Observed Interactive Effects on OSU Apparatus

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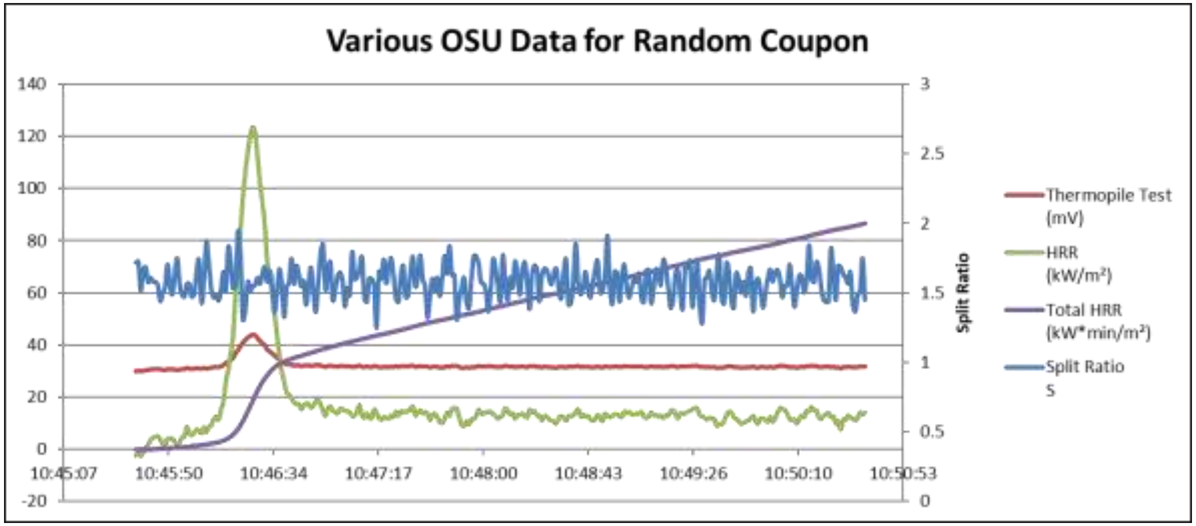
Discussion Topics

- Summary of airflow studies conducted in recent past
- Recent testing and analysis
- Further discussion

Goal: Establish an accurate baseline for the OSU tests industry-wide by understanding and then controlling the possible variation due to airflow (and other variables).

Airflow Studies Summary

- In 2015, data was presented from an OSU unit based in Charleston that checked the effect of total airflow and the airflow split ratio on the OSU parameters (peak heat, 2-minute total, and peak time).
- The test utilized common honeycomb sandwich panel with standard decorative laminate as well as a thin aluminum panel with a standard 3-M homogeneous tape.
- Data loggers recorded multiple parameters simultaneously, allowing for an in-depth review of heat release behavior.



Airflow Studies Summary

- **Multiple relationships were observed with high correlations:**

Note: Split Ratio 3:1 Cooling Air / Chamber Air

- Total Airflow variation and Split Ratio variation *are not* accounted for during calibration

- Heat Release behaves linearly with respect to Airflow (both aluminum & standard coupons):
  - Maintaining a 3:1 Split Ratio: The more total air into the system, the higher the peak.
  - Fluctuating Split Ratio: The lower the split ratio, the higher the peak.
  - Maintaining a 3:1 Split Ratio: The more total air into the system, the higher the 2-min total
  - Fluctuating Split Ratio: The lower the split ratio, the higher the 2-min total.

- Regarding the Calibration Constant (both aluminum & standard coupons):
  - Keeping a 3:1 Split Ratio: The more total air into the system, the higher the calibration constant
  - Fluctuating Split Ratio: The lower the split ratio, the higher the calibration constant

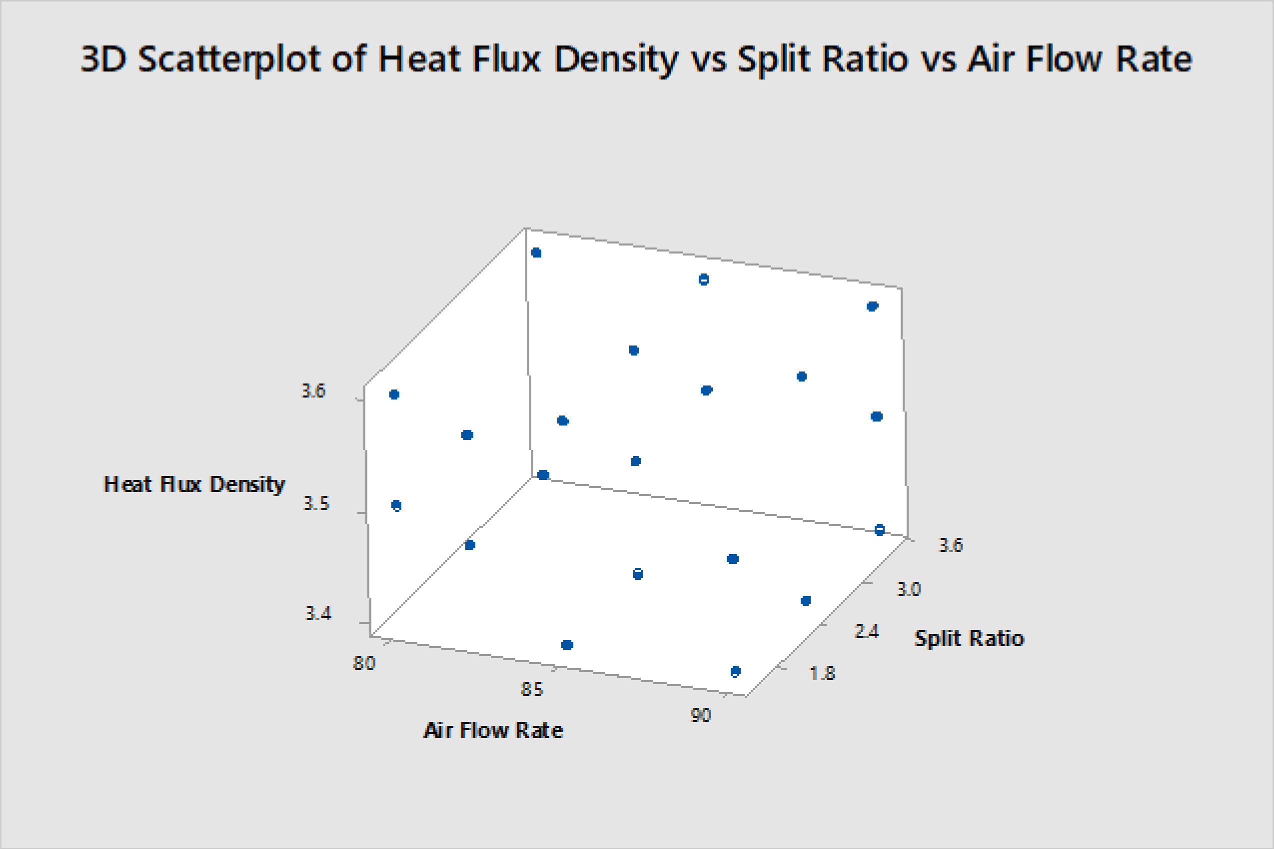
Airflow Studies Summary

- Later in 2015, the Charleston experiment was repeated using an OSU based in Everett, Washington.
- The same trends observed in Charleston were observed in Everett.
- Evidence pointed to airflow and split ratio being major contributors to OSU variability.

Planned Testing (complete)

Conduct Design of Experiment testing to determine the individual contribution of each of the three variables (Airflow, Split Ratio, and Voltage Fluctuation) to the Heat Release Results

- The experiment will provide a 3-Dimensional scatter plot, allowing for simultaneous analysis of key parameters



Background & Problem Statement

- BR&T Flammability performed an experiment to study the effects of air flow split ratio, total air flow, and heat flux density on combustion characteristics of burning specimen and their measured heat release properties.

- Applied Math to assess statistical significance of OSU HRR variables **(Thank You Katy!)**

  Assess effects of Total Flow Rate, Lower/Upper Plenum, and Heat Flux Density on calibration constant, peak heat release, peak time and 2-minute total heat release.

Experimental Design

Control Factors

- **Air flow split ratio** (Upper Plenum / Lower Plenum)
  - 1.5
  - 2.5
  - 3.5
- **Total air flow rates**
  - 80 ft^3/min
  - 85 ft^3/min
  - 90 ft^3/min
- **Heat flux density**
  - 3.2 W/cm^2
  - 3.5 W/cm^2
  - 3.8 W/cm^2

20 Combinations ran 3 times = 60 total test points

Response Factors

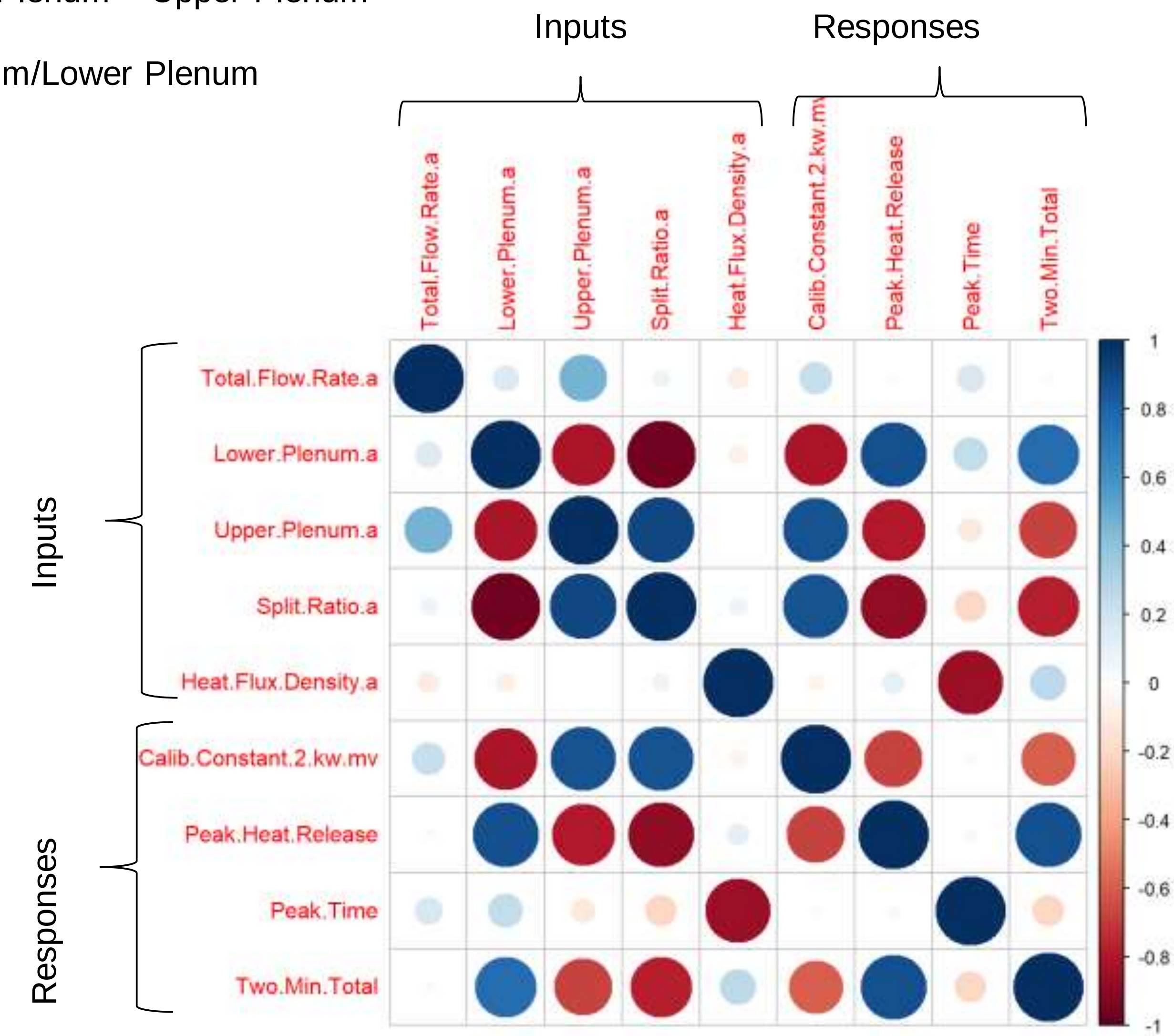
- Calibration Constant (kW/m^2-mv)
- Peak Heat Release Rate (kW/m^2)
- Peak Time (seconds)
- 2-min Total Heat Release (kW-min/m^2)

For each response, fit a linear regression model and test for significance of:

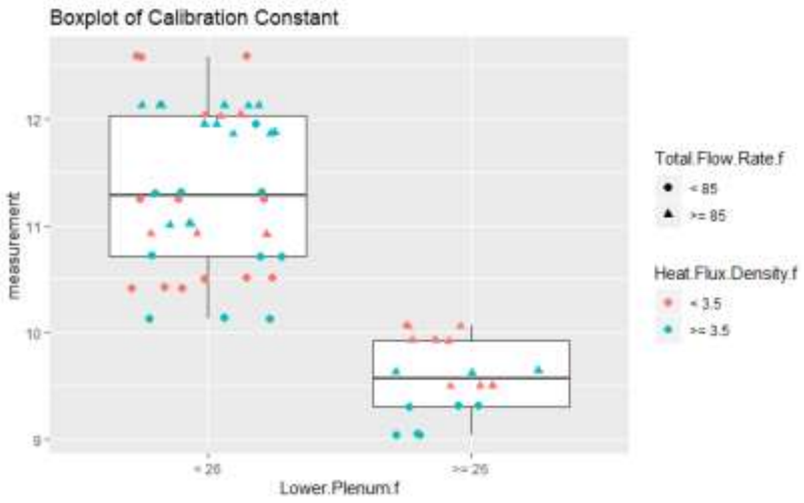
- Main effects
- Two and Three-way interactions
- Quadratic effects

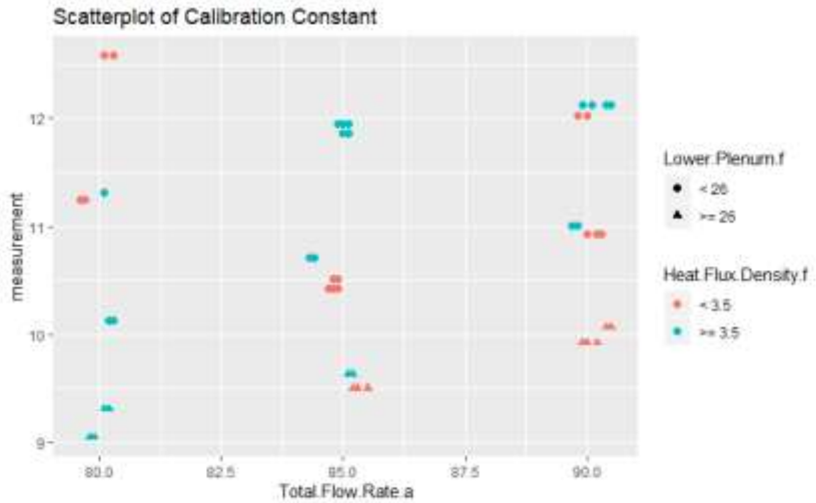
Correlation of Variables

- Total Flow Rate = Lower Plenum + Upper Plenum
- Split Ratio = Upper Plenum/Lower Plenum



Calibration Constant – Boxplots





Summary Statistics of Calibration Constant

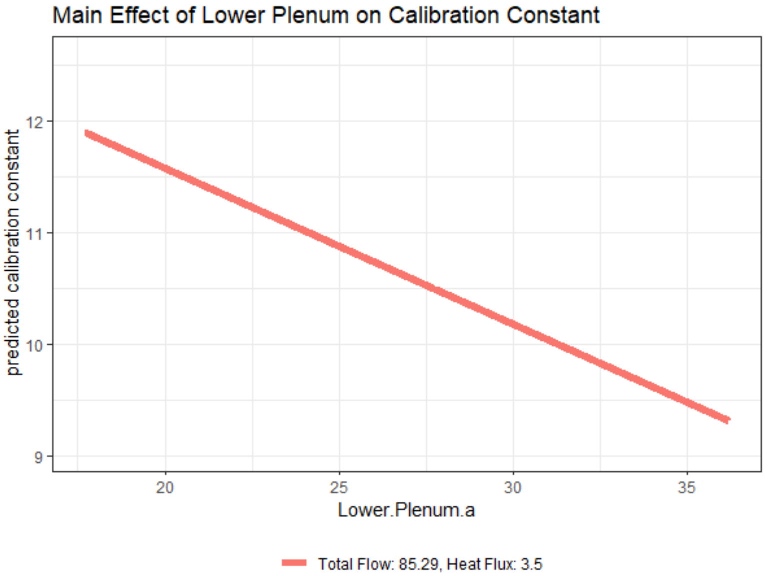
n	min	max	mean	median	sd
60	9.0452	12.582	10.821	10.82	1.0461

From the boxplot above, it appears that the more air flowing through the Lower Plenum, the less the calibration constant. There also appears to be an interaction between Total Flow Rate and Heat Flux Density on calibration constant.

Observed relationship matches prior discussions that airflow aspects are not accounted for in the calibration constant

Calibration Constant **– Effect Plots**

Note, for each plot, the other variable(s) present in the model are held at their mean level.



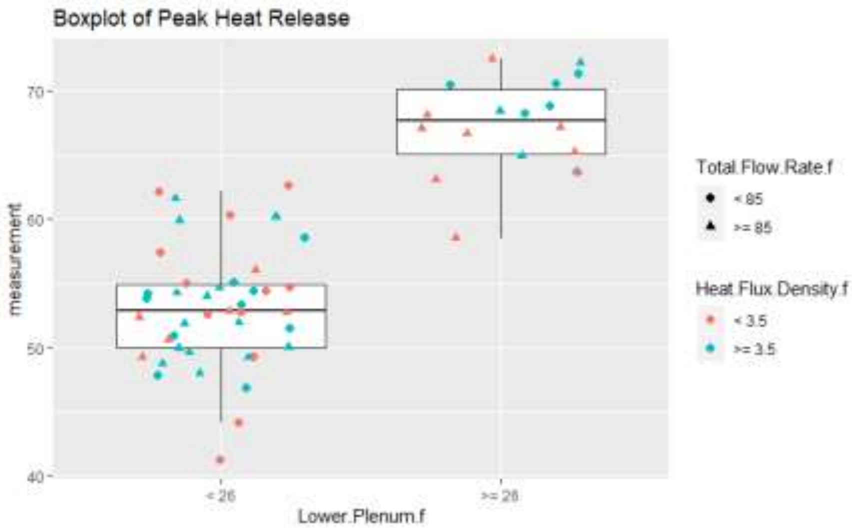
Effect	Relative Importance*
Lower Plenum	67.87%
Total Flow Rate	7.32%
Total Flow Rate*Heat Flux	4.62%
Heat Flux	0.57%

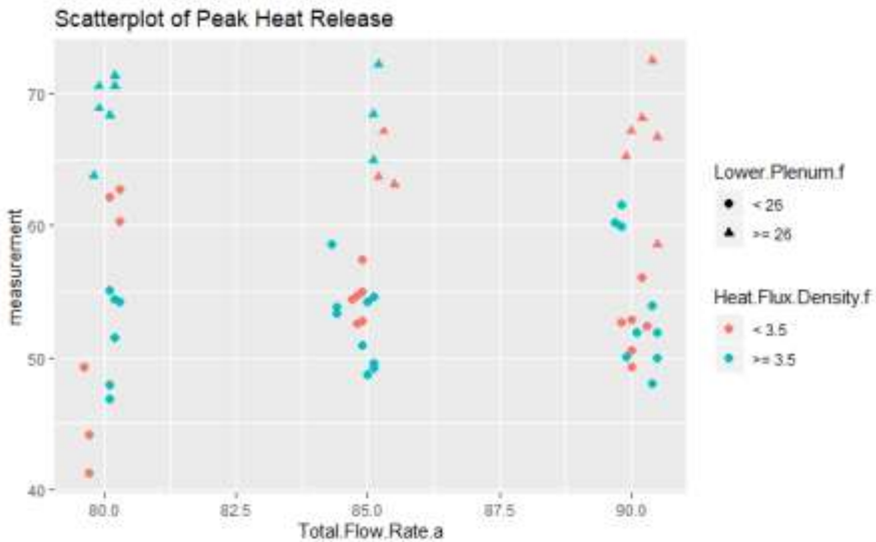
*Relative importance defined in terms of average R-squared contribution

- There is a significant negative effect of Lower Plenum on Calibration Constant. The more air that flows through Lower Plenum, the less the calibration constant.
- There is a significant 2-way interaction between Total Flow Rate and Heat Flux Density. That is, the effect of Total Flow Rate on the calibration constant depends on the level of Heat Flux Density.
- The above model explains 80% of the variation observed in Calibration Constant.

Observed relationship matches prior discussions – the lower the split ratio (more air into lower plenum), the lower the calibration constant.

Peak Heat Release – Boxplots





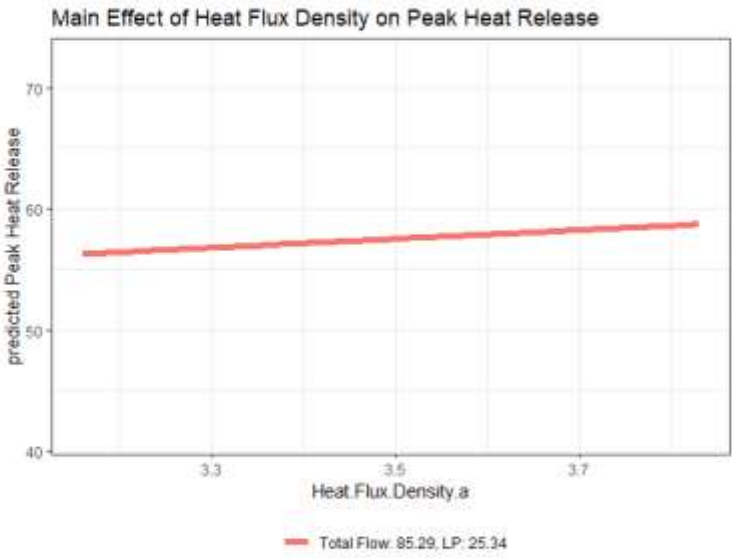
Summary Statistics of Peak Heat Release

n	min	max	mean	median	sd
60	41.29	72.48	57.37	54.655	7.8509

Increasing Lower Plenum flow appears to increase Peak Heat Release. There appears to be more variation in measurements when total flow rate was at the low setting.

Peak Heat Release – Effect Plots

Note, for each plot, the other variable(s) present in the model are held at their mean level.



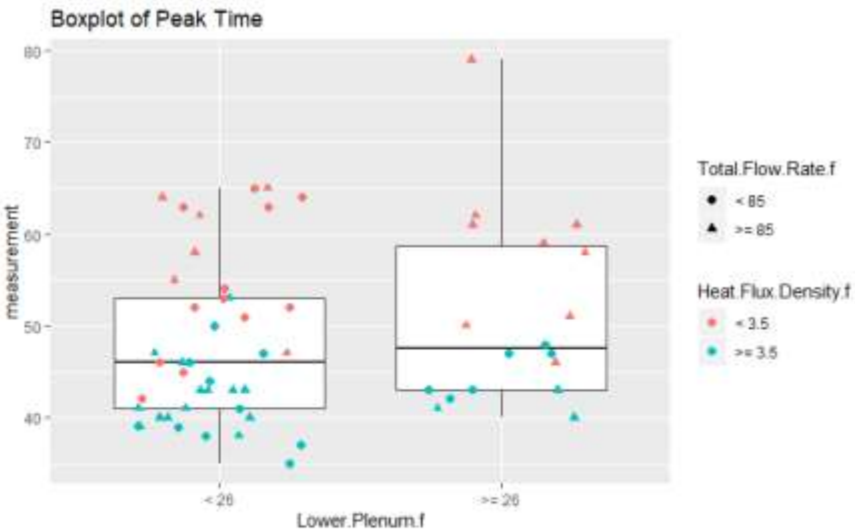
Effect	Relative Importance*
Lower Plenum	78.15%
Heat Flux	1.74%
Total Flow Rate*Lower Plenum	1.72%
Total Flow Rate	1.10%

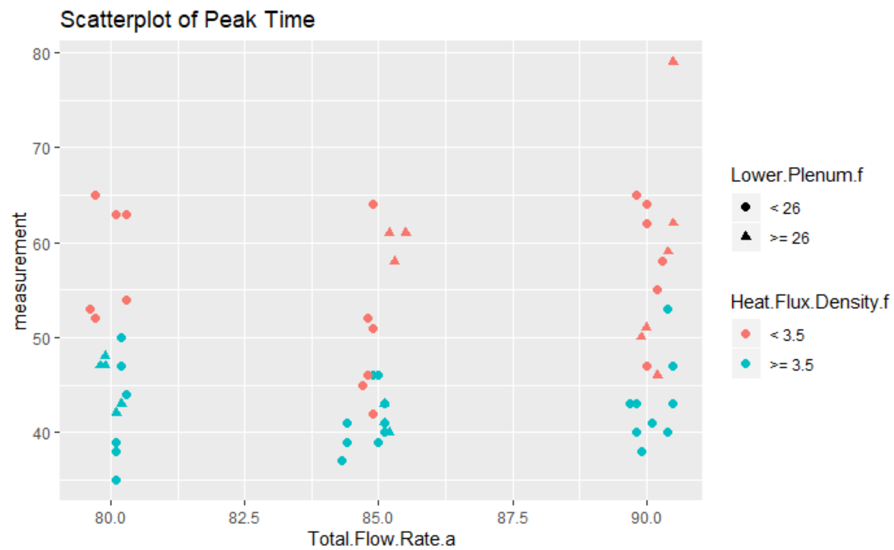
*Relative importance defined in terms of average R-squared contribution

- There is a significant positive effect of Lower Plenum airflow on Peak Heat Release. The more airflow into the Lower Plenum, the higher the Peak Heat Release.
- The above model explains 83% of the variation observed in Peak Heat Release.

Observed relationship matches prior discussions that the more air into the lower plenum, the higher the peak heat results.

Peak Time – Boxplots





Summary Statistics of Peak Time

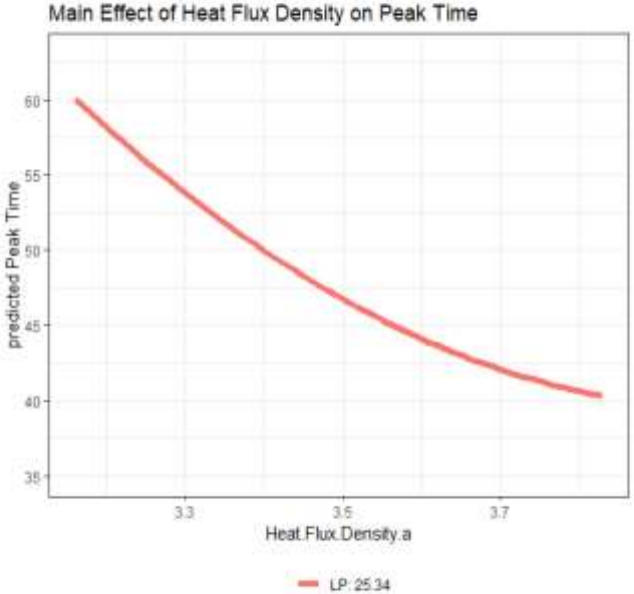
n	min	max	mean	median	sd
60	35	79	48.917	46.5	9.3633

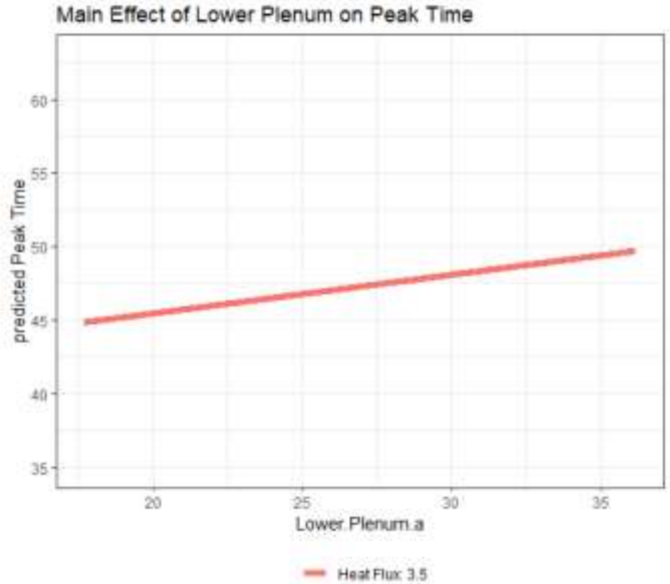
There is not an apparent trend in peak time due to total flow rate. Heat flux density is the major contributor to Peak Time. Specimen with 3.5 or greater heat flux density had lower measured peak times than those with less than 3.5 heat flux density.

Prior observations did not focus on the effect on peak time - therefore this is new / independent information.

Peak Time – Effect Plots

Note, for each plot, the other variable(s) present in the model are held at their mean level.



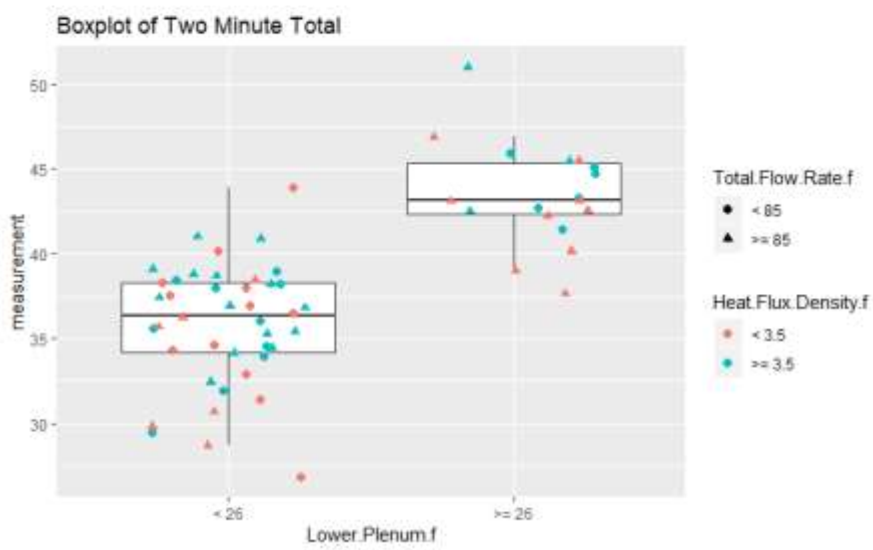


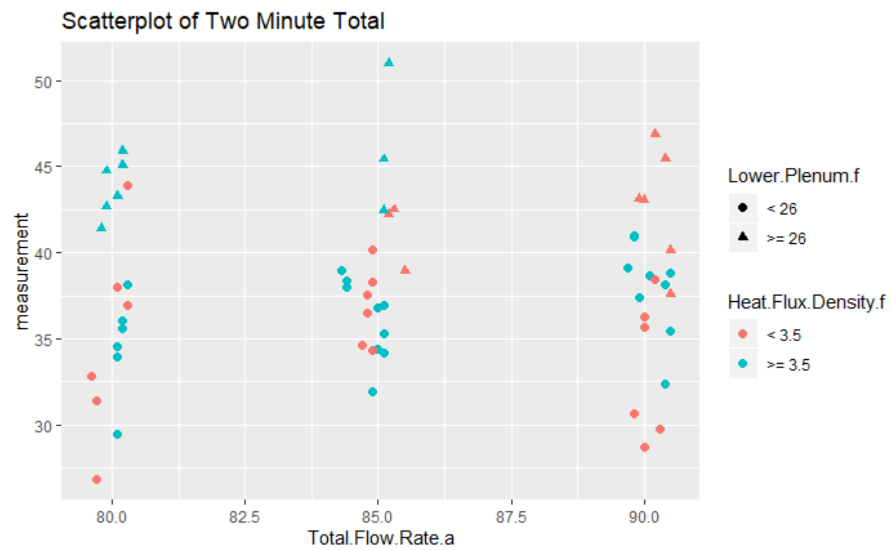
Effect	Relative Importance*
Heat Flux	71.50%
Lower Plenum	4.43%
Heat Flux^2	2.68%

*Relative importance defined in terms of average R-squared contribution

- The higher the heat flux density, the lower (quicker) the Peak Time.
- There is a statistically significant effect of Lower Plenum airflow on Peak Time.
- There is no significant effect or interaction of Total Flow Rate on Peak Time over the ranges tested.
- The above model explains 79% of the variation observed in Peak Time.

Two Minute Total – Boxplots





Summary Statistics of Two Minute Total Heat Release

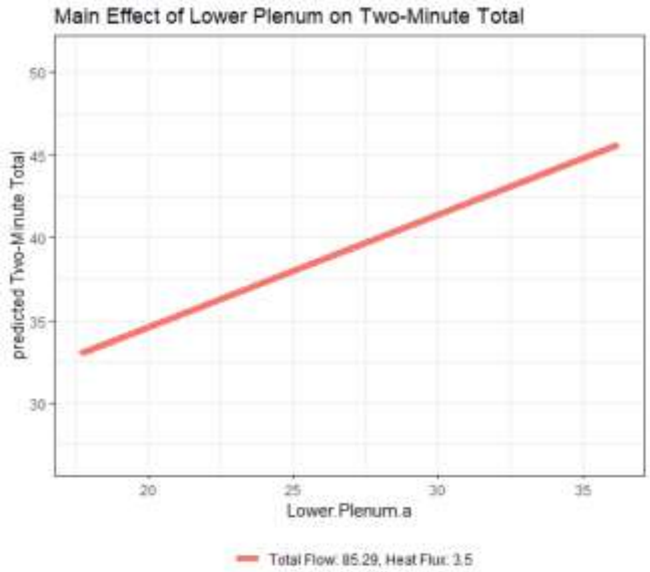
n	min	max	mean	median	sd
60	26.84	51.01	38.124	38.08	4.9034

From the boxplot above, the higher the Lower Plenum airflow, the higher the two minute total. There is not a clear trend due to heat flux density or total flow rate on 2-minute total.

Overall observed relationship matches prior discussions that the more air into the lower plenum, the higher the two minute total values except total flow rate over the ranges tested.

Two Minute Total **– Effect Plots**

Note, for each plot, the other variable(s) present in the model are held at their mean level.



Effect	Relative Importance*
Lower Plenum	62.25%
Heat Flux	8.24%
Heat Flux*Total Flow Rate	3.24%
Total Flow Rate	0.26%

*Relative importance defined in terms of average R-squared contribution

- The more airflow into the Lower Plenum, the higher the Two Minute Total Heat Release Results.
- There is a significant 2-way interaction between Total Flow Rate and Heat Flux Density. That is, the effect of Total Flow Rate is depends on the level of Heat Flux Density.
- The above model explains 74% of the variation observed in Two Minute Total.

Summary / Discussion

– **Calibration Constant:**
  - Model explains 80% of the variation of the Calibration Constant
  - Largest Contributor (68% RI) due to Lower Plenum Airflow
  - Matches observations previously presented

– **Peak Heat Release:**
  - Model explains 83% of the variation of the Peak Heat Release
  - Largest Contributor (78% RI) due to Lower Plenum Airflow
  - Matches observations previously presented

– **Peak Time:**
  - Model explains 79% of the variation of the Peak Time
  - Largest Contributor (72% RI) due to Heat Flux Density
  - Data not previously analyzed in depth – new observations

– **2-Minute Total Heat Release:**
  - Model explains 74% of the variation of the 2-min Total
  - Largest Contributor (62% RI) due to Lower Plenum Airflow
  - Matches observations previously presented overall except the observation "**there is not a clear trend due to…<u>total flow rate</u>**"

In order to reduce industry variability, the largest lever we have is to control the airflow, which will be applicable to both OSU improvement and HR2 development.

Questions

Thank you for your time !

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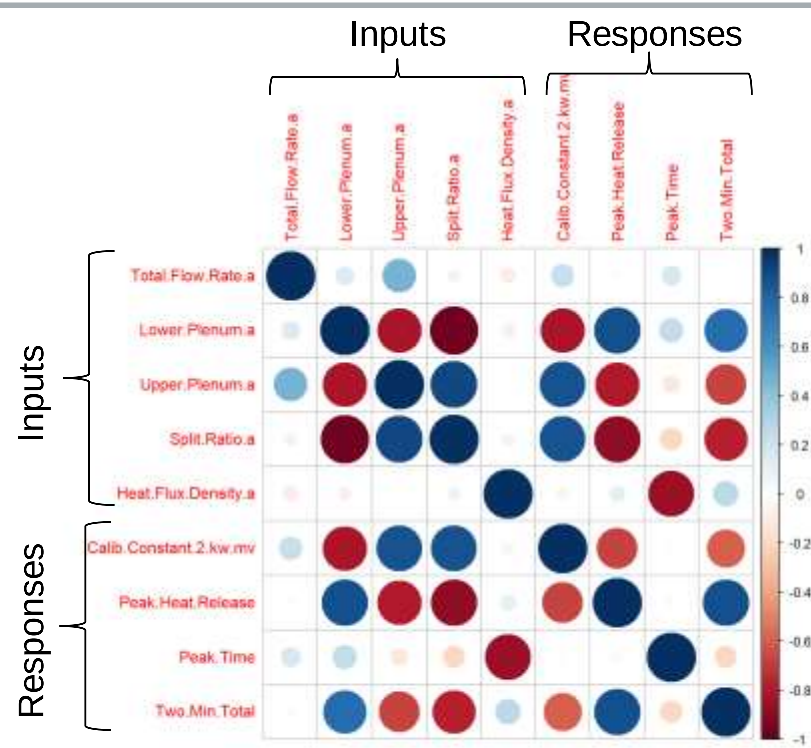
Backup

Additional Statistical Data / Observations

Correlation of Variables

- Total Flow Rate = Lower Plenum + Upper Plenum
- Split Ratio = Upper Plenum/Lower Plenum



First pass analysis assessed effects of Split Ratio, Total Flow Rate, and Heat Flux Density. Second pass analysis will assess Total Flow Rate, Lower Plenum and Heat Flux Density on the responses.

We chose to use Lower Plenum rather than Upper Plenum since it has lower correlation with Total Flow Rate and Heat Flux Density. High correlation amongst the model input variables can impact the estimated effects. Due to the nature of the design, any observed effect of Lower Plenum may in fact be an effect of Upper Plenum.

Calibration Constant – Model Results

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	7.930	1.634	4.85	<.0001
Lower.Plenum	-0.140	0.011	-13.14	<.0001
Total.Flow.Rate	0.089	0.015	5.74	<.0001
Heat.Flux.Density	-0.325	0.237	-1.37	0.1752
(Total.Flow.Rate-85.29)*(Heat.Flux.Density-3.496)	0.132	0.062	2.13	0.0379

Note, variables mean-centered if involved in interactions or higher order effects

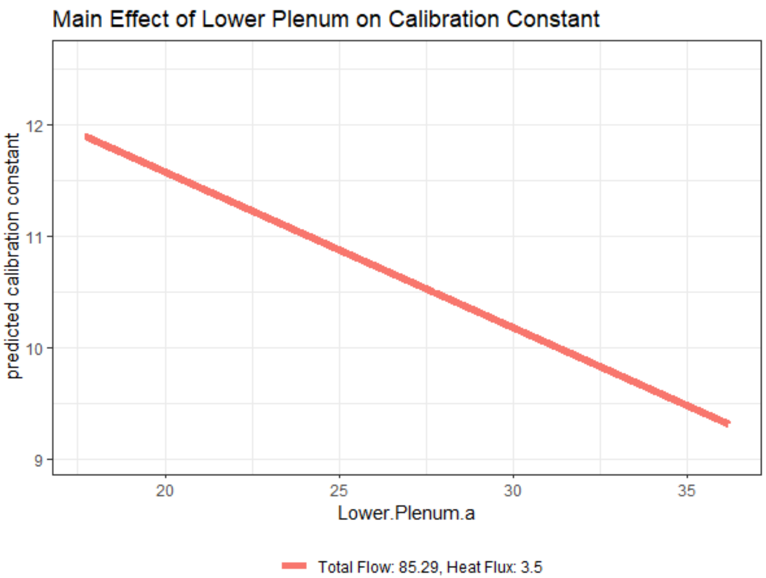
r.squared	adj.r.squared	sigma	statistic	p.value	df	df.residual
0.80378	0.78951	0.47994	56.325	0	5	55

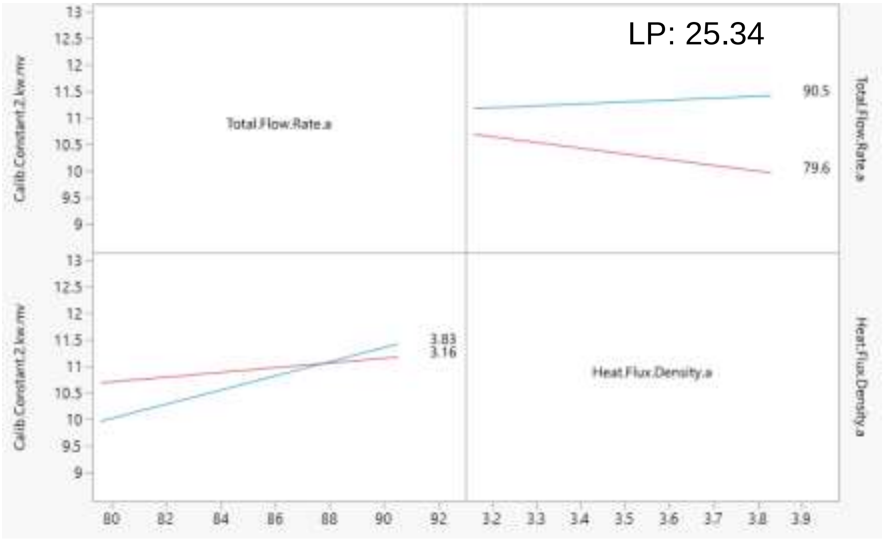
Effect	Relative Importance*
Lower Plenum	67.87%
Total Flow Rate	7.32%
Total Flow Rate*Heat Flux	4.62%
Heat Flux	0.57%

*Relative importance defined in terms of average R-squared contribution

- There is a significant negative effect of Lower Plenum on Calibration Constant.
- There is a significant 2-way interaction between Total Flow Rate and Heat Flux Density. That is, the effect of Total Flow Rate depends on the level of Heat Flux Density.
- The above model explains 80% of the variation observed in Calibration Constant.

Calibration Constant – Effect Plots





Note, for each plot, the other variable(s) present in the model are held at their mean level.

- There is a decreasing trend in calibration constant due to increasing Lower Plenum. For every one unit increase in Lower Plenum, the calibration constant is expected to decrease by 0.14 units.
- There is a larger positive effect of Total Flow Rate when Heat Flux Density is at the high setting (3.83) than at the low (3.16).
- There is little effect of Heat Flux Density when Total Flow Rate is at the high setting (90.5). When Total Flow Rate is low, there is a decreasing trend in calibration constant due to increasing Heat Flux Density.

Peak Heat Release – Model Results

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	39.677	11.591	3.42	0.0012
Lower.Plenum	1.163	0.072	16.11	<.0001
Total.Flow.Rate	-0.286	0.109	-2.63	0.0112
Heat.Flux.Density	3.655	1.731	2.11	0.0394
(Lower.Plenum-25.3383)* (Total.Flow.Rate-85.29)	-0.038	0.018	-2.15	0.0361

Note, variables mean-centered if involved in two-way interactions or higher order effects

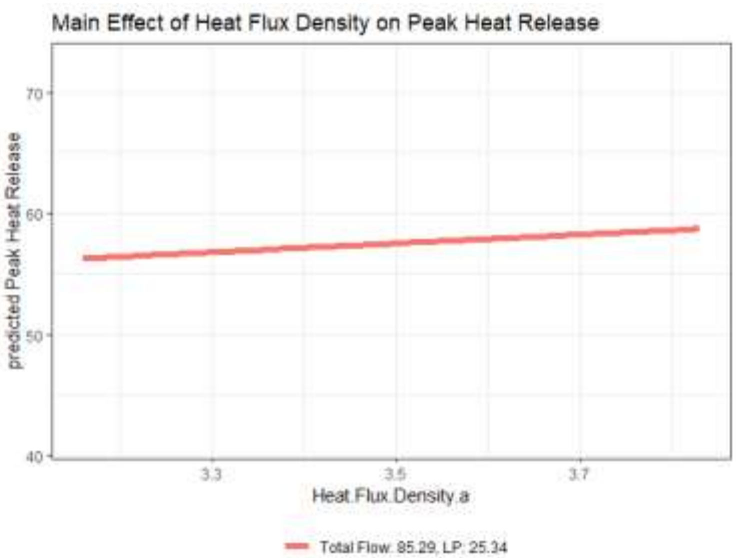
r.squared	adj.r.squared	sigma	statistic	p.value	df	df.residual
0.82715	0.81458	3.3806	65.799	0	5	55

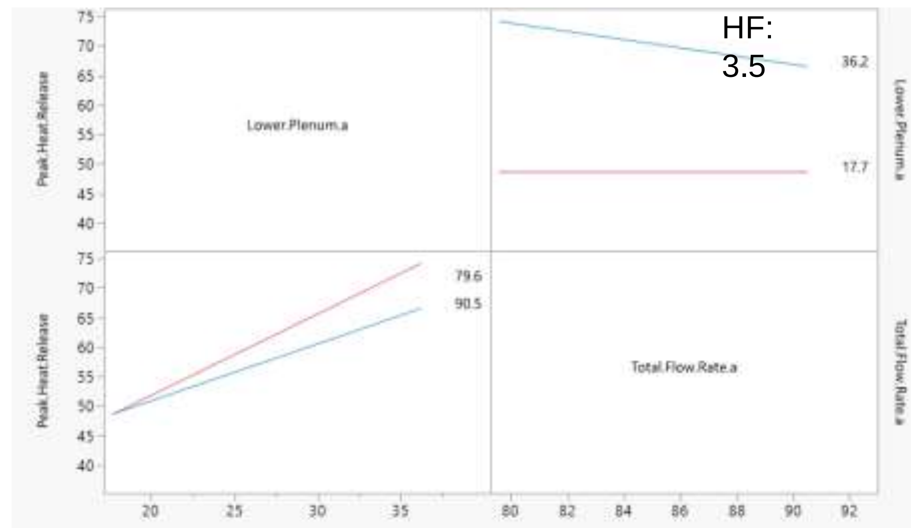
Effect	Relative Importance*
Lower Plenum	78.15%
Heat Flux	1.74%
Total Flow Rate*Lower Plenum	1.72%
Total Flow Rate	1.10%

*Relative importance defined in terms of average R-squared contribution

- There is a significant positive effect of Heat Flux Density on Peak Heat Release.
- There is a significant 2-way interaction between Total Flow Rate and Lower Plenum. That is, the effect of Total Flow Rate depends on the level of Lower Plenum.
- The above model explains 83% of the variation observed in Peak Heat Release.

Peak Heat Release – Effect Plots





Note, for each plot, the other variable(s) present in the model are held at their mean level.

- There is an increasing trend in Peak Heat Release with increasing Heat Flux Density. For every 1 W/cm^2 increase in Heat Flux Density, Peak Heat Release increases by 3.66 kW/m^2 on average.
- The effect of Lower Plenum on Peak Heat Release is more pronounced (steeper positive slope) when Total Flow Rate is at the low setting.
- When Lower Plenum is at the low setting, there is minimal effect of Total Flow Rate on Peak Heat Release. When Lower Plenum is set to high, increasing Total Flow Rate has a negative effect on Peak Heat.

Peak Time – Model Results

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	143.162	8.233	17.39	<.0001
Lower.Plenum	0.263	0.093	2.81	0.0068
Heat.Flux.Density	-29.449	2.180	-13.51	<.0001
(Heat.Flux.Density-3.496)* (Heat.Flux.Density-3.496)	29.433	12.401	2.37	0.0211

Note, variables mean-centered if involved in two-way interactions or higher order effects

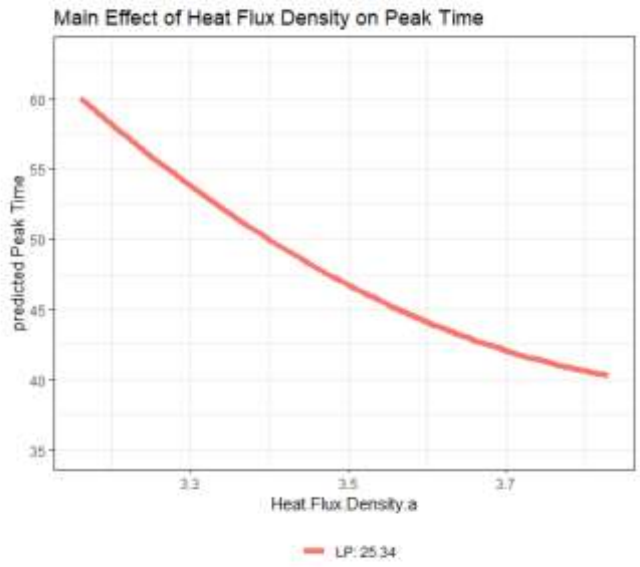
r.squared	adj.r.squared	sigma	statistic	p.value	df	df.residual
0.78607	0.77461	4.4452	68.591	0	4	56

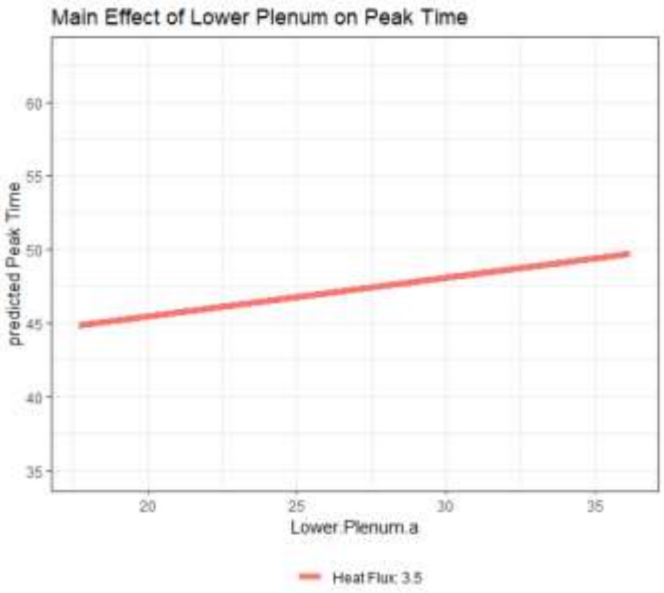
Effect	Relative Importance*
Heat Flux	71.50%
Lower Plenum	4.43%
Heat Flux^2	2.68%

*Relative importance defined in terms of average R-squared contribution

- There is a significant quadratic effect of Heat Flux Density on Peak Time. The effect of Heat Flux Density is overall negative but tapers off due to the present quadratic effect.
- There is a significant positive effect of Lower Plenum on Peak Time.
- There is no significant effect or interaction of Total Flow Rate on Peak Time over the ranges tested.
- The above model explains 79% of the variation observed in Peak Time.

Peak Time – Effect Plots





Note, for each plot, the other variable(s) present in the model are held at their mean level.

- There is a decreasing trend in peak time with increasing heat flux density. The predicted drop in peak time from a 3.16 to 3.83 heat flux density is ~20 seconds.
- For every one unit increase in Lower Plenum, there is a predicted 0.26 second increase in peak time on average.

Two Minute Total – Model Results

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3.638	8.817	0.41	0.6815
Lower.Plenum	0.681	0.057	11.88	<.0001
Total.Flow.Rate	-0.051	0.084	-0.61	0.5466
Heat.Flux.Density	6.193	1.278	4.84	<.0001
(Total.Flow.Rate-85.29)*(Heat.Flux.Density-3.496)	1.011	0.336	3.01	0.0039

Note, variables mean-centered if involved in two-way interactions or higher order effects

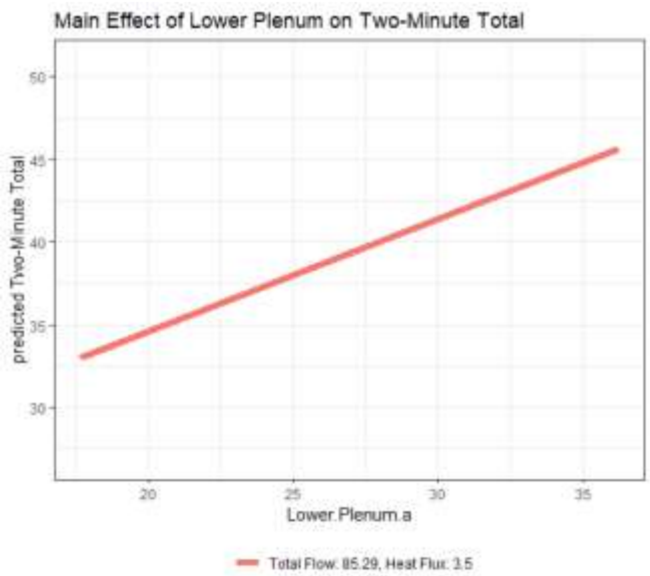
r.squared	adj.r.squared	sigma	statistic	p.value	df	df.residual
0.74	0.72109	2.5896	39.134	0	5	55

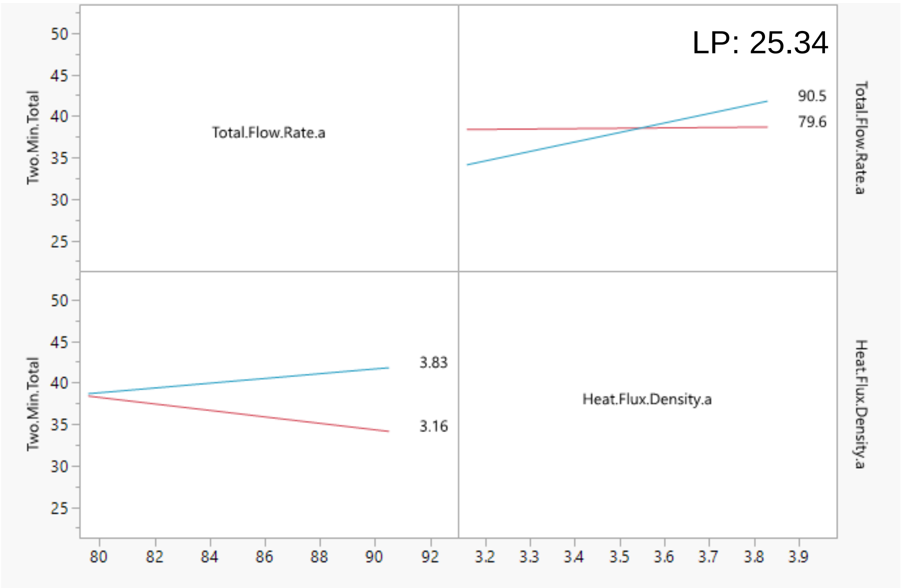
Effect	Relative Importance*
Lower Plenum	62.25%
Heat Flux	8.24%
Heat Flux*Total Flow Rate	3.24%
Total Flow Rate	0.26%

*Relative importance defined in terms of average R-squared contribution

- There is a significant positive effect of Lower Plenum on Two Minute Total.
- There is a significant 2-way interaction between Total Flow Rate and Heat Flux Density. That is, the effect of Total Flow Rate is depends on the level of Heat Flux Density.
- The above model explains 74% of the variation observed in Two Minute Total.

Two Minute Total – Effect Plots





Note, for each plot, the other variable(s) present in the model are held at their mean level.

- For every one unit increase in Lower Plenum, there is a predicted 0.68 unit increase in 2-minute Total Heat Release.
- When Heat Flux is held at the low setting, Total Flow Rate has a negative effect on 2-minute Total. Whereas, when Heat flux is held at the high setting, the effect of Total Flow Rate is slightly positive.
- Heat Flux Density has a positive effect on 2-minute Total when Total Flow Rate is at the high setting (90.5). The effect is less pronounced as Total Flow Rate decreases to the low setting (80).

Conclusion

Summary of Results:

- Calibration Constant:
  - Negative effect of Lower Plenum
  - Significant 2-way interaction between Total Flow Rate and Heat Flux Density
- Peak Heat Release
  - Positive effect of Heat Flux Density
  - Significant 2-way interaction between Total Flow Rate and Lower Plenum
- Peak Time
  - Negative effect of Heat Flux Density (w/ quadratic)
  - Small positive effect of Lower Plenum
- 2-Minute Total Heat Release:
  - Positive effect of Lower Plenum
  - Significant 2-way interaction between Total Flow Rate and Heat Flux Density

- There are significant interactions between Total Flow Rate and Heat Flux Density on Calibration Constant and 2-minute Total Heat Release.
- There is a significant interaction between Total Flow Rate and Lower Plenum on Peak Heat Release.
- Lower Plenum has a negative effect on Calibration Constant but a positive effect on Peak Time and 2-Minute Total.
- Heat Flux Density has a positive effect on Peak Heat Release and a negative effect on Peak Time.
- Total flow rate did not have a statistically significant effect on Peak Time.

Caution on interpretation: Since Lower and Upper Plenum changed together in this study, we cannot determine the effect of Lower and Upper Plenum separately. Hence, all significant effects related to Lower Plenum may be due to the effect of Upper, Lower and/or their interaction.