OSU Calorimetry Test BSS7322

Parametric Study Regarding Airflow into OSU Combustion Chamber

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Agenda / Topics of Discussion:

- Background
- Determination of Density of Moist Air
- Effect of Orifice Plate Tolerance on Airflow into Combustion Chamber
- Determination of Flowrates by Varying Temperature, Pressure, Humidity
- Determination of the Tolerance Effect on Calibration Constant (Kh)
- OSU Airflow Modeling
- Conclusion

Background:

- The Ohio State University Calorimetry (OSU) test used throughout the aircraft industry to determine the heat release of panels flown in the aircraft cabin interior
  - Significant variation in round robin data acquired among industry labs has been noted
  - Roughly 50 % of variation remains unexplained
  - FTWG making progress in determining root cause
    - Airflow highly suspected

- Certain airflow parameters are not regulated:
  - Incoming airflow relative humidity
  - Local atmospheric barometric pressure

- Parametric study conducted to capture variation due to changing atmospheric conditions
  - Published tolerances for OSU apparatus were maintained
    - Incoming air temperature range of 21 to 24˚C
    - Differential pressure across orifice plate of 200 mmHg
      - *Approximate* air flow rate of 0.04 m^3/s
    - Orifice plate diameter of 19.1 ± 0.1 mm

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

Determination of Density of Moist Air:

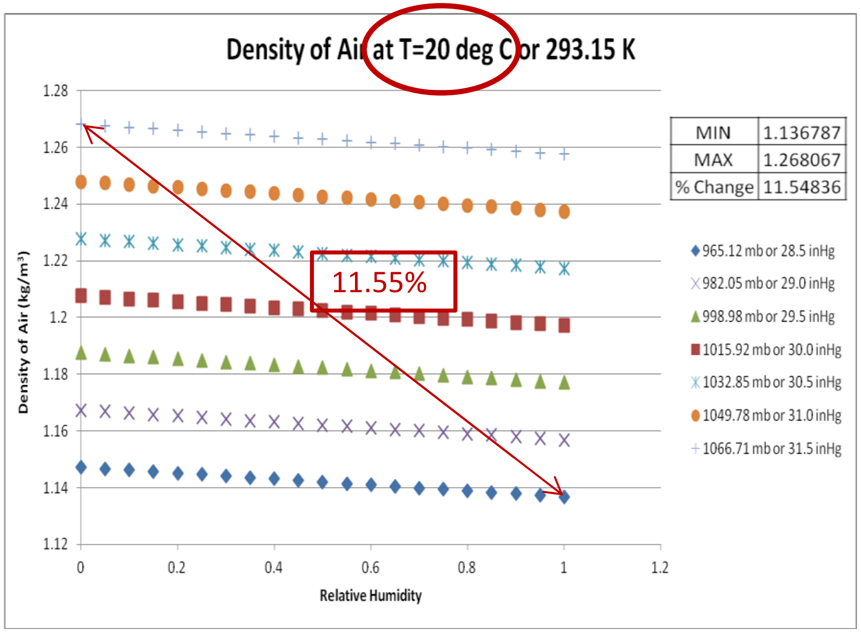
- Initial thought: To what extent does humidity have on the density of air ?

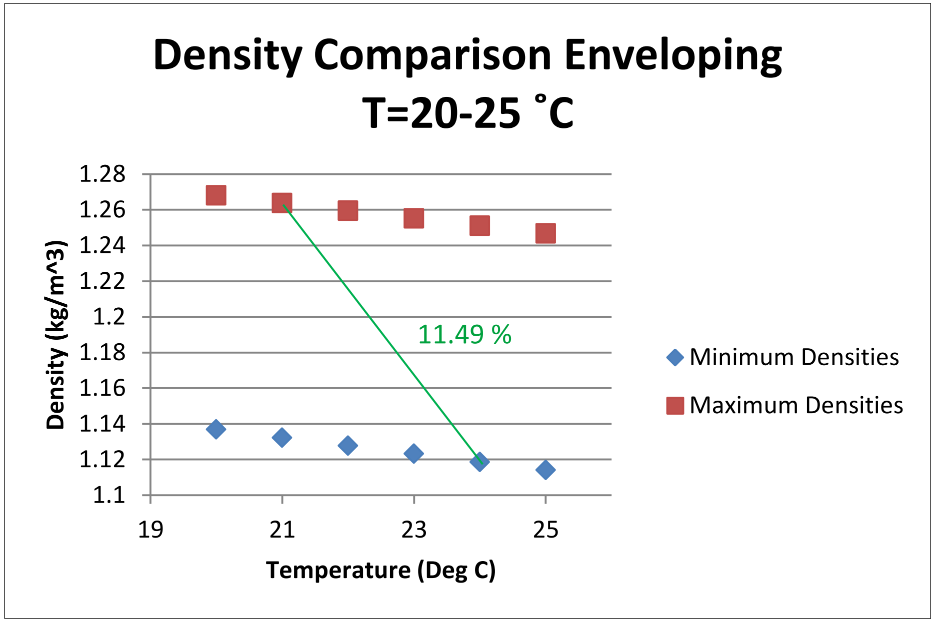
  - Ideal gas law developed to account for properties exhibited by a real gas

- Spreadsheet developed to envelope probable atmospheric weather conditions
  - Atmospheric pressure range from 965.12 mb (28.5 inHg) to and including 1066.71 mb (31.5 inHg)
  - The atmospheric temperature ranged from 20 to 25˚C
  - The relative humidity ranged from 0% to 100 %

- All combinations were checked, resulting in over three thousand iterations and a variability assessment

Results Regarding Moist Air Density:





Note: Graphs were also produced but are not presented for Temperatures of 21, 22, 23, 24, 25˚C

Temp	Min Dens	Max Dens
20	1.136787	1.2680672
21	1.132248	1.2637432
22	1.127704	1.2594487
23	1.123153	1.2551834
24	1.118593	1.250947
25	1.114023	1.2467392

- **Observation:**
  - ***Possible to have a noticeable change in air density just by keeping the temperature within tolerances, due to uncontrolled humidity and a change in barometric pressure. Can vary by over 11.5% due to uncontrolled humidity and barometric pressure.***

<u>Effect of Orifice Plate Tolerance on Airflow into Combustion Chamber</u>:

- Current FAA regulation requires the airflow to be regulated to <u>*approximately*</u> 0.04 m^3/s (85 ft^3/s) by means of an orifice plate with the following tolerances:

  - Square-edge circular, 24-gauge stainless steel, 0.5 ± 0.1 mm (0.024 ± 0.005 inch) thick
  - Placed in a circular pipe with diameter of 38 mm (1.5 inch)
  - *The orifice hole itself should be 19.1 ± 0.1 mm (0.750 ± 0.002 inch)*
  - The differential pressure across this plate should measure 200 mmHg (7.87 inHg)

- Using Bernoulli equation, the volumetric flowrate can be determined by the following:

$$Q = C_f A_o \sqrt{\frac{2\Delta p}{\rho}}$$

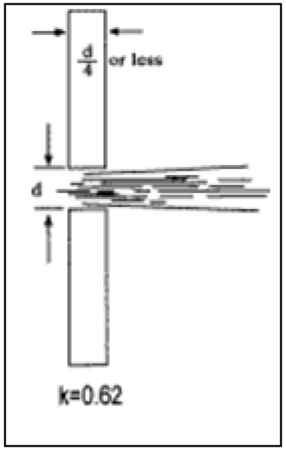
Where Q is volumetric flowrate in m^3/s

C_f is flow coefficient that has been determined experimentally -- *For thin plate, square edged circular $C_f = 0.62$*

Ao is the area of the orifice (m^2)

Δp is the differential pressure (N/m^2)

ρ is the density of the air (kg/m^3)

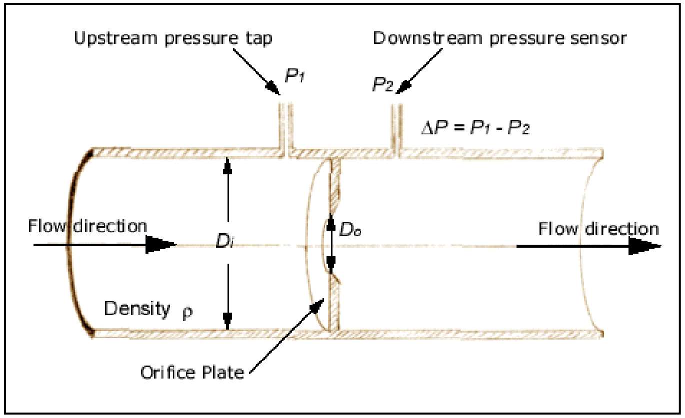


www.efunda.com/formulae/fluids/calc_orifice_flowmeter.cfm

Results of Orifice Plate Tolerance:

- The design tolerance of the orifice plate is 19.1 ± 0.1 mm
- The differential pressure must be approximately 200 mmHg
  - Note: Has been seen to fluctuate between 180 to 220 mmHg at a constant pressure regulator setting.

- Nine scenarios were checked to see the effect of orifice area and differential pressure on volumetric flowrate. The three cases which warrant discussion are listed below:
  - Nominal Orifice Area with Nominal Differential Pressure
  - Tolerance Low Orifice Area with Low Differential Pressure
  - Tolerance High Orifice Area with High Differential Pressure



http://www.mcnallyinstitute.com/13-html/13-12.htm

- ***Nominal Conditions:***
  - Ao_{NOM} = *19.1 mm*
  - ΔP_{NOM} = *200 mmHg*
  - $\rho_{AIR\ (Assumed)}$ = 1.200 kg/m^3
  - ***Q = 0.03745* m³/s**

- NOTE: Even at nominal dimensions, this represents a 6.4 % departure from the expected flowrate of Q=0.04 m^3/s.

Results of Orifice Plate Tolerance:

- ***Tolerance Low Conditions:***
  - Ao_{LOW} = *19.0 mm*
  - ΔP_{LOW} = *180 mmHg*
  - $\rho_{AIR\ (Assumed)}$= 1.200 kg/m^3
  - ***Q*** **= 0.0352 m^3/s**
  - Represents a **12.1 %** departure from the expected flowrate
  - *Largest departure* from expected flowrate within the nine checked scenarios

- ***Tolerance High Conditions:***
  - Ao_{HIGH} = *19.2 mm*
  - ΔP_{HIGH} = *220 mmHg*
  - $\rho_{AIR\ (Assumed)}$= 1.200 kg/m^3
  - **Q=0.0397 m^3/s**
  - Represents a **0.78 %** departure from the expected flowrate
  - Closest approach to expected flowrate within the nine checked scenarios

- Interesting observations:

  - An exact 0.04 m^3/s flow rate is not achievable under the studied parametric conditions.

  -Difference between lowest volumetric flowrate (0.0352 m^3/s) and highest (0.0397 m^3/s) is **12.89 %.**

  - ***May have an effect on combustion dynamics and ultimately results.***

Determination of Flowrates by Varying Temperature, Pressure, Humidity:

- How much air is actually getting into the combustion chamber ?
  - Determined exact densities for pressures, temperatures, and humidity using excel spreadsheet
  - Used exact densities and iterated Bernoulli equation to determine flowrates

- Results:
  - It is *impossible* to achieve Q=0.04 m^3/s under common atmospheric conditions and *nominal* spec values

  - To achieve Q=0.04 m^3/s for incoming air temperatures ranging from 20 to 25˚C:
    - Atmospheric pressure should range from 998.98 mb (for T=20, 21, 22˚C) and 1015.92 mb (T=23, 24, 25˚C)
    - Differential Pressure will always need to read 220 mmHg
    - Orifice Plate diameter will always need to be 19.2 mm
    - Density based on temperature, pressure, and humidity will always need to be about 1.18 kg/m^3
    - Anything other than that will not produce 0.04 m^3/s volumetric flowrate

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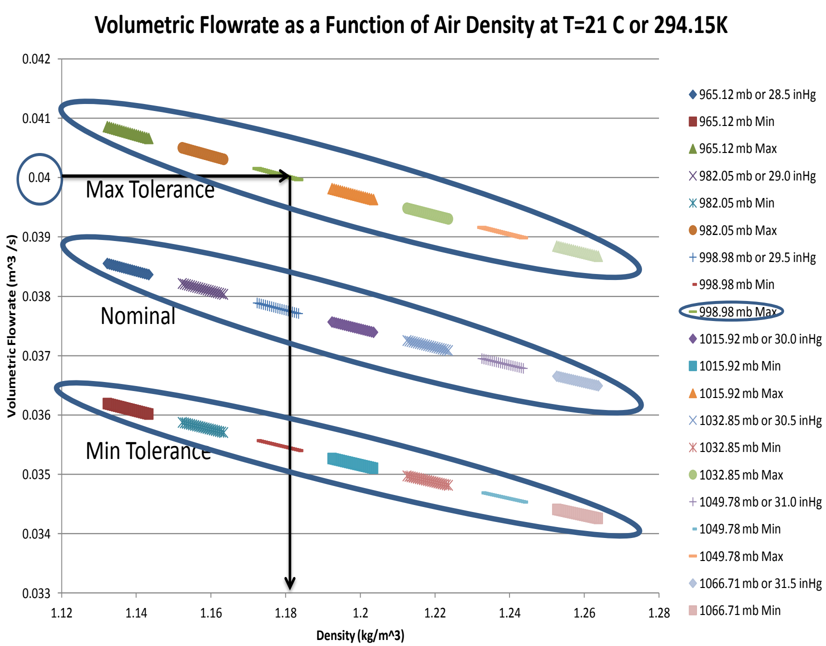
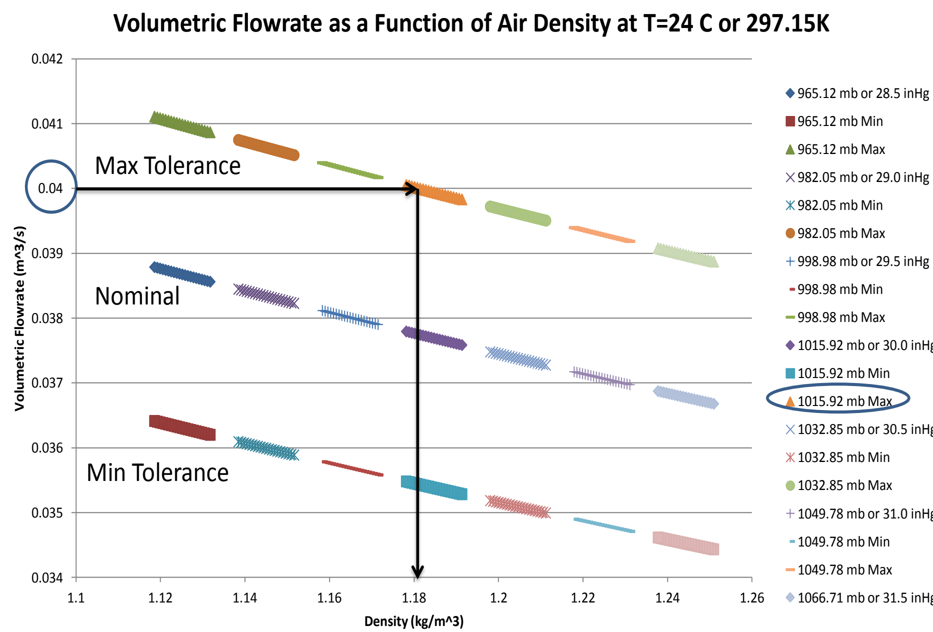
Results of Flowrate Study:



In order to achieve a 0.04 m^3/s volumetric flow rate, Pa = 998.98 mb / 29.5 inHg, and a RH of about 20 %,which will give the air density of 1.1813 kg/m^3 at 21 deg C. Additionally, from the chart, the OSU orifice plate will need to be 19.2 mm in diameter, with differential pressure set at 220 mmHg. Following a nominal trajectory will not give the required flowrate in this case.



In order to achieve a 0.04 m^3/s volumetric flow rate, Pa = 1015.92 mb / 30.0 inHg, and a RH of about 75 %, which will give the air density of 1.1815 kg/m^3 at 24 deg C. Additionally, from the chart, the OSU orifice plate will need to be 19.2 mm in diameter, with differential pressure set at 220 mmHg. Following a nominal trajectory will not give the required flowrate in this case.

- Notes:
  - For Max Tolerance: *Ao=19.2 mm, ΔP=220 mmHg*
  - For Nominal Tolerance: *Ao=19.1 mm, ΔP=200 mmHg*
  - For Min Tolerance: *Ao=19.0 mm, ΔP=180 mmHg*

Results of Flowrate Study:

- For temperature ranging from T=21 to 24˚C:
  - Lowest volumetric flowrate possible is Q_{min}=0.034258 m^3/s
  - Corresponds also to the highest air density of 1.263743 kg/m^3
  - **Results in a 14.36 % departure from the nominal Q=0.04 m^3/s expected flowrate**

  - Greatest volumetric flowrate possible is Q_{max}=0.041108 m^3/s
  - Corresponds to the lowest air density of 1.118593 kg/m^3,
  - **Results in a 2.77 % departure from the nominal Q=0.04 m^3/s expected flowrate**

- **Observation:** If the minimum flowrate (0.034258 m^3/s) is compared to the maximum flowrate possible (0.041108 m^3/s), the difference between the two becomes **16.66 %.** This may also affect the burn output of the coupons, and paints a picture of the inherent variability within the OSU system.

Determination of the Tolerance Effect on Calibration Constant (Kh):

- Calibration constant acts as a normalization factor between OSU shutdown and future operations.
  - This directly effects the heat release peak/total calculations

- Takes into account methane flowrates, thermopile voltages, ambient temperatures and pressures, and water vapor pressure.

The calibration constant (Kh) is defined as:

$$kh = 25.31 \bullet ((F1 - F0)/(V1 - V0)) \bullet (273/Ta) \bullet ((Pa - Pv)/760)$$

where:
kh = calibration factor (kW/mV/m2)
F0 = flow rate methane (L/min) at baseline (approximately 1 L)
F1 = flow rate of methane (L/min) at higher upward step flow (approx. 4, 6, or 8 L/min)
V0 = thermopile voltage (mV) at baseline
V1 = thermopile voltage (mV) at higher upward step flow
Ta = ambient temperature (degrees Kelvin)
Pa = ambient pressure (mm Hg)
Pv = water vapor pressure at the temperature of the wet test meter water temperature (mm Hg)

Determination of the Tolerance Effect on Calibration Constant (Kh):

- The methane flowrates and thermopile voltages were not considered in this study and were assumed constant equal to one. Calibration equation simplifies to:

$$kh = (273/Ta) \bullet ((Pa - Pv)/760)$$

- Parameters:
  - Temperature ranged from 21 to 24˚C
  - Pv was obtained from thermodynamic data tables
  - Pressure was varied from 723.9mmHg (28.5 inHg) to 800.1 mmHg (31.5 inHg)

Ta = 21 C		Kh
	min	0.85878002
	max	0.89670907

Ta = 24 C		Kh
	min	0.90468282
	max	0.94339479

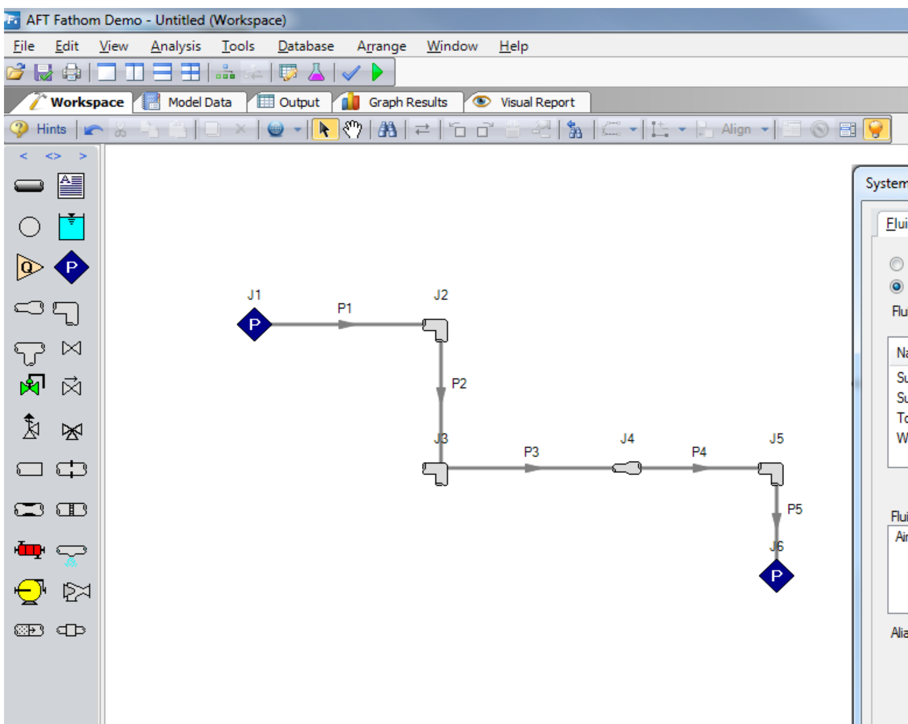
- Results:
  - Within the OSU operating conditions ranging from T=21 to 24˚C:
    - Kh minimum: 0.858780
    - Kh maximum: 0.943395

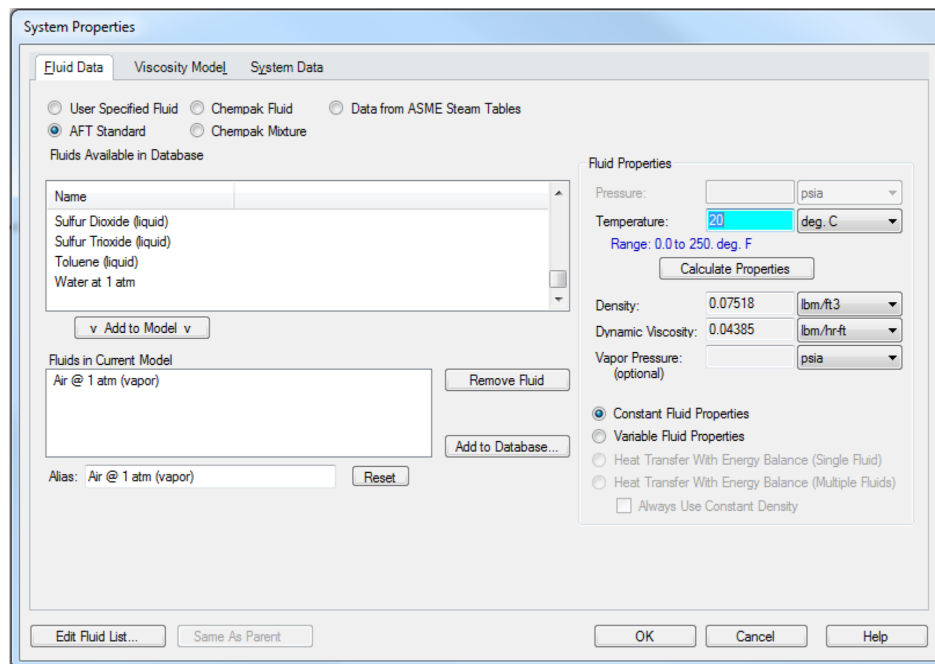
  - This corresponds to a **9.85 %** possible change within the calibration constant itself, neglecting multiple other parameters that may have an effect.

OSU Airflow Modeling and Discussion

Modeling:

- Interested in mathematical solution of practical setup
  - -Used COTS program *AFT Fathom* Demo version to develop model
    - - Limited to 5 joints; Broke OSU setup into sections
    - - Air was assumed at 20˚C and 1 atm.





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Workspace | Model Data | Output | Graph Results | Visual Report

General | Warnings

Title: AFT Fathom Demo Model
Analysis run on: 8/6/2013 15:41:04
Application version: AFT Fathom Version 8 Demo
Input File: Untitled
Output File: C:\AFT Products\AFT Fathom 8 Demo\Untitled_1.out

Execution Time= 0.08 seconds
Total Number Of Head/Pressure Iterations= 0
Total Number Of Flow Iterations= 4
Total Number Of Temperature Iterations= 0
Number Of Pipes= 5
Number Of Junctions= 6
Matrix Method= Gaussian Elimination

Pressure/Head Tolerance= 0.0001 relative change
Flow Rate Tolerance= 0.0001 relative change
Temperature Tolerance= 0.0001 relative change
Flow Relaxation= (Automatic)
Pressure Relaxation= (Automatic)

Volumetric Flow Rate expected as 0.04 m^3/s

Sonic Velocity at T=20C: α ~ 344 m/s

Mach: 280.66/344 = 0.82

Pipes

Pipe	Name	Vol. Flow Rate (m3/sec)	Velocity (meters/sec)	P Static Max (psia)	P Static Min (psia)	Elevation Inlet (feet)	Elevation Outlet (feet)	dP Stag. Total (psid)	dP Static Total (psid)	dP Gravity (psid)	dH (feet)	P Static In (psia)	P Static Out (psia)	P Stag. In (psia)	P Stag. Out (psia)
1	Pipe	0.04240	280.66	29.82	28.85	5.208	5.208	0.964417	0.964417	0.000E+00	1,847.247	29.82	28.85	36.70	35.73
2	Pipe	0.04240	280.66	23.36	19.57	5.208	4.292	3.788302	3.788302	-4.786E-04	7,257.043	23.36	19.57	30.24	26.45
3	Pipe	0.04240	280.66	14.07	13.21	4.292	4.292	0.861086	0.861086	0.000E+00	1,649.328	14.07	13.21	20.95	20.09
4	Pipe	0.04240	37.19	14.79	14.75	4.292	4.208	0.040027	0.040027	-4.351E-05	76.751	14.79	14.75	14.91	14.87
5	Pipe	0.04240	37.19	14.70	14.70	4.208	4.208	0.001484	0.001484	0.000E+00	2.842	14.70	14.70	14.82	14.82

All Junctions | Area Change | Assigned Pressure | Bend

Jct	Name	P Static In (mm Hg)	P Static Out (mm Hg)	P Stag. In (psia)	P Stag. Out (psia)	Vol. Flow Rate Thru Jct (gal/min)	Mass Flow Rate Thru Jct (lbm/sec)	Loss Factor (K)
1	Assigned Pressure	1,542.0	1,542.0	36.70	36.70	672.0	0.1126	0.0000
2	Bend	1,492.1	1,207.9	35.73	30.24	672.0	0.1126	0.7990
3	Bend	1,012.0	727.7	26.45	20.95	672.0	0.1126	0.7990
4	Area Change	683.2	765.0	20.09	14.91	672.0	0.1126	0.7526
5	Bend	762.9	760.3	14.87	14.82	672.0	0.1126	0.4200
6	Assigned Pressure	760.2	760.2	14.82	14.82	672.0	0.1126	0.0000

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Workspace | Model Data | Output | Graph Results | Visual Report

General | Warnings

For an explanation of Warnings, click an item in this list and press F1 or search for 'Warnings' in the Help system.

CAUTION Pipe 2 length is shorter than the elevation change (between Junction 2 (Bend) and 3 (Orifice)).

Pipes

Pipe	Name	Vol. Flow Rate (m3/sec)	Velocity (meters/sec)	P Static Max (mm Hg)	P Static Min (mm Hg)	Elevation Inlet (feet)	Elevation Outlet (feet)	dP Stag. Total (psid)	dP Static Total (psid)	dP Gravity (psid)	dH (feet)	P Static In (psia)	P Static Out (psia)	P Stag. In (psia)	P Stag. Out (psia)
1	Pipe	0.04240	37.19	985.1	982.2	4.2083	4.2083	0.05509	0.05509	0.000E+00	95.94	19.05	18.99	19.18	19.13
2	Pipe	0.04240	37.19	979.3	976.9	4.2083	1.5833	0.04650	0.04650	-1.507E-03	83.61	18.94	18.89	19.07	19.02
3	Pipe	0.04240	37.19	768.9	767.8	1.5833	0.5000	0.02063	0.02063	-6.220E-04	37.01	14.87	14.85	15.00	14.98
4	Pipe	0.04240	37.19	765.0	764.3	0.5000	0.5000	0.01338	0.01338	0.000E+00	23.30	14.79	14.78	14.92	14.91
5	Pipe	0.04240	37.19	761.4	760.2	0.5000	1.6667	0.02270	0.02270	6.699E-04	38.38	14.72	14.70	14.86	14.83

All Junctions | Assigned Flow | Assigned Pressure | Bend | Orifice

Jct	Name	P Static In (mm Hg)	P Static Out (mm Hg)	P Stag. In (psia)	P Stag. Out (psia)	Vol. Flow Rate Thru Jct (gal/min)	Mass Flow Rate Thru Jct (lbm/sec)	Loss Factor (K)
1	Assigned Flow	985.1	985.1	19.18	19.18	672.1	0.1238	0.0000
2	Bend	[illegible]	979.2	19.13	19.07	672.1	0.1238	0.4200
3	Orifice	976.9	768.9	[illegible]	15.00	672.1	0.1238	30.2824
4	Bend	767.8	[illegible]	14.98	14.92	672.1	0.1238	0.4200
5	Bend	764.3	761.4	14.91	14.86	672.1	0.1238	0.4200
6	Assigned Pressure	760.2	760.2	14.83	14.83	672.1	0.1238	0.0000

ΔP across Orifice Plate = 208 mmHg, Expect 200 mmHg

Workspace | Model Data | **Output** | Graph Results | Visual Report

General | Warnings

For an explanation of Warnings, click an item in this list and press F1 or search for 'Warnings' in the Help system.

CAUTION Pipe 5 length is shorter than the elevation change (between Junction 2 (Tee or Wye) and 6 (Assigned Pressure)).
CAUTION Pipe 3 length is shorter than the elevation change (between Junction 3 (Area Change) and 4 (Area Change)).

Need to Compare Pipe 2 to Pipe 5 flows:

Pipe 2: 0.007683 / 0.0424 = 18.1 %

Pipe 5: 0.034717/ 0.0424 = 81.9 %

Pipes

Pipe	Name	Vol. Flow Rate (m3/sec)	Velocity (meters/sec)	P Static Max (psia)	P Static Min (psia)	Elevation Inlet (feet)	Elevation Outlet (feet)	dP Stag. Total (psid)	dP Static Total (psid)	dP Gravity (psid)	dH (feet)	P Static In (psia)	P Static Out (psia)	P Stag. In (psia)	P Stag. Out (psia)
1	Pipe	0.042400	37.190	14.83	14.82	1.667	2.292	0.0114591	0.0114591	3.263E-04	21.324	14.83	14.82	14.95	14.94
2	Pipe	0.007683	6.739	14.92	14.92	2.292	2.292	0.0008572	0.0008572	0.000E+00	1.642	14.92	14.92	14.92	14.92
3	Pipe	0.007683	44.152	14.68	14.66	2.292	2.667	0.0158724	0.0158724	1.958E-04	30.027	14.68	14.66	14.85	14.83
4	Pipe	0.007683	6.477	14.70	14.70	2.667	2.917	0.0021399	0.0021399	1.305E-04	3.849	14.70	14.70	14.71	14.70
5	Pipe	0.034717	30.451	14.74	14.70	2.292	5.042	0.0351241	0.0351241	1.436E-03	64.527	14.74	14.70	14.82	14.78

Expected 25 % / 75% flow…. Do not see it in cal constant

All Junctions | Multiple Losses | Area Change | Assigned Flow | Assigned Pressure | Tee or Wye

Jct	Name	P Static In (mm Hg)	P Static Out (mm Hg)	P Stag. In (psia)	P Stag. Out (psia)	Vol. Flow Rate Thru Jct (gal/min)	Mass Flow Rate Thru Jct (lbm/sec)	Loss Factor (K)
1	Assigned Flow	766.8	766.8	14.95	14.95	672.1	0.11257	0.0000
2	Tee or Wye	769.7	769.7	14.94	14.94	N/A	N/A	See Mult. Losses
3	Area Change	771.4	758.9	14.92	14.85	121.8	0.02040	18.9585
4	Area Change	758.1	760.3	14.83	14.71	121.8	0.02040	0.7281
5	Assigned Pressure	760.2	760.2	14.70	14.70	121.8	0.02040	0.0000
6	Assigned Pressure	760.2	760.2	14.78	14.78	550.3	0.09217	0.0000

13th International Symposium on Fire and Flammability (INTERFLAM 2013)
Royal Holloway College, UK, 24-26 June, 2013

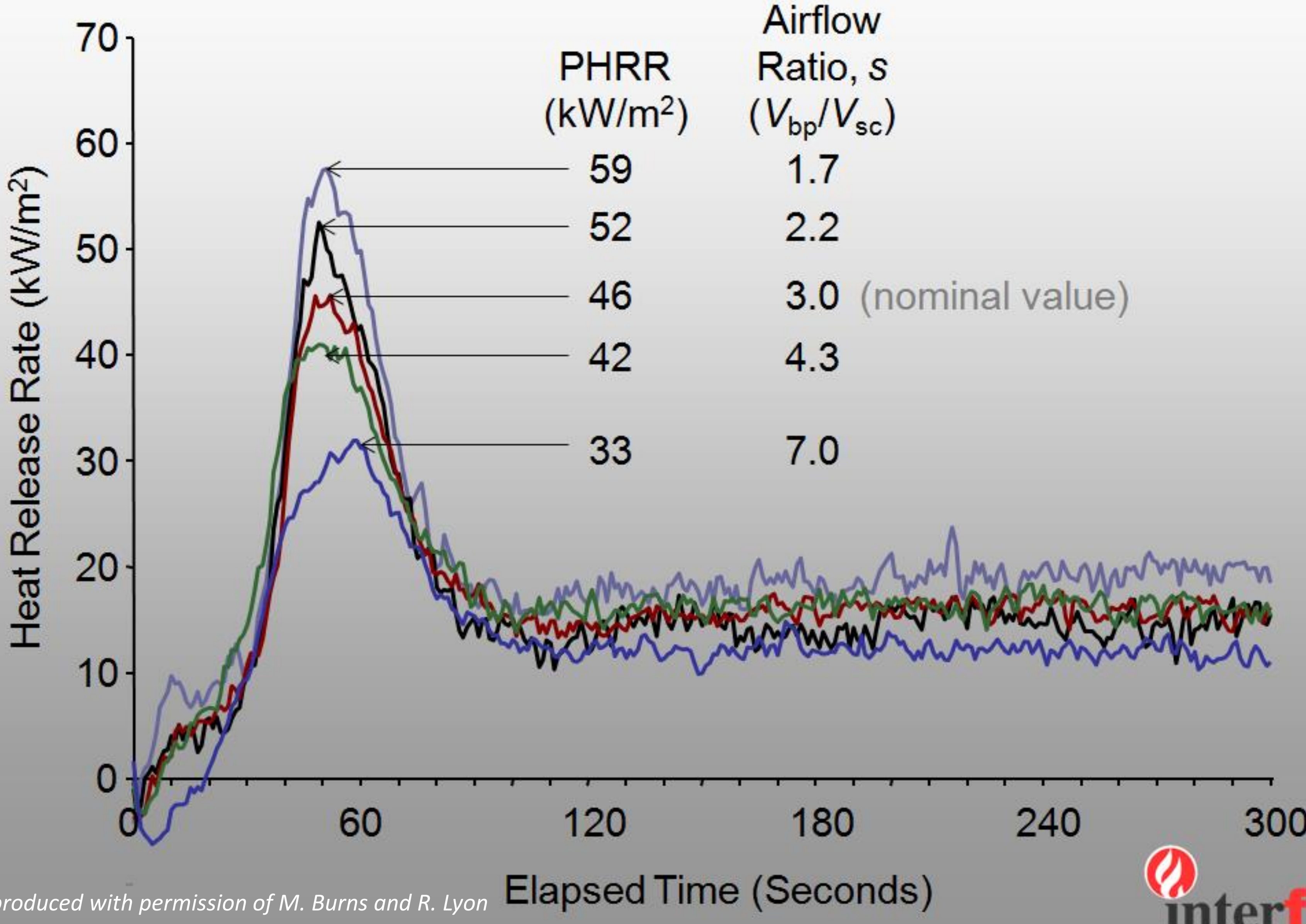
Sources of Variability in Heat Release Rate Measured in the Ohio State University Apparatus

Richard N. Walters, Matthew Fulmer, Sean Crowley, Michael Burns, and Richard E. Lyon

Federal Aviation Administration
Airport and Aircraft Safety Division
W.J. Hughes Technical Center
Atlantic City International Airport, NJ 08405

interflam

Effect of Air Flow Ratio on Heat Release Rate History of Phenolic Panel by Thermopile (TP) Method



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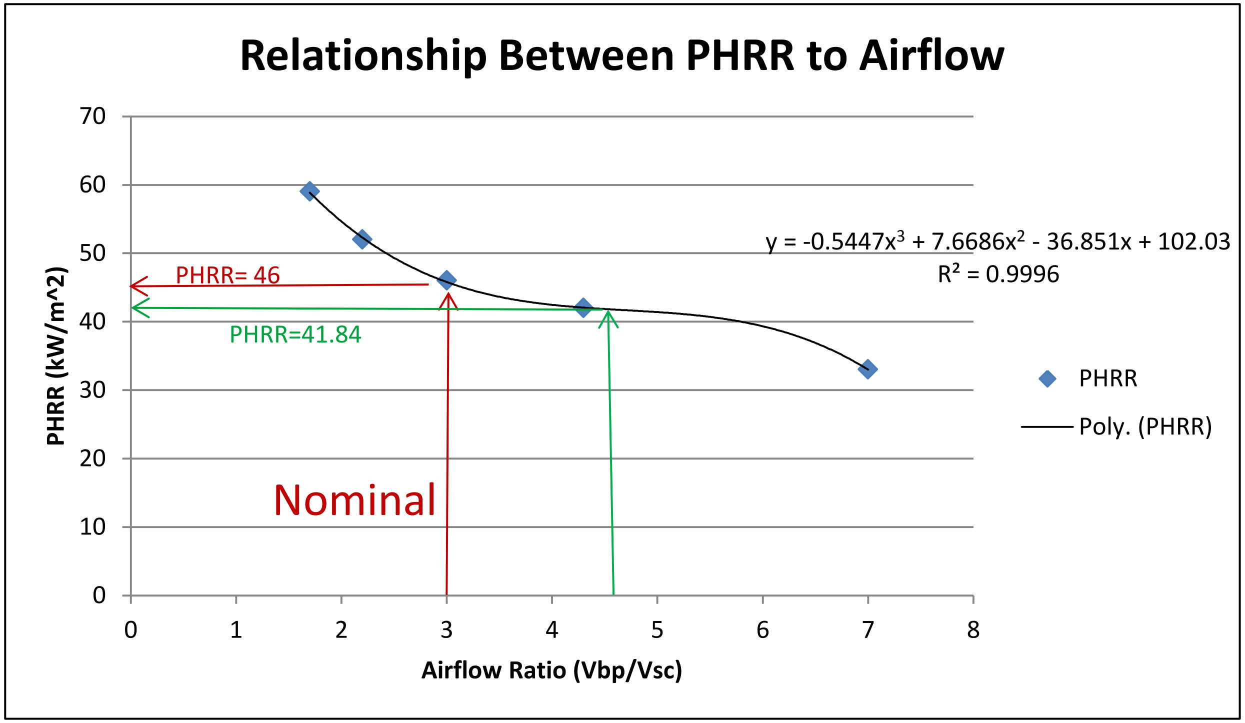

A (hypothetical) 81.9 / 18.1 % split results in an airflow ratio of 4.52 (nominal is 3.0)

Plugging 4.52 into above equation yields a ***Theoretical PHRR based on modified airflow ratio:*** ***41.84 kW/m²***

The average PHRR of the past 100 Round Robin coupons (20 sets of five coupons) in Charleston from 24 APR 13 to 22 OCT 13 is 41.88 kW/m²

Good Correlation !!

Recommendation:

- All else being the same, except changing stage 3 pipe 5 to ID of 1.278 (schedule 80, 1.25 OD), the results were re-run.

Need to Compare Pipe 2 to Pipe 5 flows:

Pipe 2: 0.009623 / 0.0424 = 22.7 %

Pipe 5: 0.032777/ 0.0424 = 77.3 %

Pipes

Pipe	Name	Vol. Flow Rate (m3/sec)	Velocity (meters/sec)	P Static Max (psia)	P Static Min (psia)
1	Pipe	0.042400	37.190	14.95	14.94
2	Pipe	0.009623	8.440	15.04	15.04
3	Pipe	0.009623	55.303	14.66	14.64
4	Pipe	0.009623	8.113	14.70	14.70
5	Pipe	0.032777	39.605	14.77	14.70

- Airflow split ratio now becomes 3.41 (was 4.52)

-Theoretical PHRR would increase to 43.94 kW/m^2 (was 41.84 kW/m^2)

- Corresponds to a 5.0 % increase in PHRR

Conclusions:

- Parametric study conducted that explored the effect of varying atmospheric temperature, pressure, and humidity as well as the tolerance effects of the orifice plate and calibration constant with regard to atmospheric changes.

- Up to a ***12 % variation in air density*** can occur based on temperature, humidity, and pressure differences.

- Up to a ***17 % variation in volumetric flow rate*** of combustion chamber inbound air can occur as the ambient conditions change and the OSU equipment tolerances are accounted for.

- Up to a ***10 % variation can occur in the calibration constant*** as atmospheric conditions change.

- Modeling may be a good starting point to determine actual airflow split ratio which yields a theoretical HRR.

- Comparison of theoretical HRR to reported HRR validates model and may serve as a normalization factor for the purposes of round robin comparison.