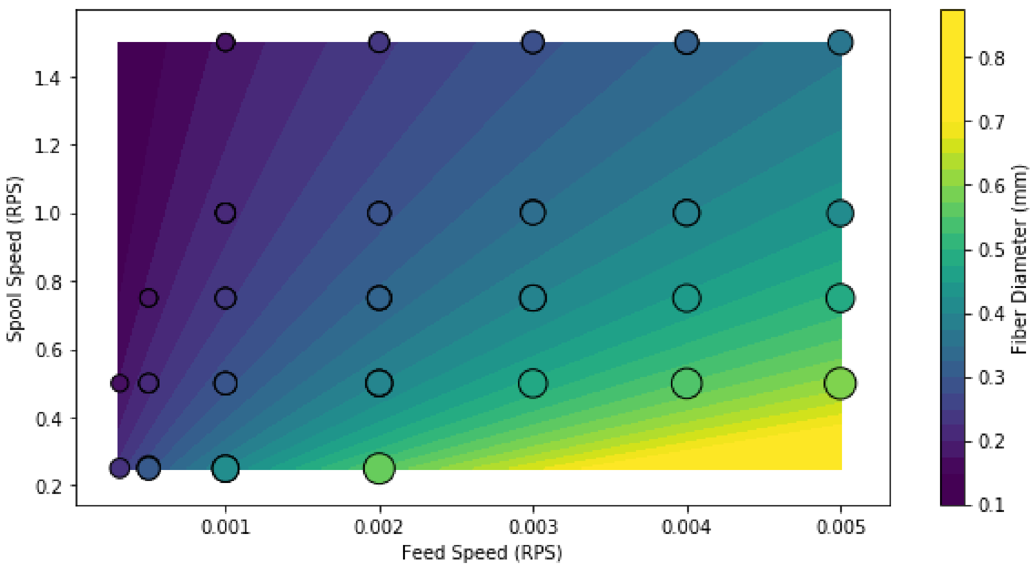
In [8]:
```
# plot model as a 3D surface versus feed and spool speed
%matplotlib notebook
# create prediction using a meshgrid to represent x (feed) , y (spool) and z (diameter) values
feeds = np.linspace(.0003,.005)
spools = np.linspace(.25,1.5)
xx, yy = np.meshgrid(feeds, spools)
sqrts = np.sqrt(np.divide(xx,yy))
dias = model.predict(sqrts.flatten().reshape(-1,1))
zz = dias.reshape(xx.shape)
# plot
fig = plt.figure()
ax1 = Axes3D(fig)
ax1.scatter(data['Feed Rate Ave (RPS)'],data['Spool Rate Ave (RPS)'],data['Filament Diamter Ave (m
m)'],c=data['Filament Diamter Ave (mm)'])
ax1.plot_surface(xx,yy,zz,cmap=plt.cm.viridis,alpha=.5)
ax1.set_xlabel('Feed Rate Ave (RPS)')
ax1.set_ylabel('Spool Rate Ave (RPS)')
ax1.set_zlabel('Filament Diamter Ave (mm)')
print('Fiber Diameter versus Feed and Spool Speed')
```




```
Fiber Diameter versus Feed and Spool Speed
```

In [9]:
```
# showing the above in a 2D plot
%matplotlib inline
fig, ax1 = plt.subplots()
fig.set_size_inches(10,5)
CS = ax1.contourf(xx,yy,zz, levels=30, alpha=1.0, vmin=0.15, vmax=.7)
ax1.scatter(data['Feed Rate Ave (RPS)'],data['Spool Rate Ave (RPS)'], s=500*data['Filament Diamter Ave (mm)'], c=data['Filament Diamter Ave (mm)'],edgecolors='black',vmin=0.15, vmax=.7)
ax1.set_ylabel('Spool Speed (RPS)')
ax1.set_xlabel('Feed Speed (RPS)')
CB = fig.colorbar(CS)
CB.ax.set_ylabel('Fiber Diameter (mm)')
print('Fiber Diameter versus Feed and Spool Speed')
```

```
Fiber Diameter versus Feed and Spool Speed
```

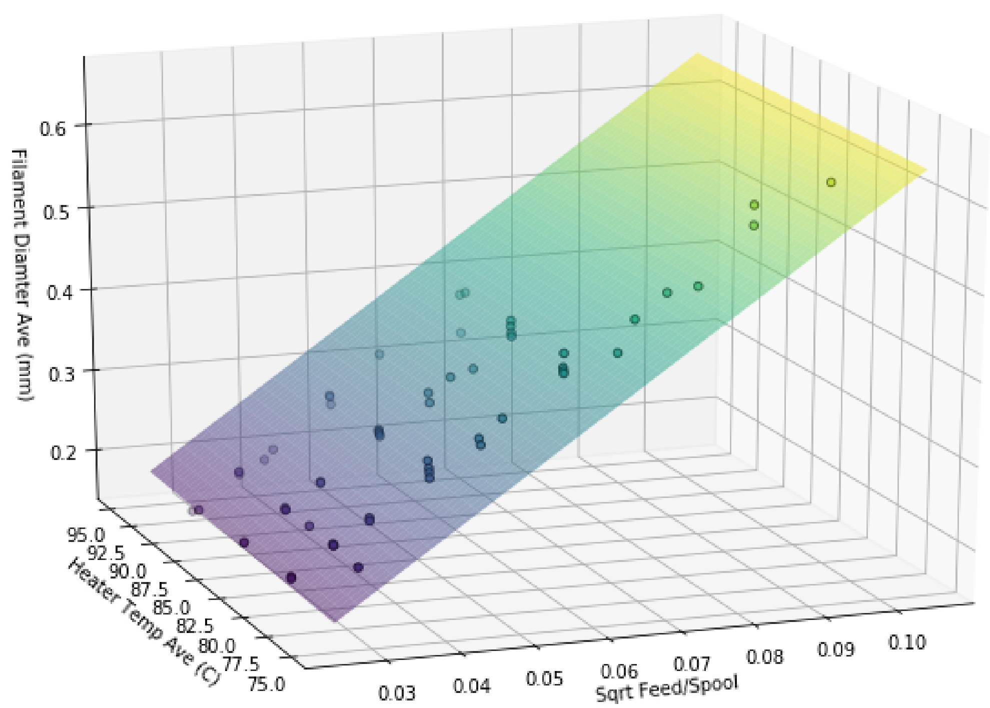


In [10]:
```
# Add heater temperature for multi-variable regression
# input data - autmatically reshaped to be column vectors
X = data[['Sqrt Feed/Spool','Heater Temp Ave (C)']].to_numpy()
#print(X)
# target data - row vector
Y = data['Filament Diamter Ave (mm)'].to_numpy()
# create model, fit data, report coefficients
model2 = LinearRegression()
model2.fit(X,Y)
print('Slopes = ', model2.coef_)
print('Intercept = ', model2.intercept_)
print('Score (R^2) = ', model2.score(X,Y))
```

```
Slopes =  [5.83116286e+00 4.17516686e-04]
Intercept =  -0.004973260581682903
Score (R^2) =  0.990761373259778
```

In [11]:

```python
# plot model as a 3D surface versus sqrt feed/spool and temperature
%matplotlib notebook
# create prediction using a meshgrid to represent x (sqrt(feed/spool)) and z (diameter) values
sqrts = np.linspace(.025,.105)
temps = np.linspace(75,95)
xx, yy = np.meshgrid(sqrts, temps)
#print(xx.flatten())
#np.array([xx.flatten(),yy.flatten()]).T
dias = model2.predict(np.array([xx.flatten(),yy.flatten()]).T)
zz = dias.reshape(xx.shape)
# plot
fig = plt.figure()
ax1 = Axes3D(fig)
ax1.scatter(data['Sqrt Feed/Spool'],data['Heater Temp Ave (C)'],data['Filament Diamter Ave (mm)'],
c=data['Filament Diamter Ave (mm)'],edgecolors='black',vmin=.15,vmax=.65)
ax1.plot_surface(xx,yy,zz,cmap=plt.cm.viridis,alpha=.5,vmin=.15,vmax=.65)
ax1.set_xlabel('Sqrt Feed/Spool')
ax1.set_ylabel('Heater Temp Ave (C)')
ax1.set_zlabel('Filament Diamter Ave (mm)')
print('Fiber Diameter Model versus Sqrt (feed/spool) and Temperature')
```

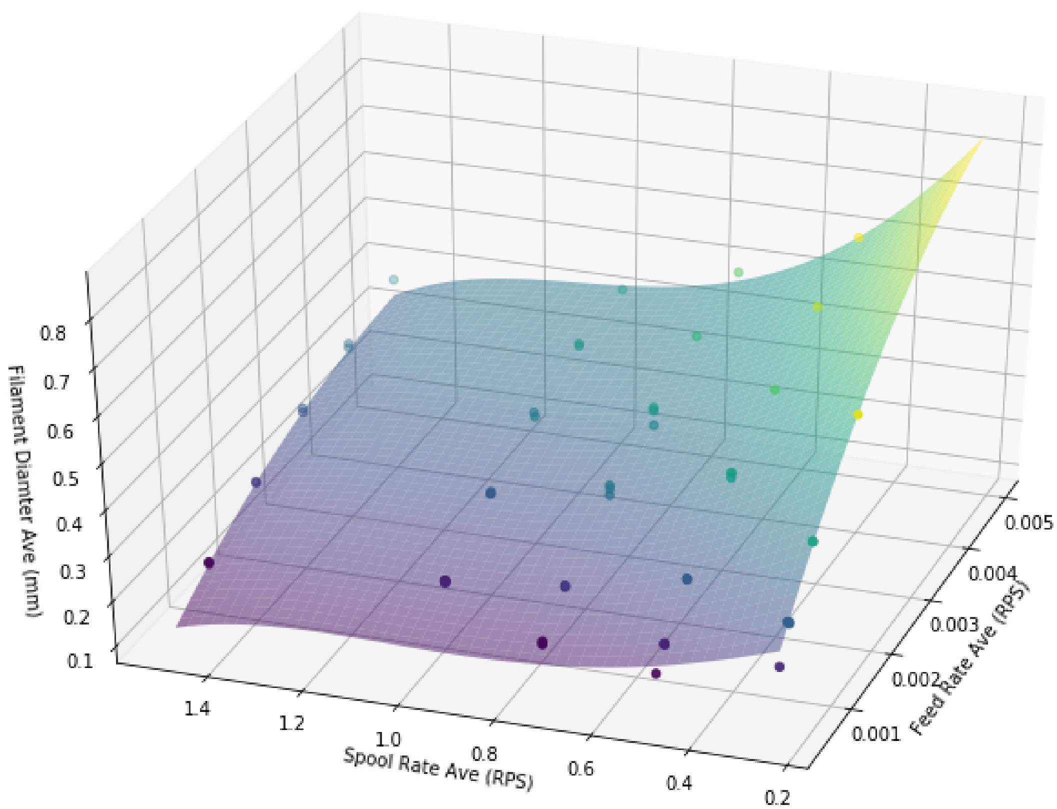



```
Fiber Diameter Model versus Sqrt (feed/spool) and Temperature
```

In [12]:
```
# show multi-variable regression with a polynomial modifier (4th degree shown)
pipe = Pipeline([('poly', PolynomialFeatures(degree=4)),('linreg', LinearRegression())])
X = data[['Feed Rate Ave (RPS)','Spool Rate Ave (RPS)','Heater Temp Ave (C)']].to_numpy()
Y = data['Filament Diamter Ave (mm)'].to_numpy()
model3 = pipe.fit(X,Y)
print('Coefficients = ', model3.named_steps['linreg'].coef_)
print('Intercept = ', model3.named_steps['linreg'].intercept_)
print('Score (R^2) = ', model3.score(X,Y))
```

```
Coefficients =  [-1.38333850e+04  3.05082771e+05 -7.99177495e+02 -2.31990783e+01
 -1.92031989e+04 -1.21357652e+03 -1.08159461e+04 -4.78690790e-01
  2.82931367e+01  3.13915698e-01 -7.27652031e+02 -2.78063977e+05
  4.29778719e+03  1.04247185e+03  1.38345240e+01  1.27717465e+02
 -3.60125793e-01  2.60421468e-02 -3.33762674e-01 -1.70976208e-03
 -1.03407440e+01 -1.32739715e+03  5.64714942e+03 -1.43894043e+04
  3.88793784e+03 -5.53565528e+01 -7.28530068e+01 -8.93949548e+00
 -5.83368594e-02 -5.01696898e-01 -2.21322886e-01  1.10023686e-02
 -2.81707884e-04  1.31164714e-03  2.81006743e-06]
Intercept =  14440.812827407366
Score (R^2) =  0.9960060426153632
```

In [13]:
```
# plot with 4th order model, setting one temeprature
feeds = np.linspace(.0003,.005)
spools = np.linspace(.25,1.5)
# choose 80C
temps = np.ones(50)*80
xx, yy, aa = np.meshgrid(feeds, spools, temps)
dias = model3.predict(np.array([xx.flatten(),yy.flatten(),aa.flatten()]).T)
zz = dias.reshape(xx.shape)
# plot
fig = plt.figure()
ax1 = Axes3D(fig)
ax1.scatter(data['Feed Rate Ave (RPS)'],data['Spool Rate Ave (RPS)'],data['Filament Diamter Ave (m
m)'],c=data['Filament Diamter Ave (mm)'])
ax1.plot_surface(xx[:,:,0],yy[:,:,0],zz[:,:,0],cmap=plt.cm.viridis,alpha=.5)
ax1.set_xlabel('Feed Rate Ave (RPS)')
ax1.set_ylabel('Spool Rate Ave (RPS)')
ax1.set_zlabel('Filament Diamter Ave (mm)')
print('Fiber Diameter versus Feed and Spool Speed')
```

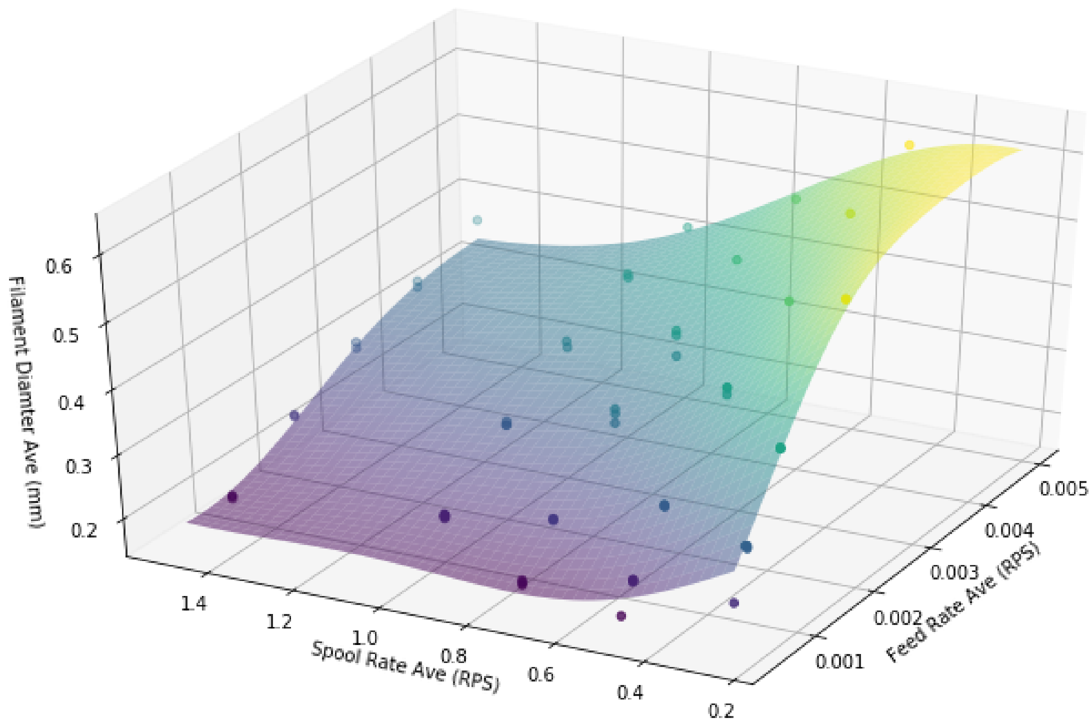



```
Fiber Diameter versus Feed and Spool Speed
```

In [14]:
```
# show a support vector machine model
pipe = Pipeline([('scale', StandardScaler()),('svr', SVR(C=1.0, epsilon=0.01))])
X = data[['Feed Rate Ave (RPS)','Spool Rate Ave (RPS)','Heater Temp Ave (C)']].to_numpy()
Y = data['Filament Diamter Ave (mm)'].to_numpy()
model4 = pipe.fit(X,Y)
print('Score (R^2) = ', model4.score(X,Y))
```

```
Score (R^2) =  0.9923640867627394
```

In [15]:
```
# plot with SVM model, setting one temeprature
feeds = np.linspace(.0003,.005)
spools = np.linspace(.25,1.5)
# choose 80C
temps = np.ones(50)*80
xx, yy, aa = np.meshgrid(feeds, spools, temps)
dias = model4.predict(np.array([xx.flatten(),yy.flatten(),aa.flatten()]).T)
zz = dias.reshape(xx.shape)
# plot
fig = plt.figure()
ax1 = Axes3D(fig)
ax1.scatter(data['Feed Rate Ave (RPS)'],data['Spool Rate Ave (RPS)'],data['Filament Diamter Ave (m
m)'],c=data['Filament Diamter Ave (mm)'])
ax1.plot_surface(xx[:,:,0],yy[:,:,0],zz[:,:,0],cmap=plt.cm.viridis,alpha=.5)
ax1.set_xlabel('Feed Rate Ave (RPS)')
ax1.set_ylabel('Spool Rate Ave (RPS)')
ax1.set_zlabel('Filament Diamter Ave (mm)')
print('Fiber Diameter versus Feed and Spool Speed')
```




```
Fiber Diameter versus Feed and Spool Speed
```

Fiber Diameter - Standard Deviation Modeling

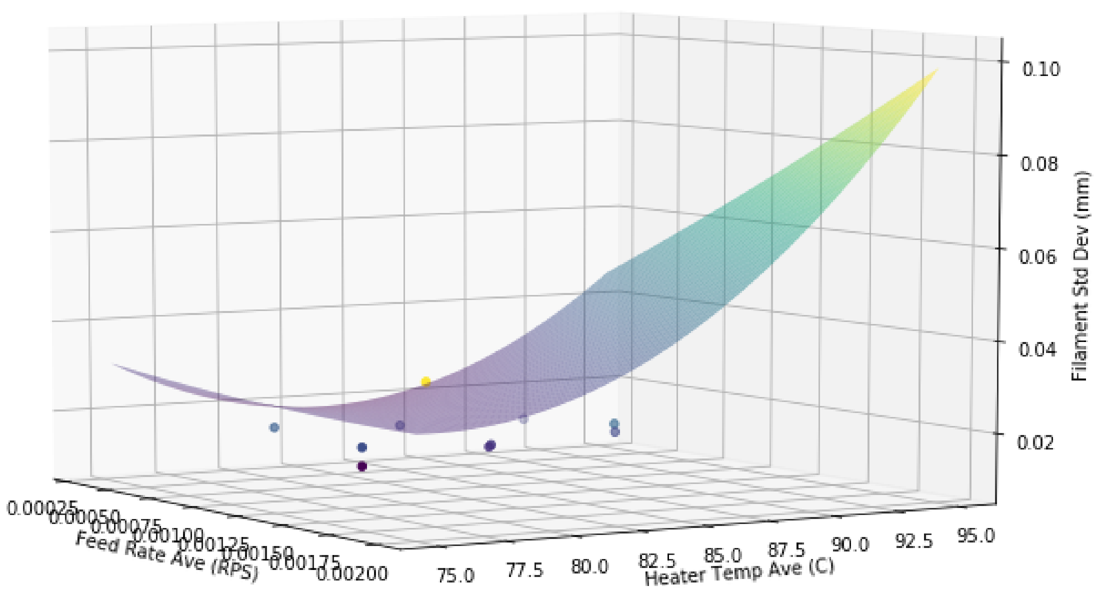
Develop a model for standard deviation with unknown influences.

In [84]:
```
# multi-variable regression with a polynomial modifier
pipe = Pipeline([('poly', PolynomialFeatures(degree=2)),('linreg', LinearRegression())])
X = data[['Feed Rate Ave (RPS)','Spool Rate Ave (RPS)','Heater Temp Ave (C)']].to_numpy()
Y = data['Filament Std Dev (mm)'].to_numpy()
model5 = pipe.fit(X,Y)
print('Score (R^2) = ', model5.score(X,Y))
```

```
Score (R^2) =  0.5510268240028662
```

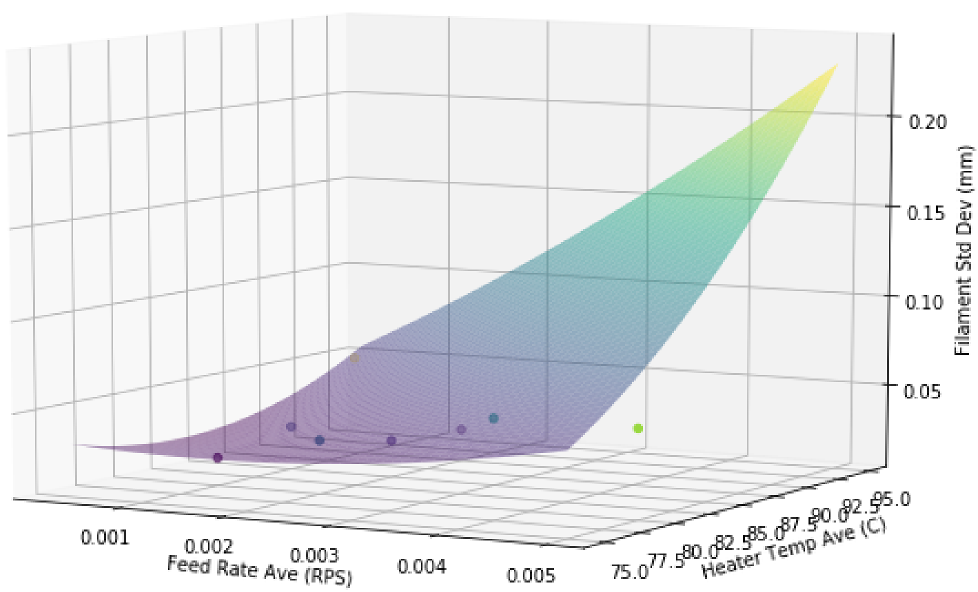
In [72]:

```
# plot result at a given fiber diameter- .214mm
feeds = np.linspace(.0003,.002)
# solve for spool rates using simple equation
spools = feeds / (.214/5.8)**2
#print(spools)
temps = np.linspace(75,95)
xx, yy, aa = np.meshgrid(feeds, spools, temps)
#print(xx)
#print(xx[:,:,0])
#
#print(yy)
#print(aa)
dias = model5.predict(np.array([xx.flatten(),yy.flatten(),aa.flatten()]).T)
zz = dias.reshape(xx.shape)
# clip .214mm data from frame
df = data[data['Filament Diamter Ave (mm)'] < .22]
df = df[df['Filament Diamter Ave (mm)'] > .21]
# plot
fig = plt.figure()
ax1 = Axes3D(fig)
ax1.scatter(df['Feed Rate Ave (RPS)'],df['Heater Temp Ave (C)'],df['Filament Std Dev (mm)'],c=df[
'Filament Std Dev (mm)'])
ax1.plot_surface(xx[0,:,:],aa[0,:,:],zz[0,:,:],cmap=plt.cm.viridis,alpha=.5)
ax1.set_xlabel('Feed Rate Ave (RPS)')
ax1.set_ylabel('Heater Temp Ave (C)')
ax1.set_zlabel('Filament Std Dev (mm)')
print('Fiber Diameter Std Dev versus Feed and Temperature (.214mm nom)')
```




```
Fiber Diameter Std Dev versus Feed and Temperature (.214mm nom)
```

In [76]:
```
# plot result at a given fiber diameter- .41mm
feeds = np.linspace(.0003,.005)
# solve for spool rates using simple equation
spools = feeds / (.41/5.8)**2
#print(spools)
temps = np.linspace(75,95)
xx, yy, aa = np.meshgrid(feeds, spools, temps)
dias = model5.predict(np.array([xx.flatten(),yy.flatten(),aa.flatten()]).T)
zz = dias.reshape(xx.shape)
# clip .214mm data from frame
df = data[data['Filament Diamter Ave (mm)'] < .42]
df = df[df['Filament Diamter Ave (mm)'] > .4]
# plot
fig = plt.figure()
ax1 = Axes3D(fig)
ax1.scatter(df['Feed Rate Ave (RPS)'],df['Heater Temp Ave (C)'],df['Filament Std Dev (mm)'],c=df[
'Filament Std Dev (mm)'])
ax1.plot_surface(xx[0,:,:],aa[0,:,:],zz[0,:,:],cmap=plt.cm.viridis,alpha=.5)
ax1.set_xlabel('Feed Rate Ave (RPS)')
ax1.set_ylabel('Heater Temp Ave (C)')
ax1.set_zlabel('Filament Std Dev (mm)')
print('Fiber Diameter Std Dev versus Feed and Temperature (.41mm nom)')
```



Fiber Diameter Std Dev versus Feed and Temperature (.41mm nom)

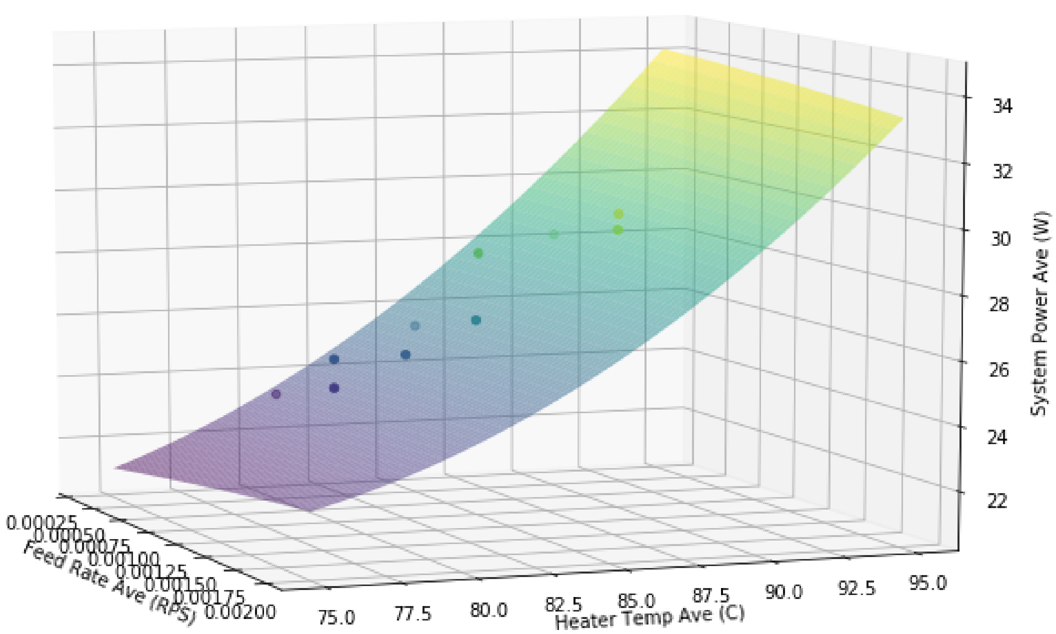
Power Consumption Modeling

Develop a model for Power with unknown influences.

In [78]:
```
# multi-variable regression with a polynomial modifier
pipe = Pipeline([('poly', PolynomialFeatures(degree=2)),('linreg', LinearRegression())])
X = data[['Feed Rate Ave (RPS)','Spool Rate Ave (RPS)','Heater Temp Ave (C)']].to_numpy()
Y = data['System Power Ave (W)'].to_numpy()
model6 = pipe.fit(X,Y)
print('Score (R^2) = ', model6.score(X,Y))
```

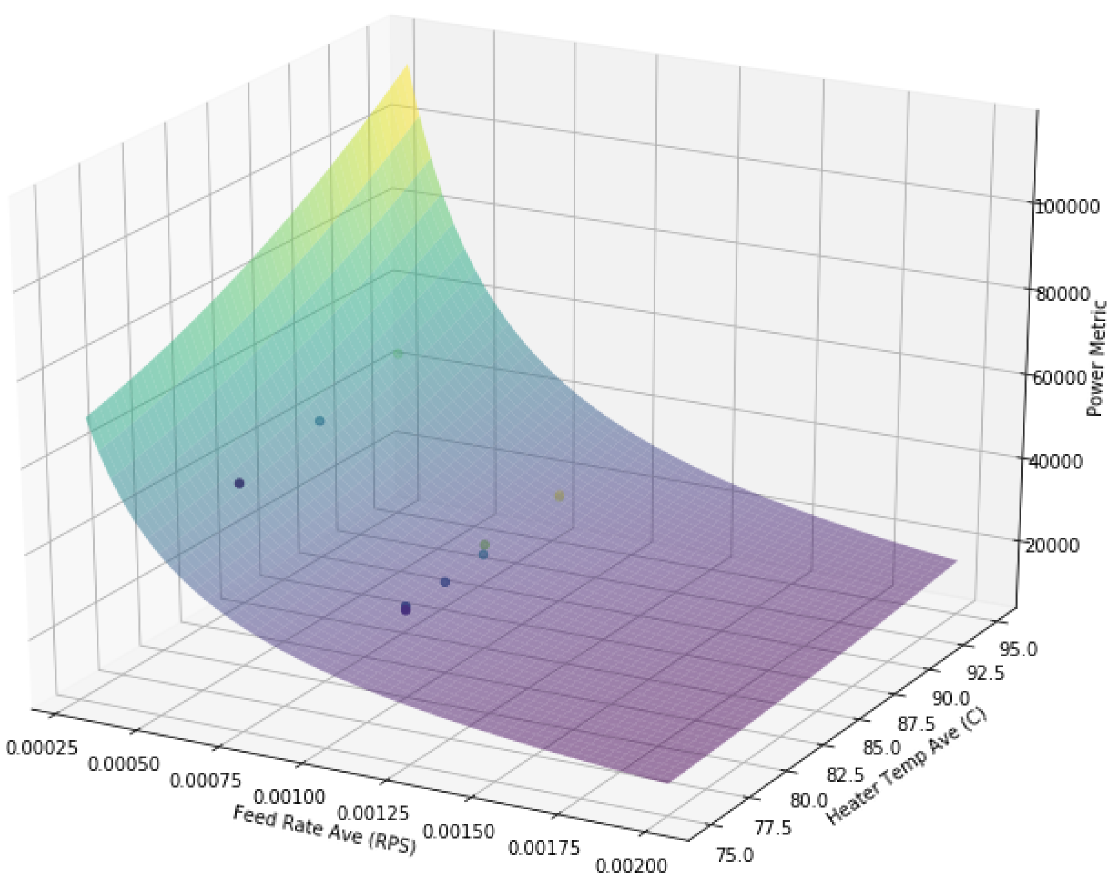
```
Score (R^2) =  0.8980641185337678
```

In [81]:
```
# plot result at a given fiber diameter- .214mm
feeds = np.linspace(.0003,.002)
# solve for spool rates using simple equation
spools = feeds / (.214/5.8)**2
#print(spools)
temps = np.linspace(75,95)
xx, yy, aa = np.meshgrid(feeds, spools, temps)
dias = model6.predict(np.array([xx.flatten(),yy.flatten(),aa.flatten()]).T)
zz = dias.reshape(xx.shape)
# clip .214mm data from frame
df = data[data['Filament Diamter Ave (mm)'] < .22]
df = df[df['Filament Diamter Ave (mm)'] > .21]
# plot
fig = plt.figure()
ax1 = Axes3D(fig)
ax1.scatter(df['Feed Rate Ave (RPS)'],df['Heater Temp Ave (C)'],df['System Power Ave (W)'],c=df['S
ystem Power Ave (W)'])
ax1.plot_surface(xx[0,:,:],aa[0,:,:],zz[0,:,:],cmap=plt.cm.viridis,alpha=.5)
ax1.set_xlabel('Feed Rate Ave (RPS)')
ax1.set_ylabel('Heater Temp Ave (C)')
ax1.set_zlabel('System Power Ave (W)')
print('System Power Ave (W) versus Feed and Temperature (.214mm nom)')
```




```
System Power Ave (W) versus Feed and Temperature (.214mm nom)
```

In [82]:
```
# plot power/production metric at a given fiber diameter- .214mm
feeds = np.linspace(.0003,.002)
# solve for spool rates using simple equation
spools = feeds / (.214/5.8)**2
#print(spools)
temps = np.linspace(75,95)
xx, yy, aa = np.meshgrid(feeds, spools, temps)
dias = model6.predict(np.array([xx.flatten(),yy.flatten(),aa.flatten()]).T)
zz = dias.reshape(xx.shape)
# clip .214mm data from frame
df = data[data['Filament Diamter Ave (mm)'] < .22]
df = df[df['Filament Diamter Ave (mm)'] > .21]
# plot
fig = plt.figure()
ax1 = Axes3D(fig)
ax1.scatter(df['Feed Rate Ave (RPS)'],df['Heater Temp Ave (C)'],df['System Power Ave (W)']/df['Fee
d Rate Ave (RPS)'],c=df['System Power Ave (W)'])
ax1.plot_surface(xx[0,:,:],aa[0,:,:],zz[0,:,:]/xx[0,:,:],cmap=plt.cm.viridis,alpha=.5)
ax1.set_xlabel('Feed Rate Ave (RPS)')
ax1.set_ylabel('Heater Temp Ave (C)')
ax1.set_zlabel('Power Metric')
print('Power Metric versus Feed and Temperature (.214mm nom)')
```




```
Power Metric versus Feed and Temperature (.214mm nom)
```

Export Models

Save models in files to import in other code. Uses pickle.

In [85]:
```
model_path = './Models/'
# linear regression for fiber diameter - model2
# inputs ['Sqrt Feed/Spool','Heater Temp Ave (C)']
pickle.dump(model2, open(model_path + 'dia_mod_1.p','wb'))

# polynomial regression (order 2) for fiber standard deviation - model5
# inputs ['Feed Rate Ave (RPS)','Spool Rate Ave (RPS)','Heater Temp Ave (C)']
pickle.dump(model5, open(model_path + 'dia_std_mod_1.p','wb'))

# polynomial regression (order 2) for system power - model6
# inputs ['Feed Rate Ave (RPS)','Spool Rate Ave (RPS)','Heater Temp Ave (C)']
pickle.dump(model6, open(model_path + 'sys_pow_mod_1.p','wb'))
```

3D Slice Practice and Examples

In [64]:
```
a = np.linspace(0,2,3)
b = np.linspace(3,5,3)
c = np.linspace(6,8,3)
#print(a)
#print(b)
#print(c)
aa, bb, cc = np.meshgrid(a,b,c)
print(aa)
print(aa[:,1,:])
print('**')
print(bb)
print(cc)
yy = aa + bb + cc
print(yy)
print('**')
print(yy[0,:,:])
```

```
[[[0. 0. 0.]
  [1. 1. 1.]
  [2. 2. 2.]]

 [[0. 0. 0.]
  [1. 1. 1.]
  [2. 2. 2.]]

 [[0. 0. 0.]
  [1. 1. 1.]
  [2. 2. 2.]]]
[[1. 1. 1.]
 [1. 1. 1.]
 [1. 1. 1.]]
**
[[[3. 3. 3.]
  [3. 3. 3.]
  [3. 3. 3.]]

 [[4. 4. 4.]
  [4. 4. 4.]
  [4. 4. 4.]]

 [[5. 5. 5.]
  [5. 5. 5.]
  [5. 5. 5.]]]
[[[6. 7. 8.]
  [6. 7. 8.]
  [6. 7. 8.]]

 [[6. 7. 8.]
  [6. 7. 8.]
  [6. 7. 8.]]

 [[6. 7. 8.]
  [6. 7. 8.]
  [6. 7. 8.]]]
[[[ 9. 10. 11.]
  [10. 11. 12.]
  [11. 12. 13.]]

 [[10. 11. 12.]
  [11. 12. 13.]
  [12. 13. 14.]]

 [[11. 12. 13.]
  [12. 13. 14.]
  [13. 14. 15.]]]
**
[[ 9. 10. 11.]
 [10. 11. 12.]
 [11. 12. 13.]]
```

In [ ]:

```

```