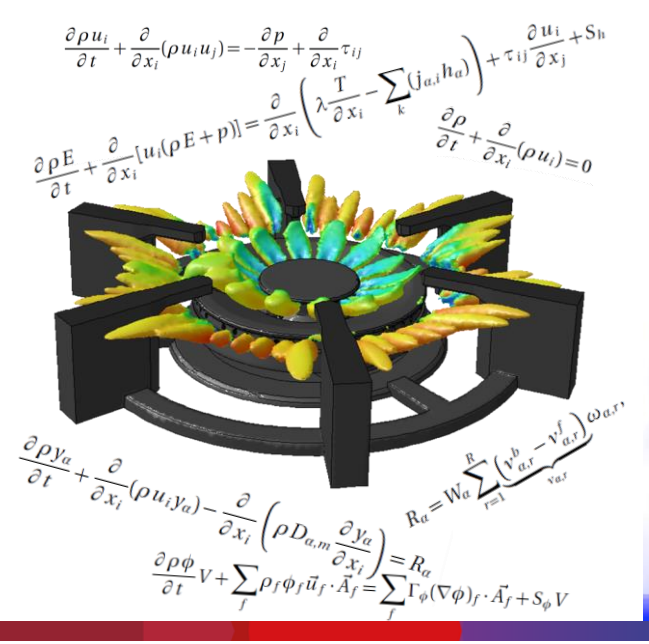


BSH Home Appliances Group

B/S/H/ UC

Optimization of the geometry of domestic gas burner injectors by using the Design Exploration Process

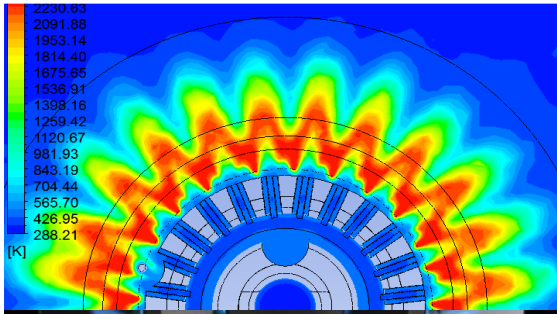
Adriana Cavada

Director: Luis Alberto Fernández
Co-director: José Salvador Ochoa

March, 2019

INNOVATION SIMULATION

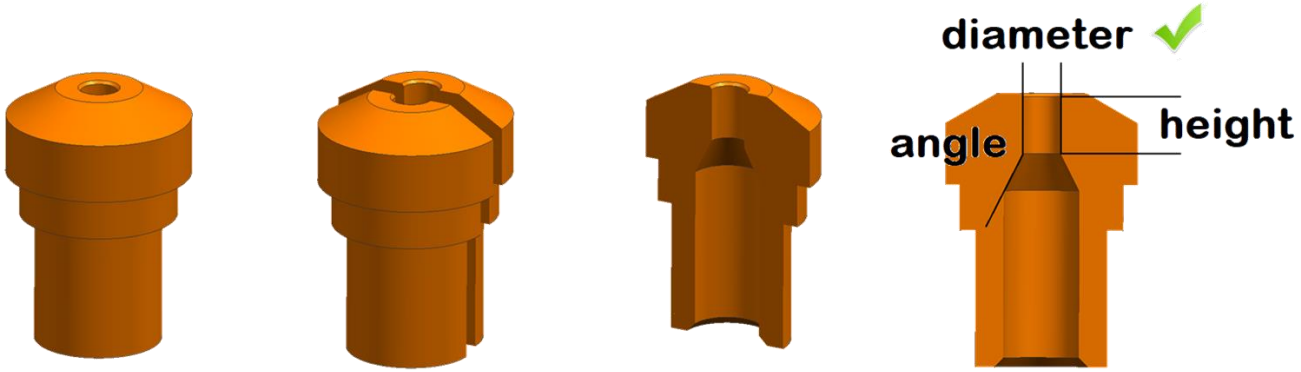
GAS COMPETENCE CENTER

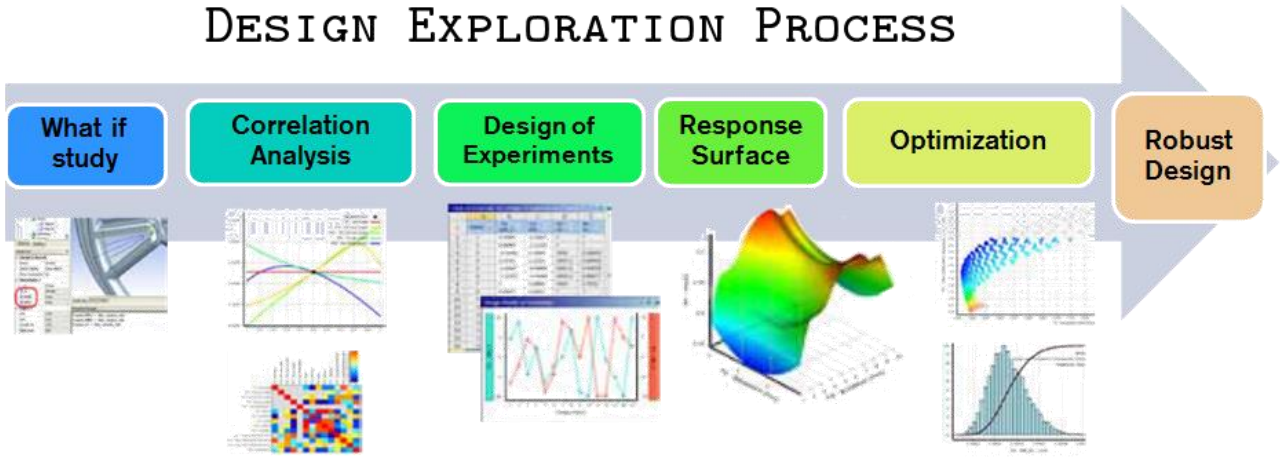


Contents

Purpose

- Analyze the influence of injectors' internal geometry on the performance of the fuel jet and its capacity to entrain air.





Workflow, Theory & Results

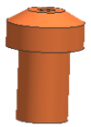
1. Geometry

Workflow, Theory & Results

1. Geometry

Project Schematic

Burner Structure



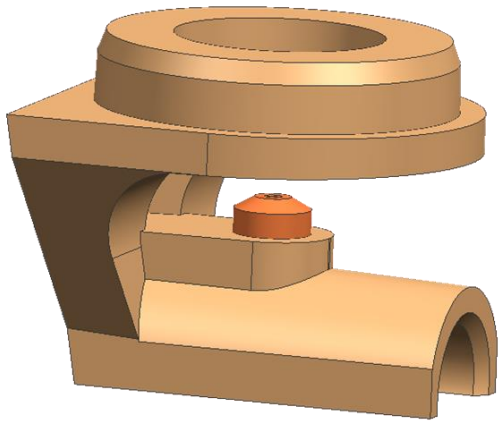
1. Injector

Workflow, Theory & Results

1. Geometry

Project Schematic

Burner Structure



2. Porta-injector

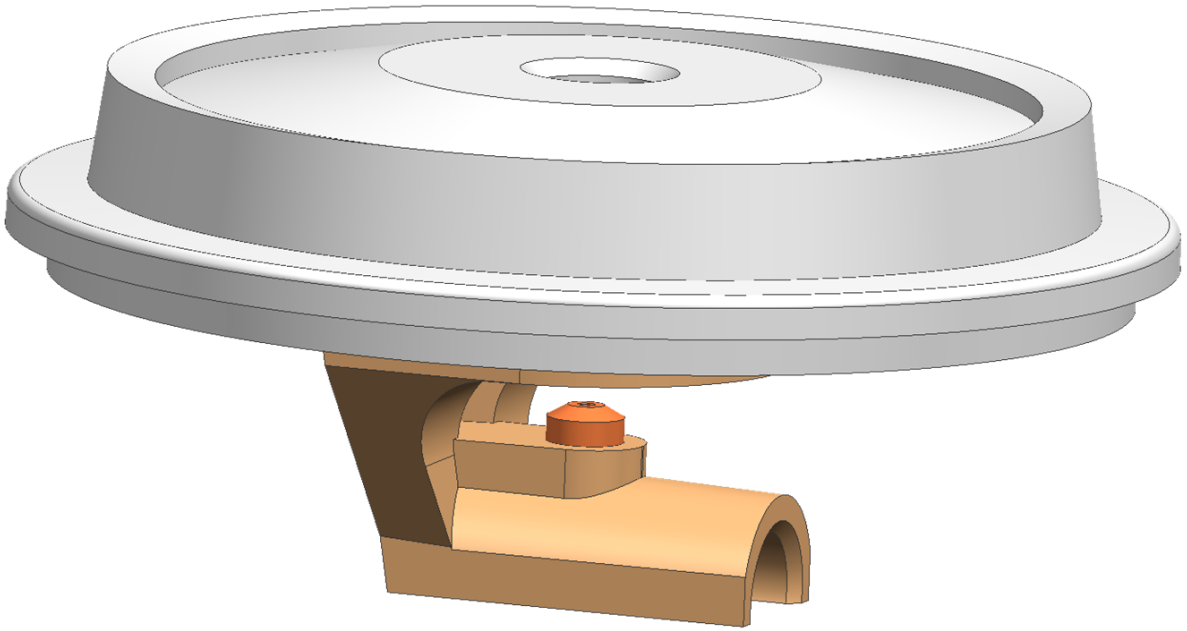
1. Injector

Workflow, Theory & Results

1. Geometry

Project Schematic

Burner Structure



3. Base

2. Porta-injector

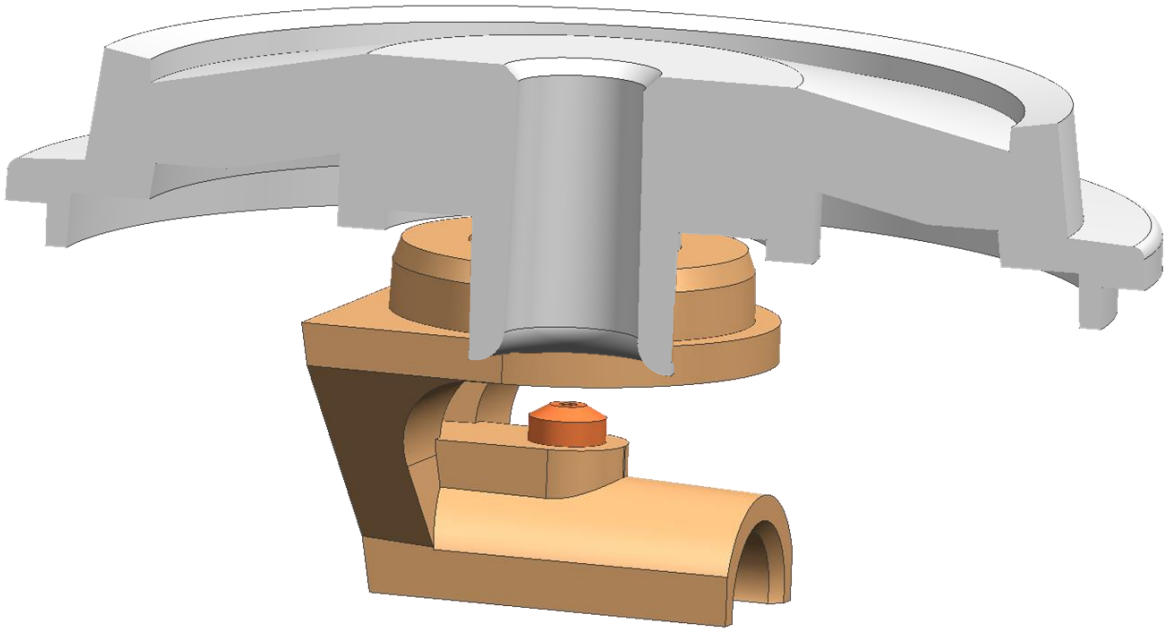
1. Injector

Workflow, Theory & Results

1. Geometry

Project Schematic

Burner Structure



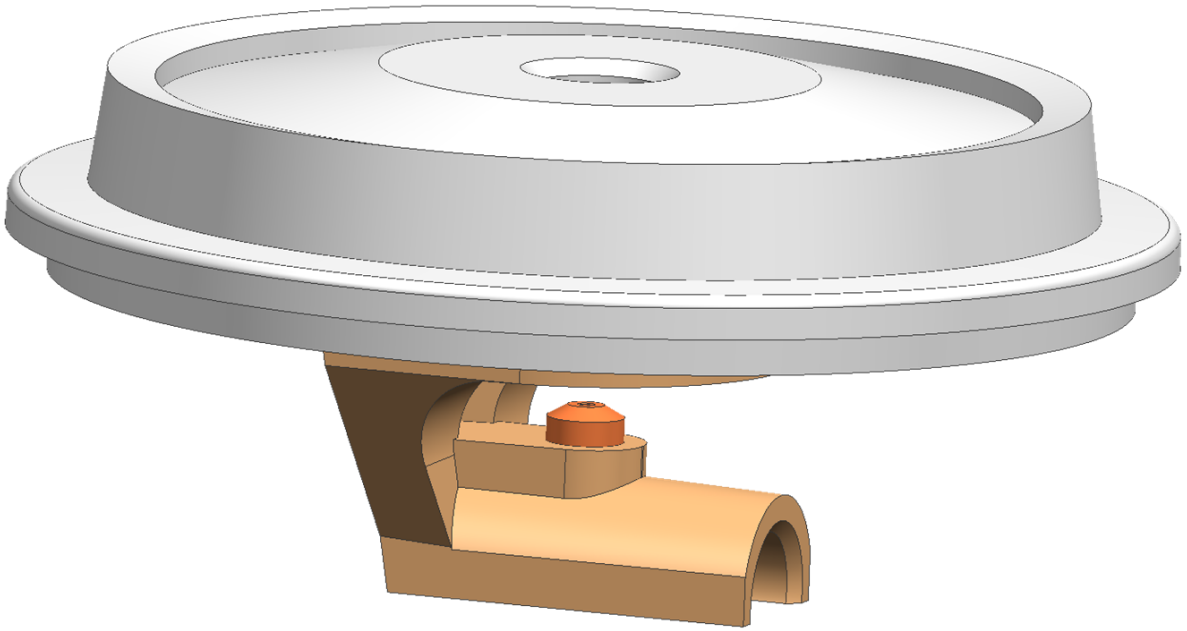
4. Venturi tube
3. Base
2. Porta-injector
1. Injector

Workflow, Theory & Results

1. Geometry

Project Schematic

Burner Structure



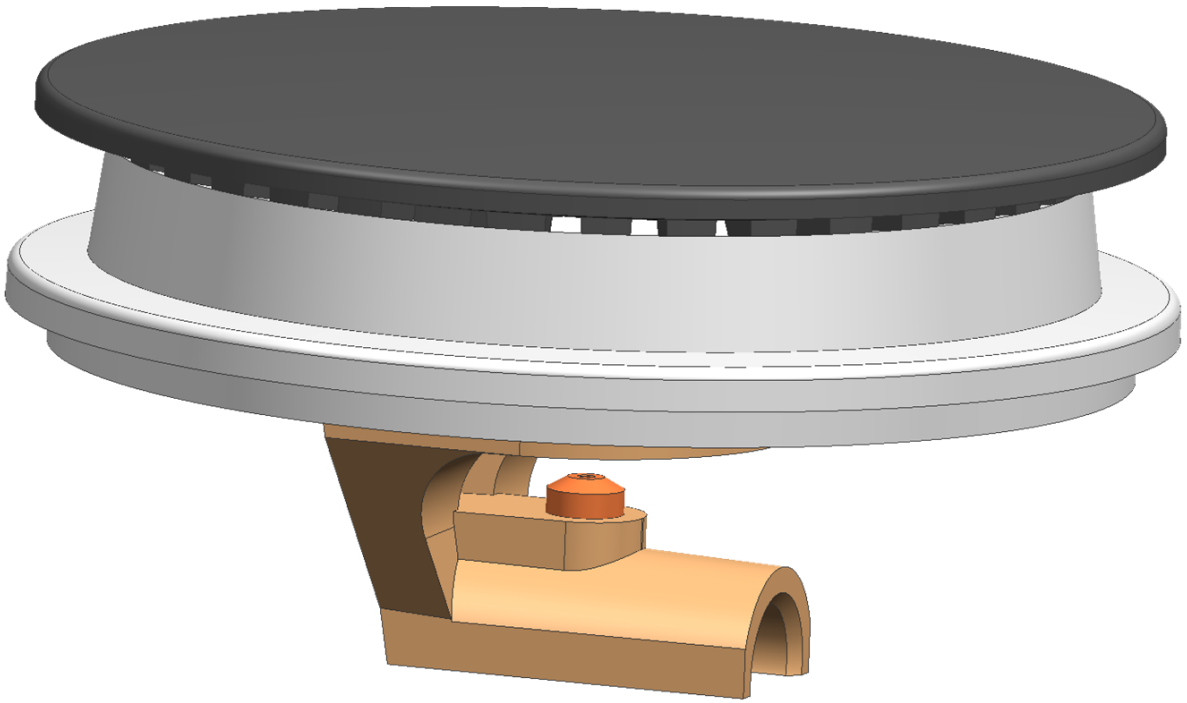
4. Venturi tube
3. Base
2. Porta-injector
1. Injector

Workflow, Theory & Results

1. Geometry

Project Schematic

Burner Structure



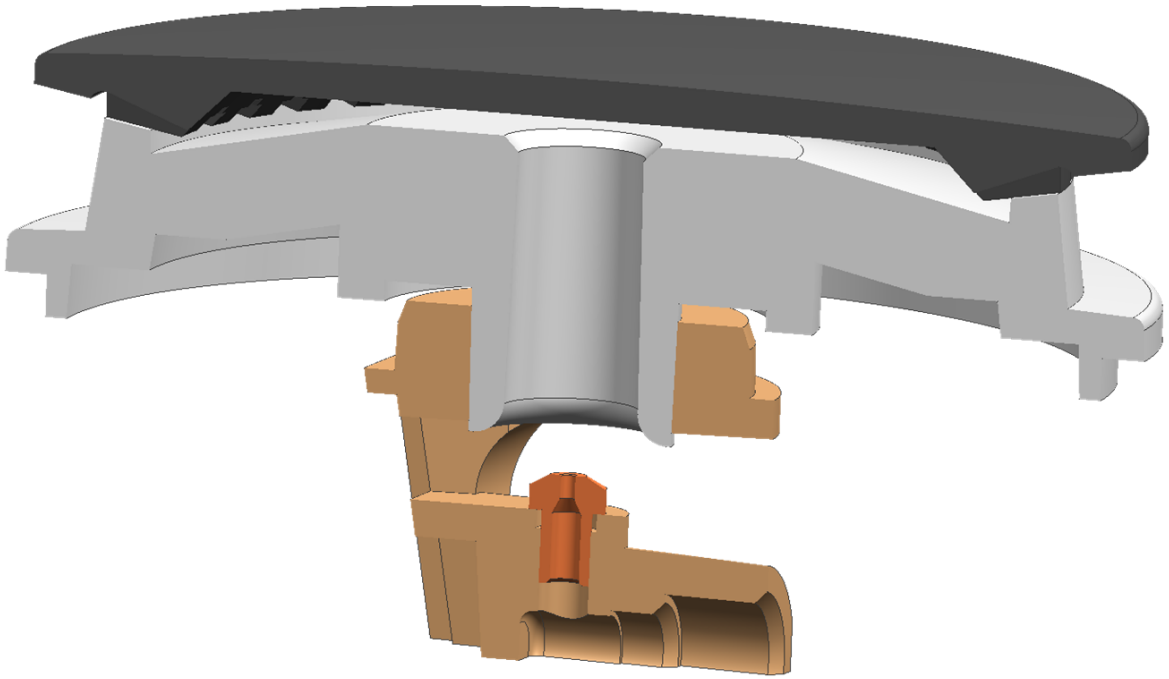
6. Ports
5. Spreader
4. Venturi tube
3. Base
2. Porta-injector
1. Injector

Workflow, Theory & Results

1. Geometry

Project Schematic

Burner performance

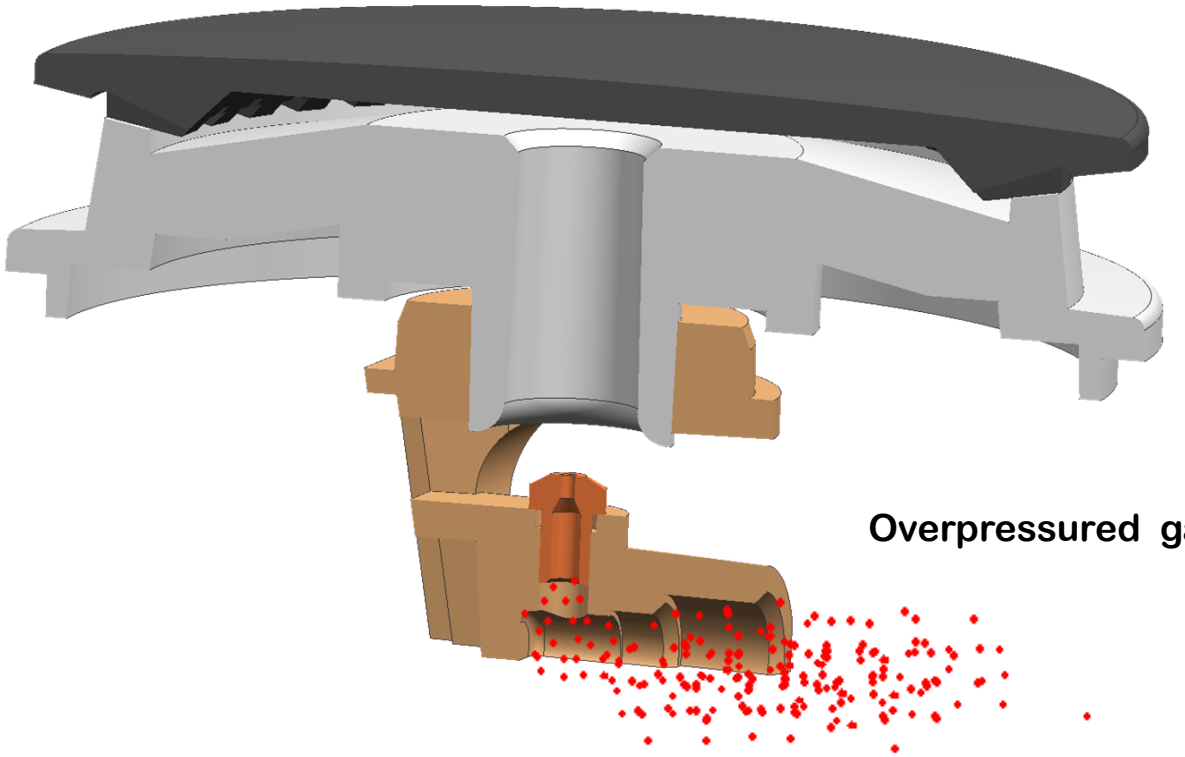


Workflow, Theory & Results

1. Geometry

Project Schematic

Burner performance



Workflow, Theory & Results

1. Geometry

Project Schematic

Burner performance

Energy conservation

$$g\,h_g = \frac{1}{2}\,v^2$$

$$\dot{V} = v\,A$$

$$\dot{V} = A\sqrt{2\,g\,h}$$

$$p_g = \rho_{gas}\,h\,g$$

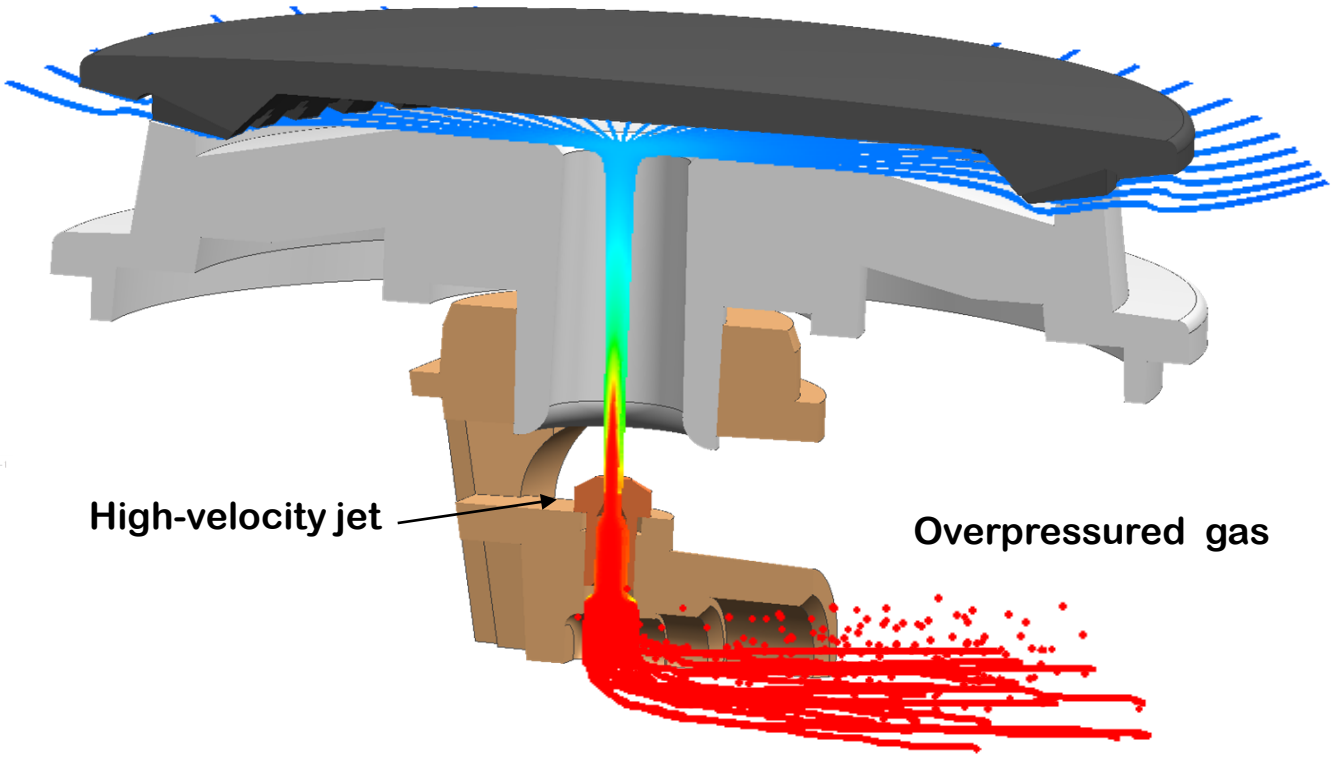
$$\dot{V} = A\sqrt{\frac{2\,p_g}{\rho_{gas}}} = A\sqrt{\frac{2\,p_g}{\rho_{aire}\,\sigma}}$$

$\dot{V}$ in $m^3 s^{-1}$
A in mm^2
p in $mbar$

$$\dot{V} = 1.278 \cdot 10^{-5} A\sqrt{\frac{p_g}{\sigma}}$$

$$q = h_s\,\dot{V}$$

$$q_{ideal} = 12.78\,A\,W\,\sqrt{p}$$

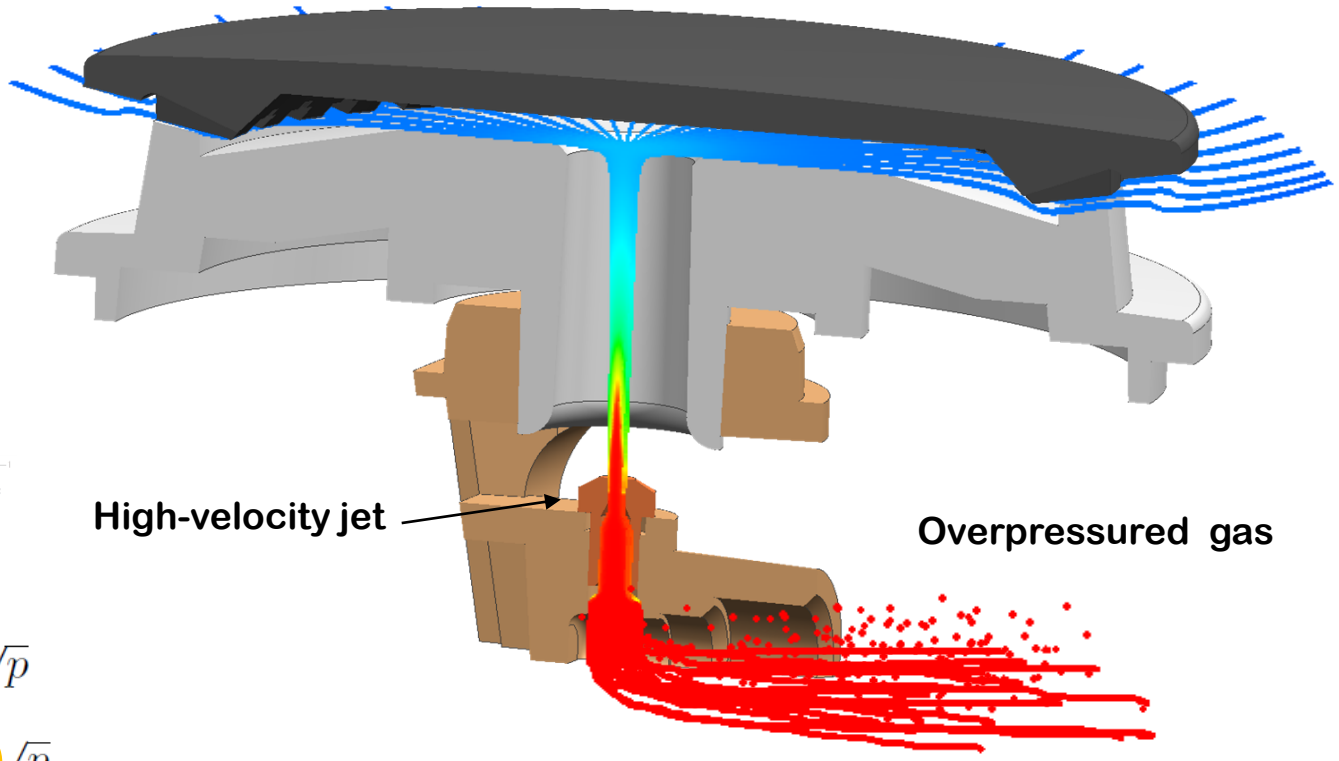


Workflow, Theory & Results

1. Geometry

Project Schematic

Burner performance



Energy conservation

$$g\,h_g = \frac{1}{2}\,v^2$$

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$\dot{V}$ in $m^3 s^{-1}$
A in mm^2
p in mbar

$$\dot{V} = 1.278 \cdot 10^{-5} A\sqrt{\frac{p_g}{\sigma}}$$

$$q = h_s\,\dot{V}$$

$$q_{ideal} = 12.78\,A\,W\,\sqrt{p}$$

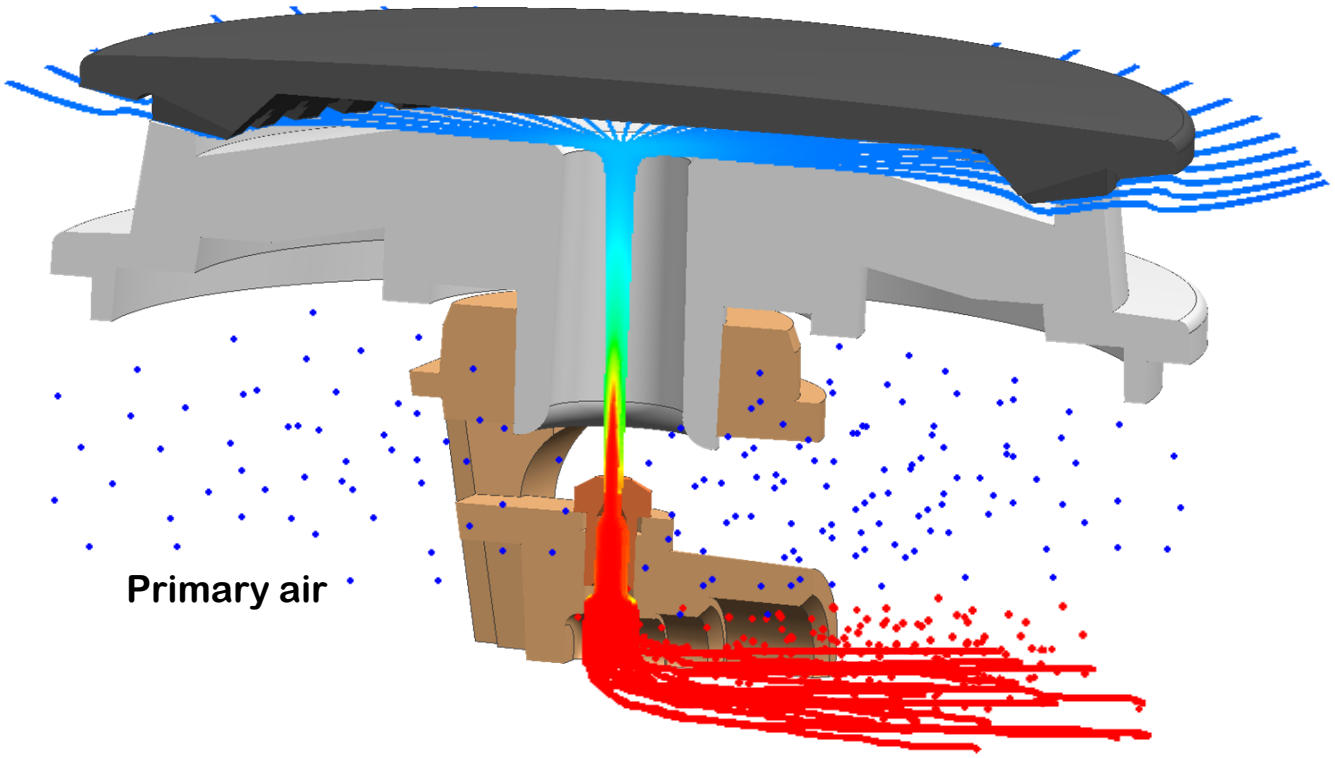
$$q_{real} = 12.78\,A\,W\,C_d\,\sqrt{p}$$

Workflow, Theory & Results

1. Geometry

Project Schematic

Burner performance



Workflow, Theory & Results

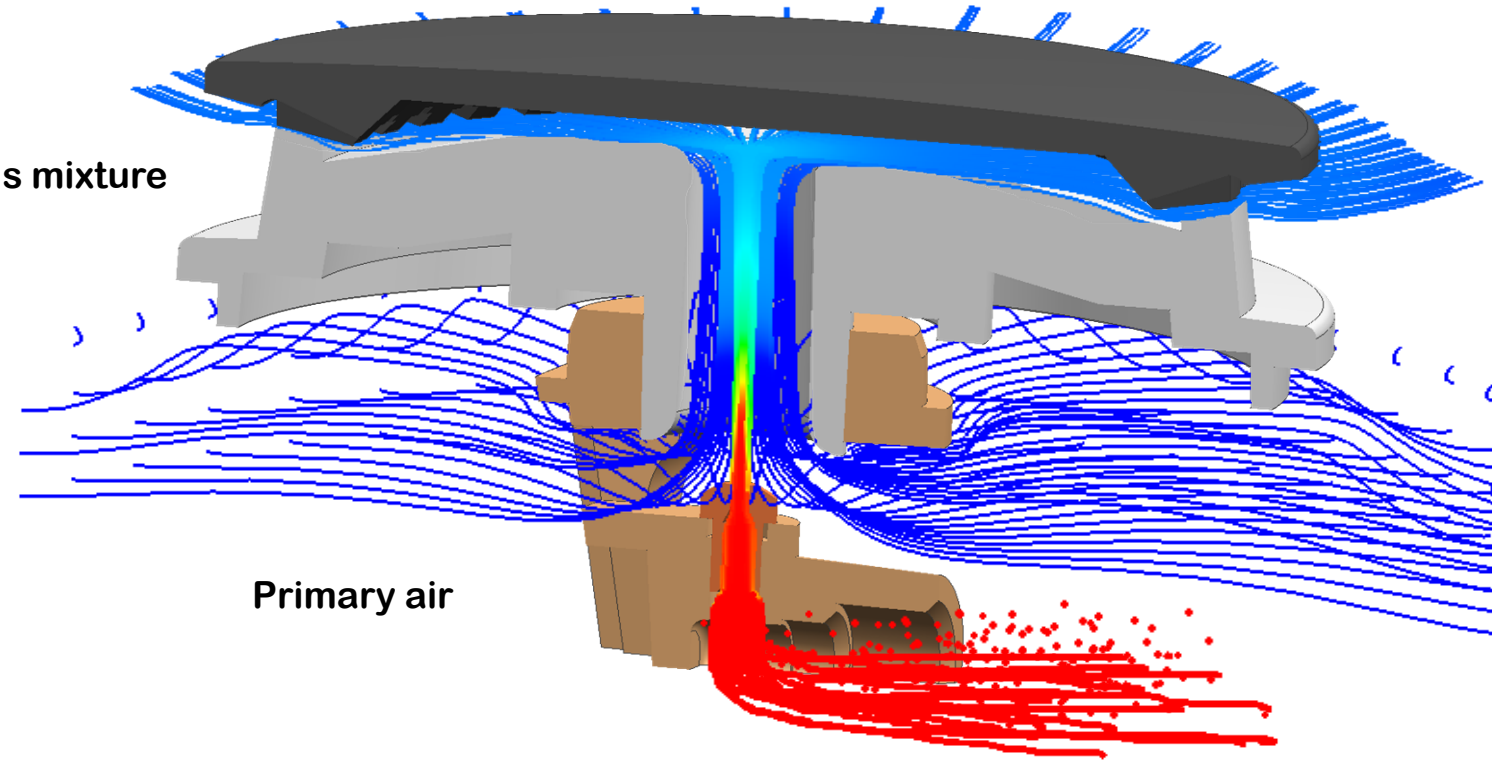
1. Geometry

Project Schematic

Burner performance

Homogeneous mixture

$$AFR = \frac{m_{air}}{m_{fuel}}$$



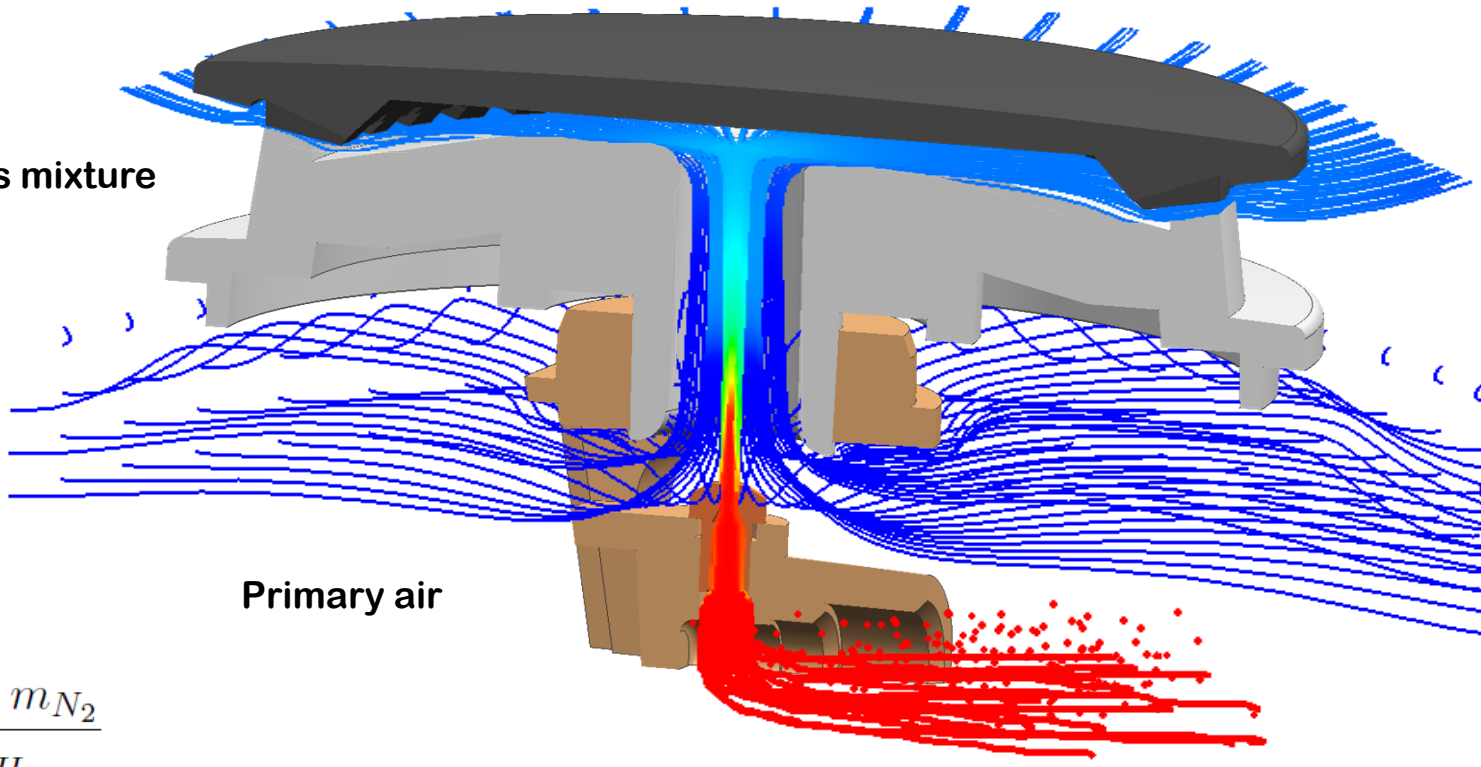
Primary air

Workflow, Theory & Results

1. Geometry

Project Schematic

Burner performance



Homogeneous mixture

$$AFR = \frac{m_{air}}{m_{fuel}}$$

Aeration

$$\lambda = \frac{AFR}{AFR_{stoich}}$$

$$= \frac{1}{17.167} \frac{m_{O_2} + m_{N_2}}{m_{CH_4}}$$

Primary air

Workflow, Theory & Results

Solve Base Case

h = 1.837 mm
α = 153°

Workflow, Theory & Results

1. Geometry

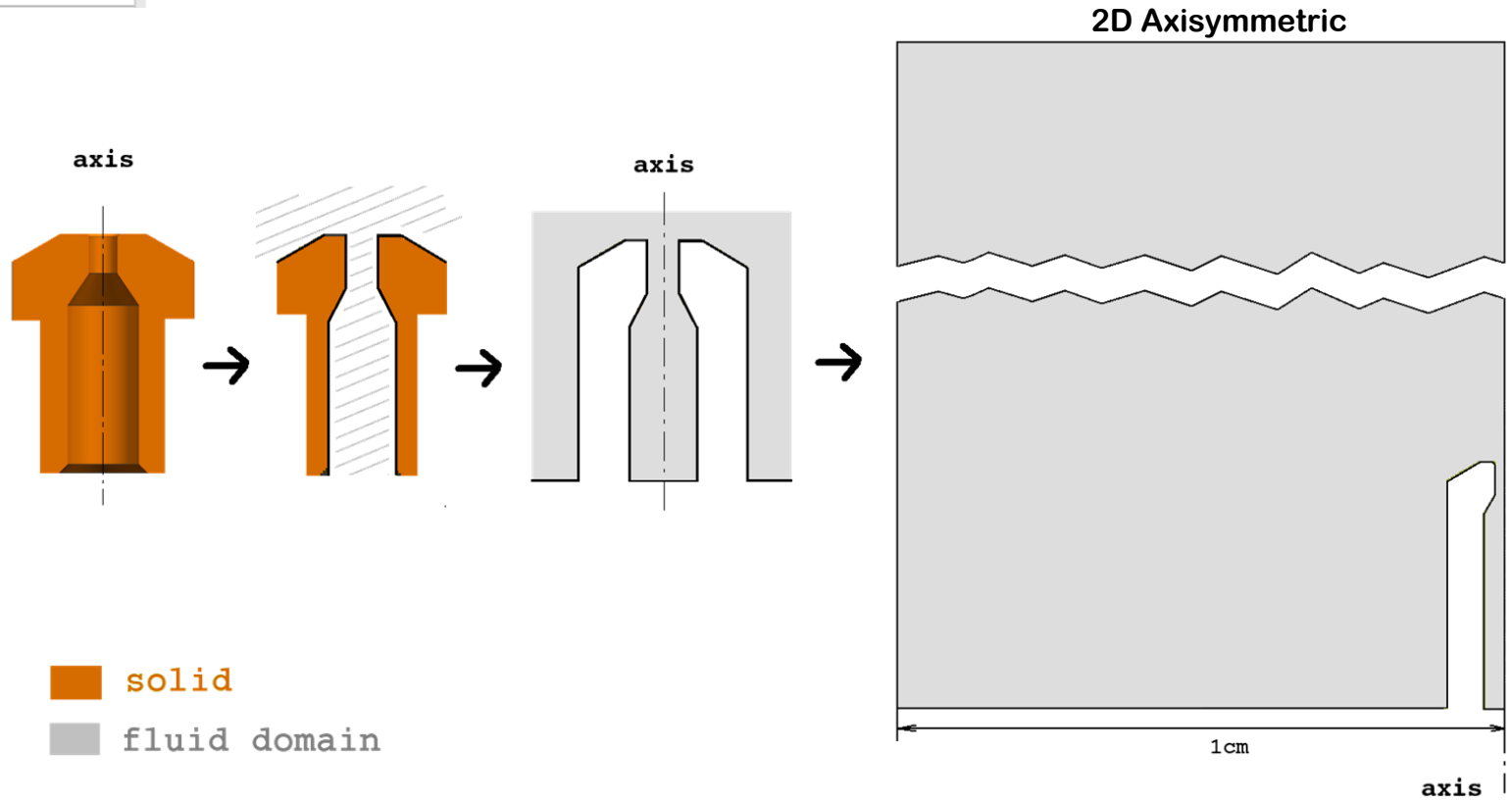
Workflow, Theory & Results

1. Geometry

Project Schematic

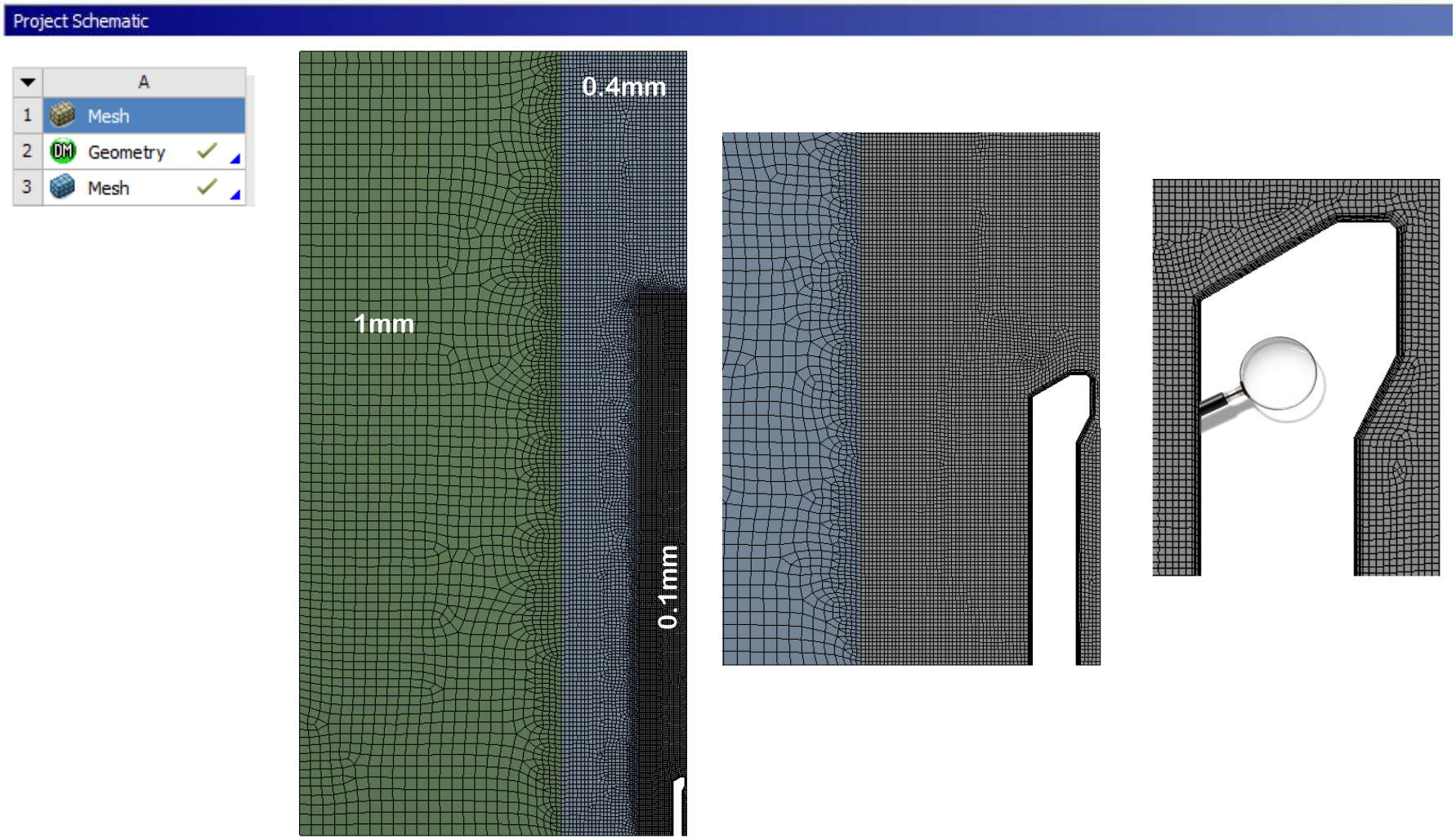
	A
1	Geometry
2	Geometry ✓

Create domain



Workflow, Theory & Results

2. Mesh



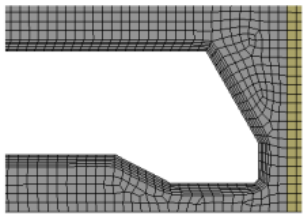
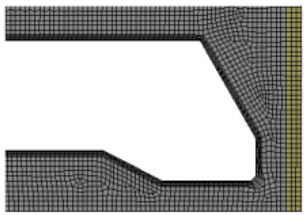
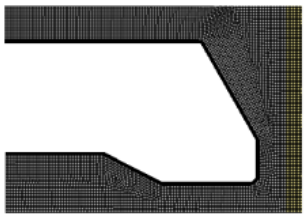
Workflow, Theory & Results

2. Mesh

Project Schematic

	A
1	Mesh
2	Geometry ✓
3	Mesh ✓

Mesh Analysis

	Coarsened Case	Base Case	Refined Case
mesh elements size (mm)	x 0.25 2 0.2 0.8	1 0.1 0.4	x 4 0.4 0.02 0.15
injector mesh detail			
cells	58896	225152	996787
skewness	0.662	0.727	0.639
CPU tpi	0.522 s	1.751 s	12.695 s
$\dot{m}_{out}$ (kg/s)	$4.101 \cdot 10^{-2}$	$4.112 \cdot 10^{-2}$	$4.111 \cdot 10^{-2}$
$\dot{m}_{fuel}$ (kg/s)	$5.282 \cdot 10^{-5}$	$5.404 \cdot 10^{-5}$	$5.384 \cdot 10^{-5}$
Y_{CH_4}	$1.280 \cdot 10^{-3}$	$1.316 \cdot 10^{-3}$	$1.310 \cdot 10^{-3}$
v_{out} (m/s)	1.153	1.159	1.162

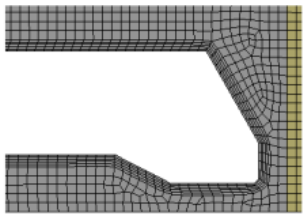
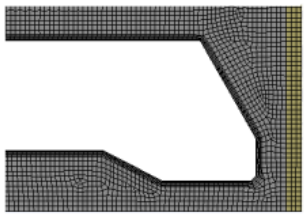
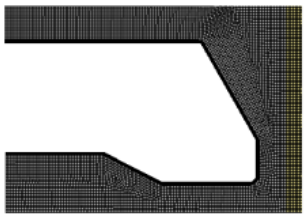
Workflow, Theory & Results

2. Mesh

Project Schematic

	A
1	Mesh
2	Geometry ✓
3	Mesh ✓

Mesh Analysis

	Coarsened Case	Base Case	Refined Case
mesh elements size (mm)	x 0.25 (2; 0.2; 0.8)	(1; 0.1; 0.4)	x 4 (0.4; 0.02; 0.15)
injector mesh detail			
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Workflow, Theory & Results

2. Mesh

Project Schematic

	A
1	Mesh
2	Geometry ✓
3	Mesh ✓

Mesh Analysis

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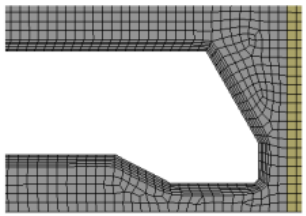
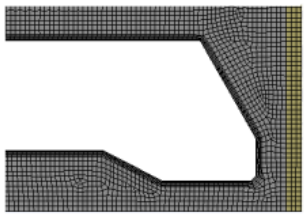
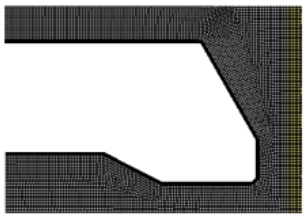
injector mesh detail			
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Workflow, Theory & Results

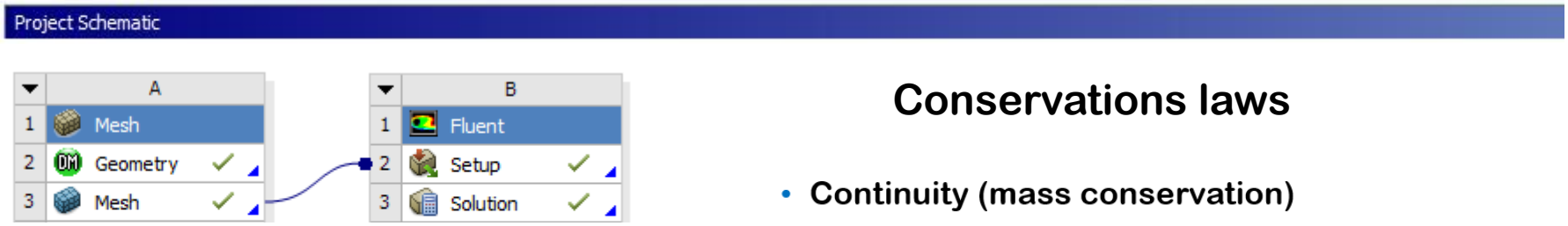
3. Setup & Solution

Workflow, Theory & Results

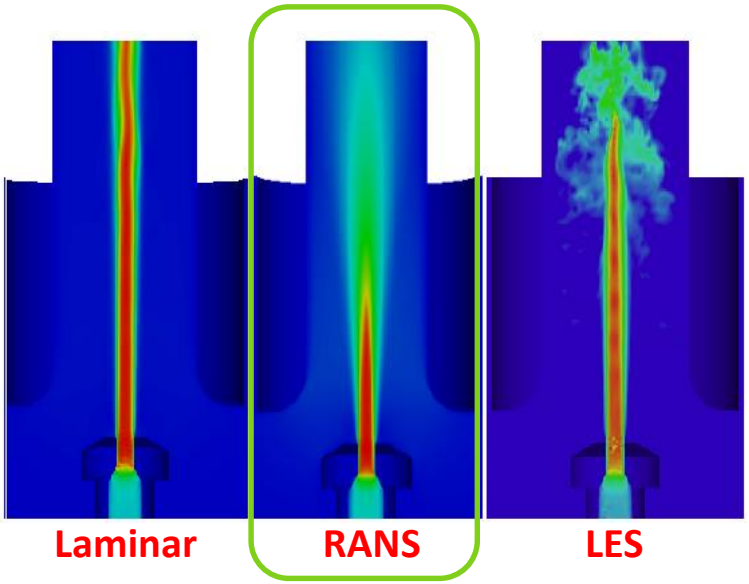
3. Setup & Solution

Workflow, Theory & Results

3. Setup & Solution



Turbulence (k-ε model)



Conservations laws

- **Continuity (mass conservation)**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

- **Momentum**

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \boldsymbol{f}$$

- **Energy**

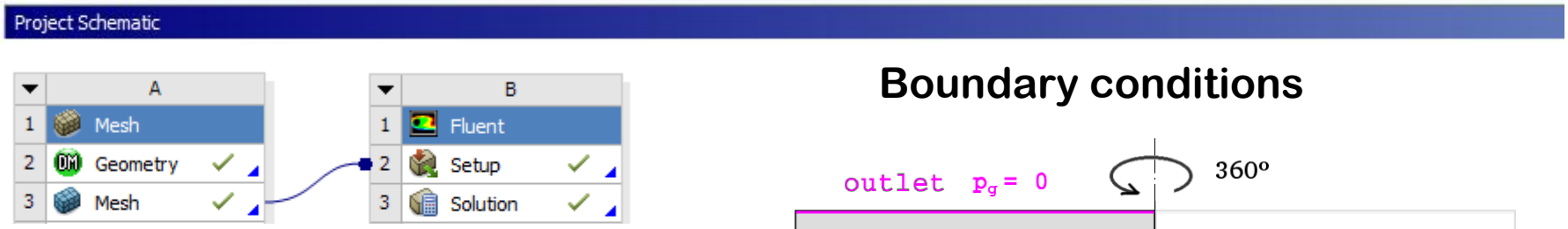
$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \boldsymbol{v} H) = -\nabla \cdot \boldsymbol{J}_H + S_H$$

- **Chemical species**

$$\frac{\partial}{\partial t}(\rho Y_\alpha) + \nabla \cdot (\rho \boldsymbol{v} Y_\alpha) = -\nabla \cdot \boldsymbol{J}_\alpha + S_\alpha \qquad \alpha = 1, \ldots, N$$

Workflow, Theory & Results

3. Setup & Solution

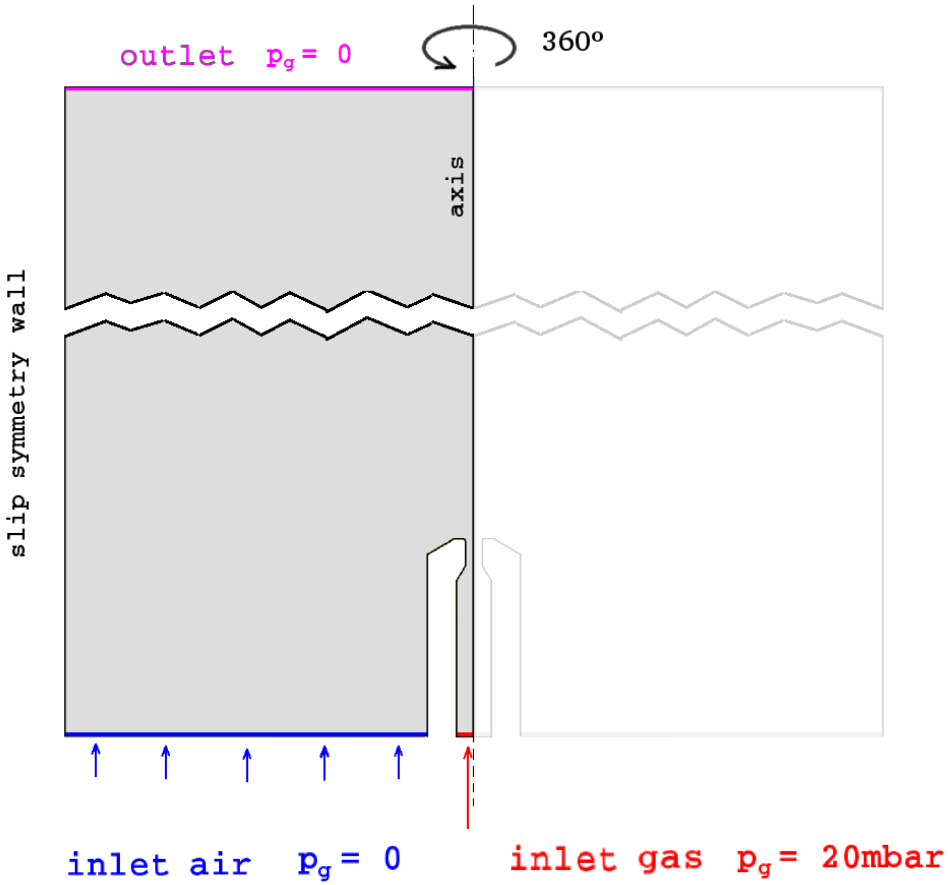


Numerical details

- **Models**
  - k-ε model
  - CH_4 One Step
  - Nonreactive
  - Ideal gas
- **Solving**
  - p-v coupling: Coupled
  - Momentum: 2nd. order upwd.
  - Turbulence: 2nd. order upwd.
  - Species: 2nd. order upwd.

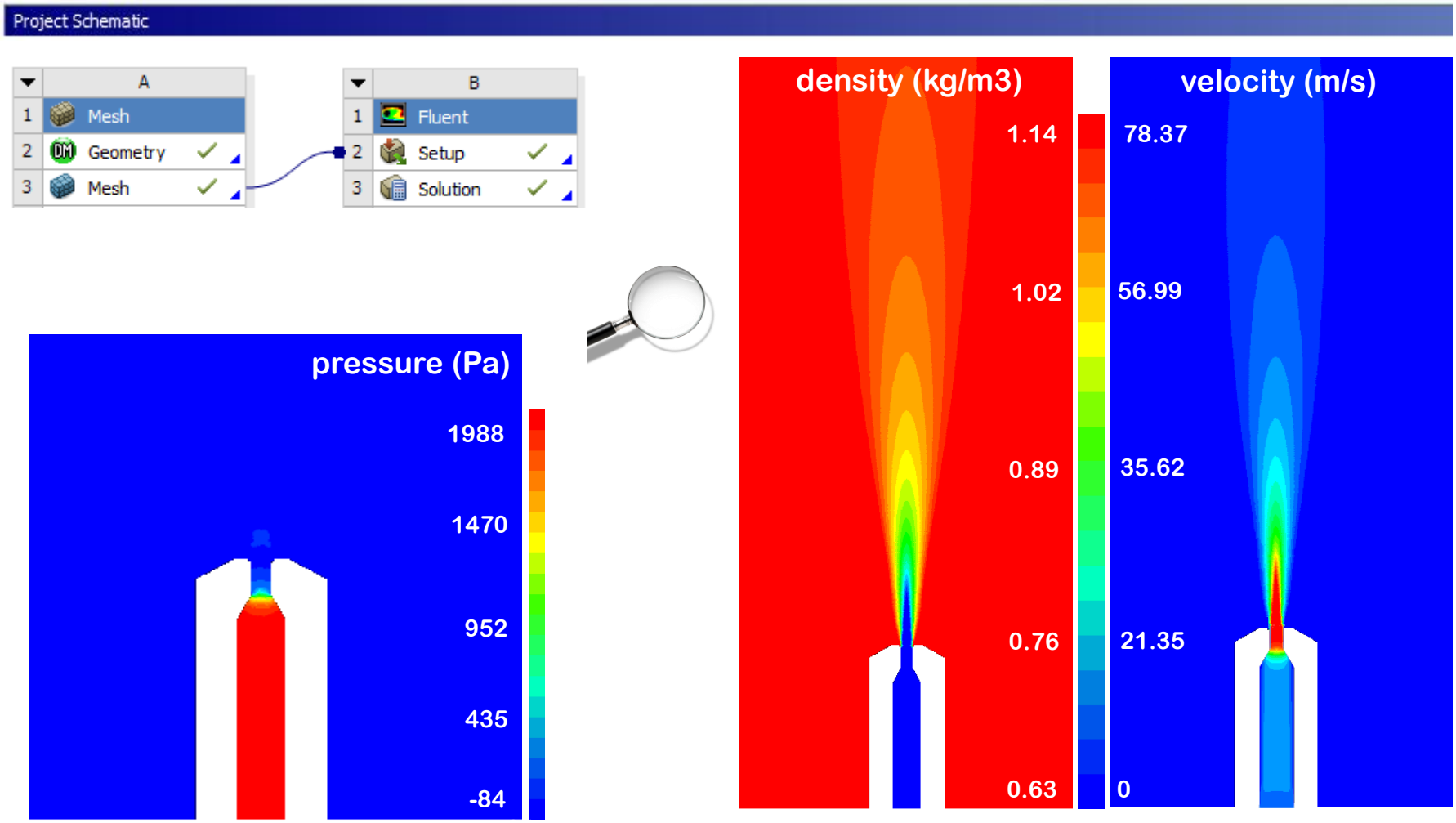
16 cpus 50' approx.

Boundary conditions



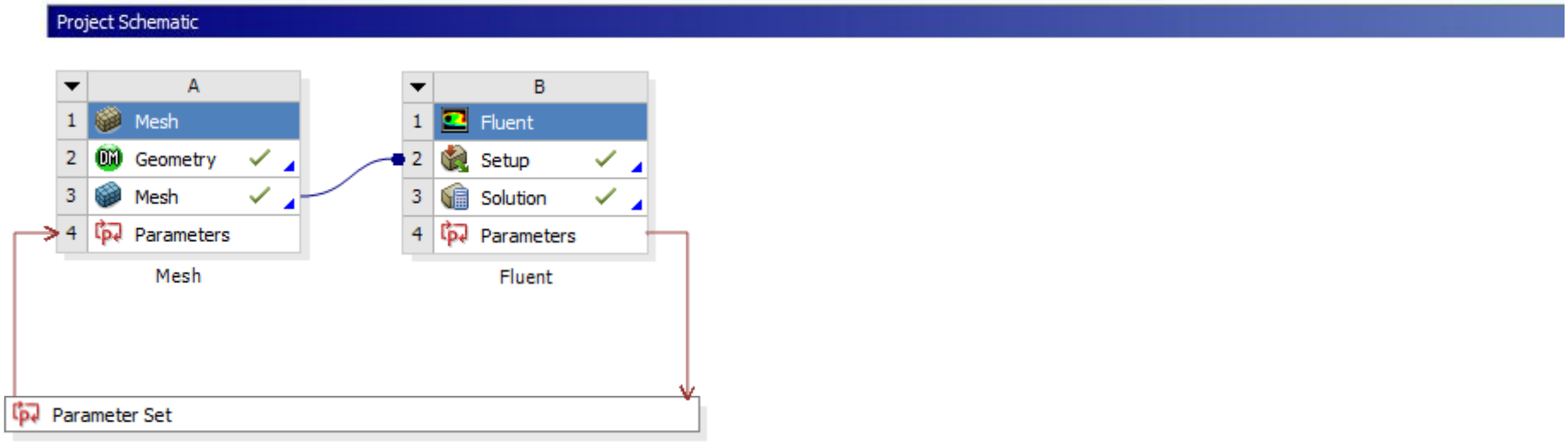
Workflow, Theory & Results

3. Setup & Solution



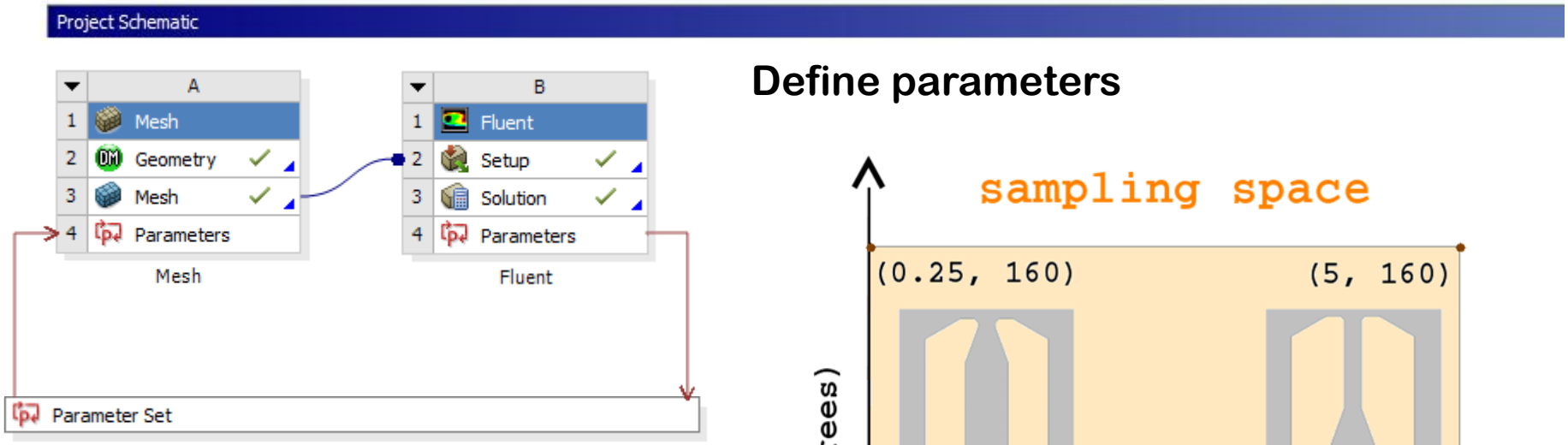
Workflow, Theory & Results

4. Parameters

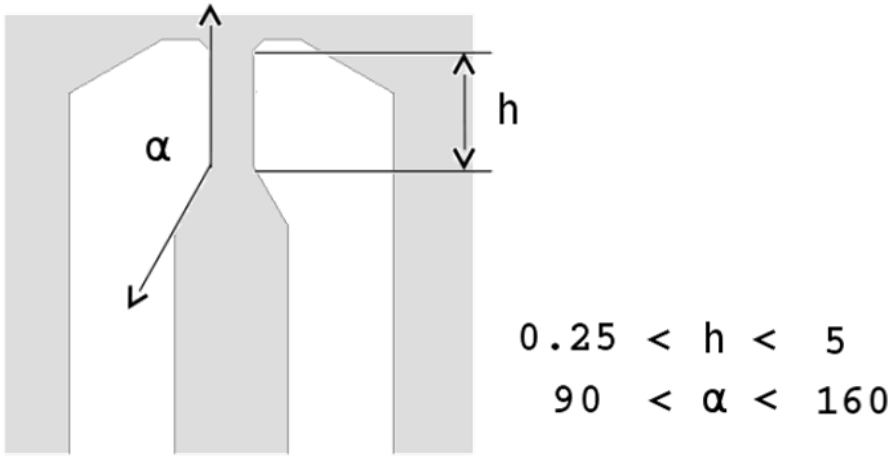


Workflow, Theory & Results

4. Parameters

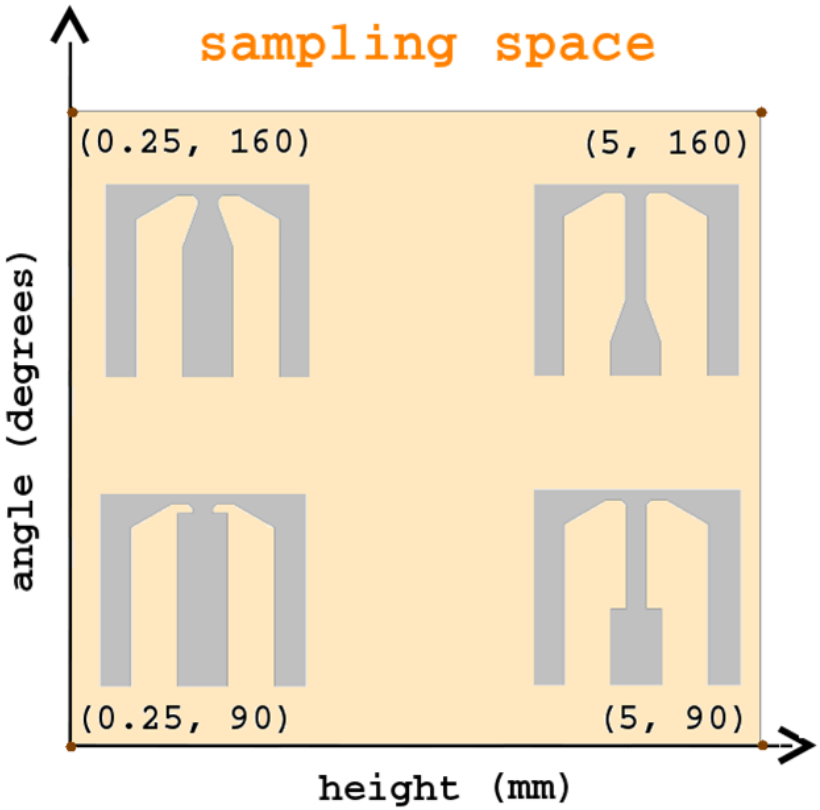


Define parameters



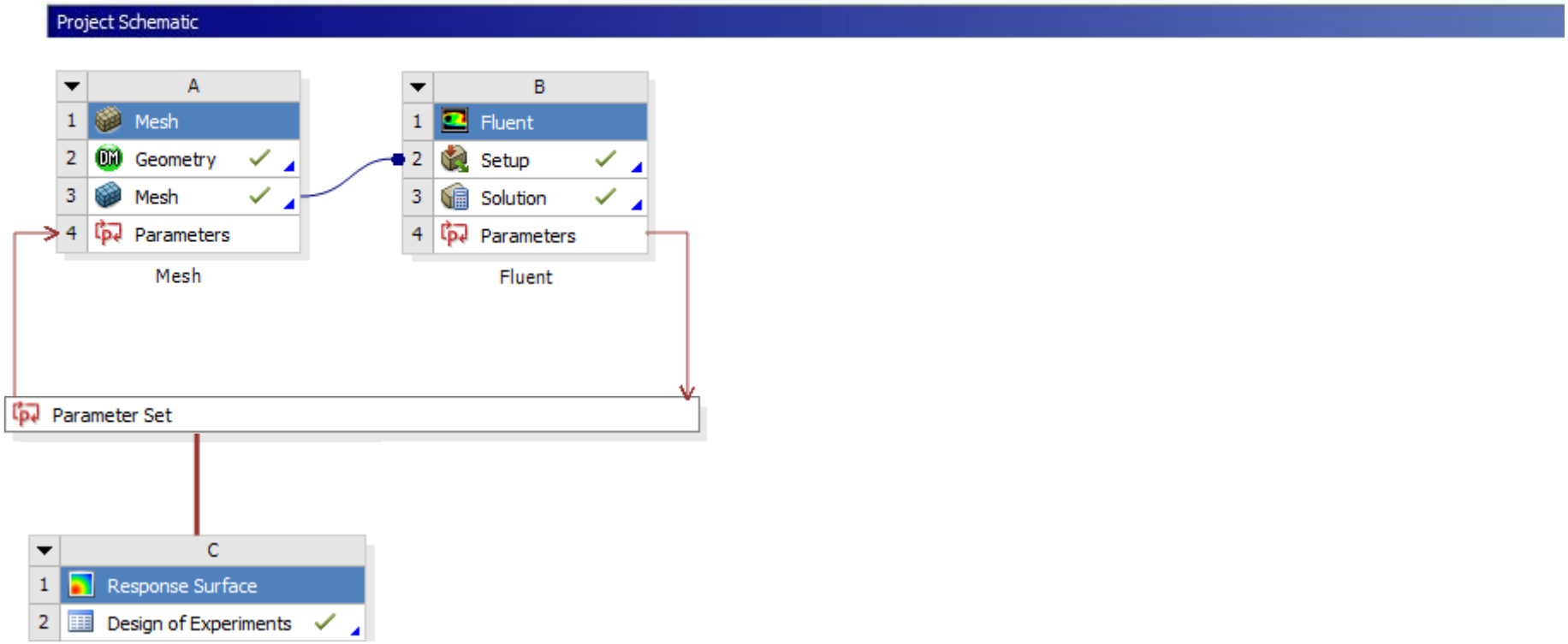
$0.25 < h < 5$

$90 < \alpha < 160$



Workflow, Theory & Results

5. DOEs

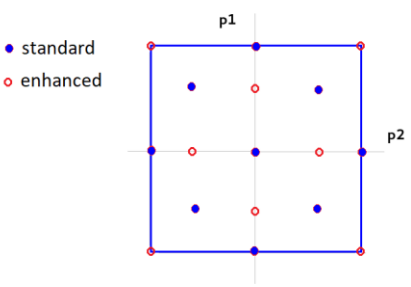


Workflow, Theory & Results

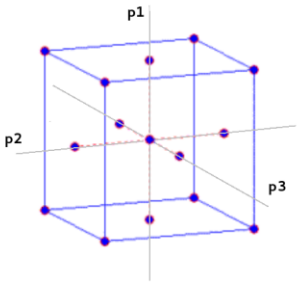
5. DOEs

Project Schematic

Factorial

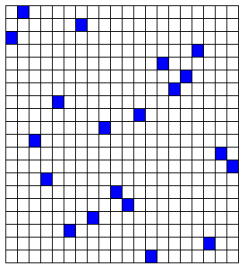


2D CCD

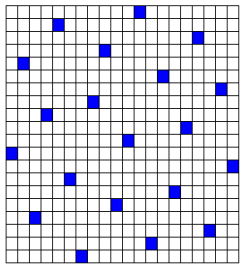


3D CCD

Space Filling



LHS



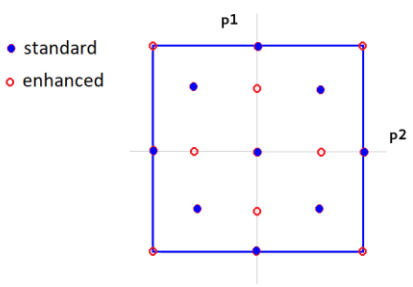
OSF

Workflow, Theory & Results

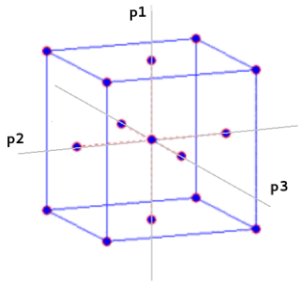
5. DOEs

Project Schematic

Factorial

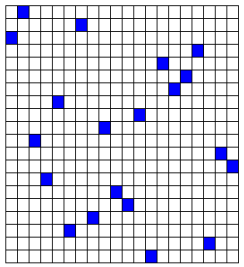


2D CCD

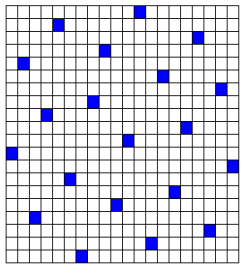


3D CCD

Space Filling

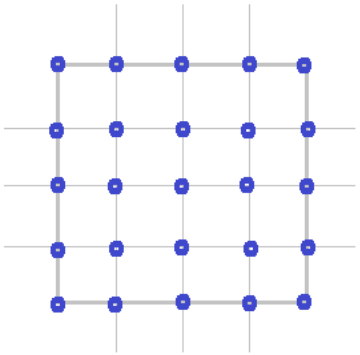


LHS



OSF

Custom

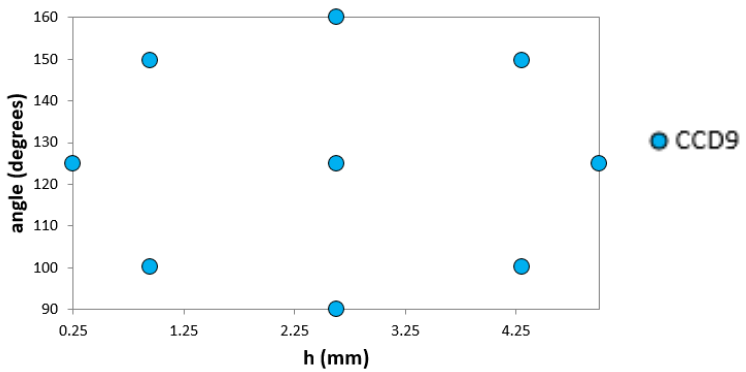


Workflow, Theory & Results

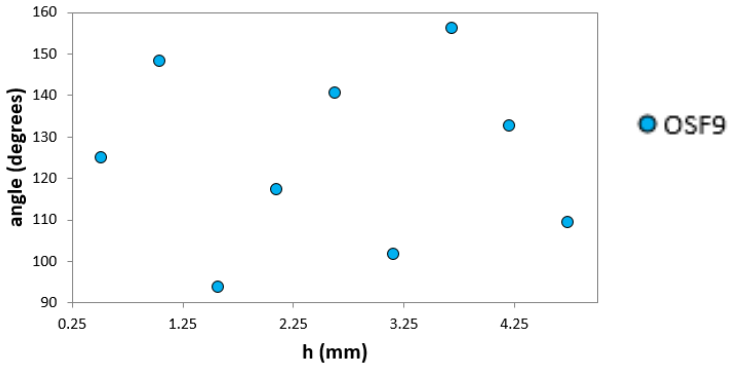
5. DOEs

Project Schematic

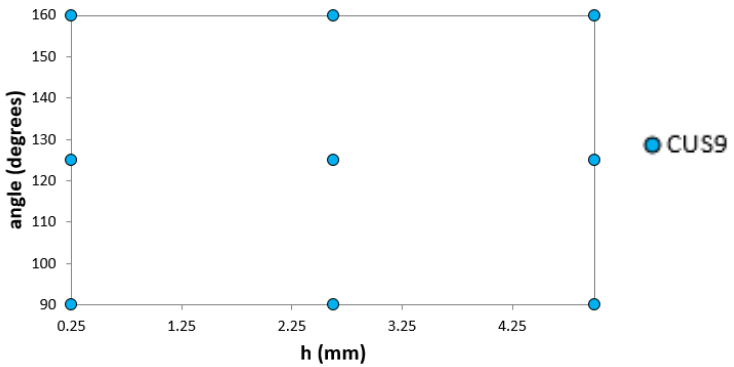
Central Composite Design CCD



Optimal Space Filling OSF



Custom CUS



9 runs

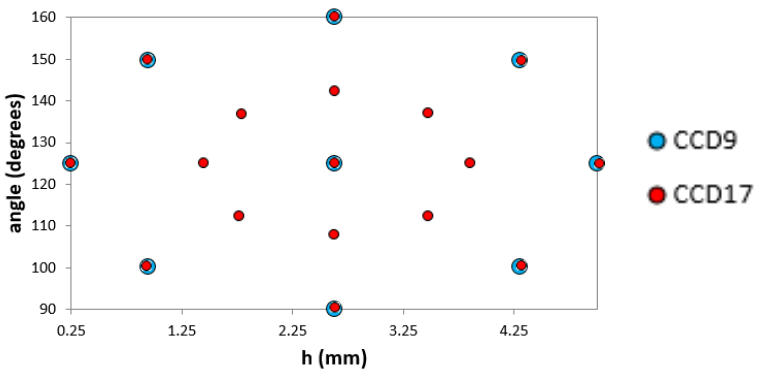
Total: 149 configurations

Workflow, Theory & Results

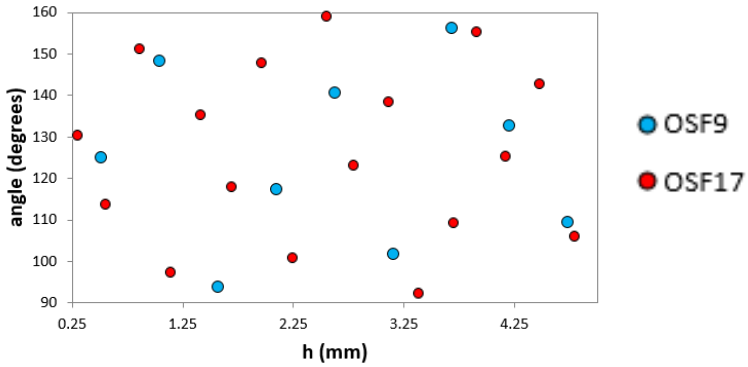
5. DOEs

Project Schematic

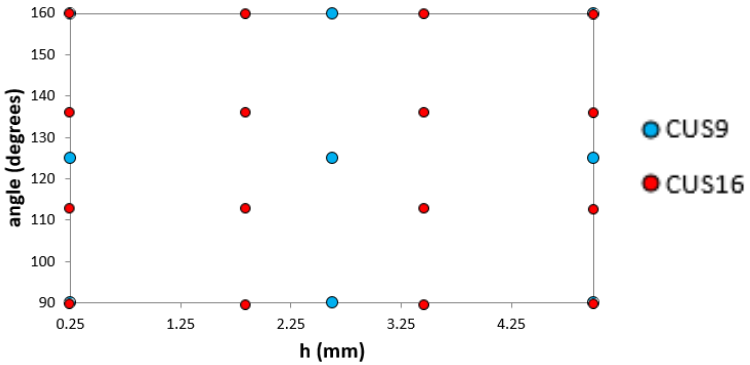
Central Composite Design CCD



Optimal Space Filling OSF



Custom CUS



16-17 runs

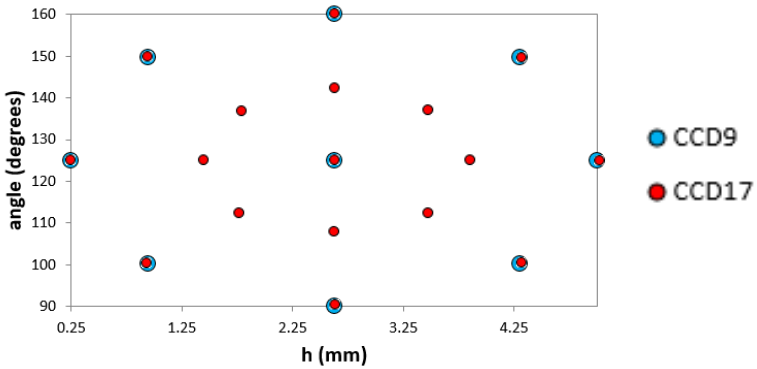
Total: 149 configurations

Workflow, Theory & Results

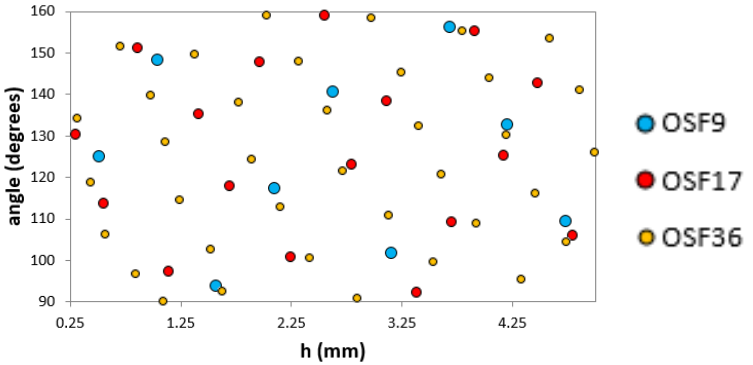
5. DOEs

Project Schematic

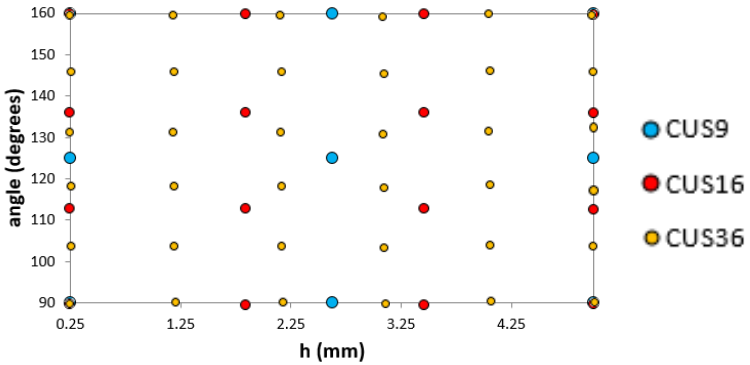
Central Composite Design CCD



Optimal Space Filling OSF



Custom CUS

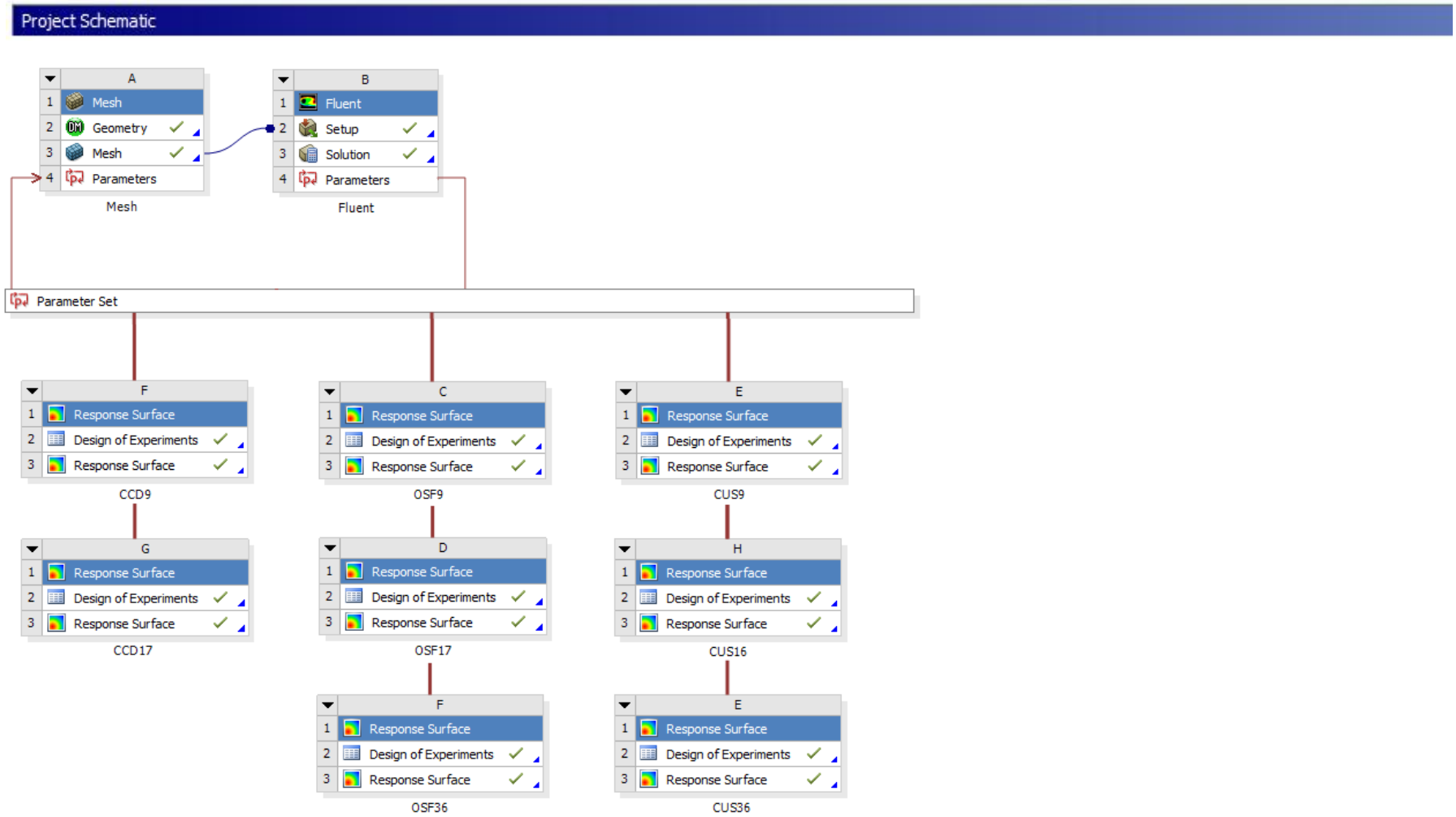


36 runs

Total: 149 configurations

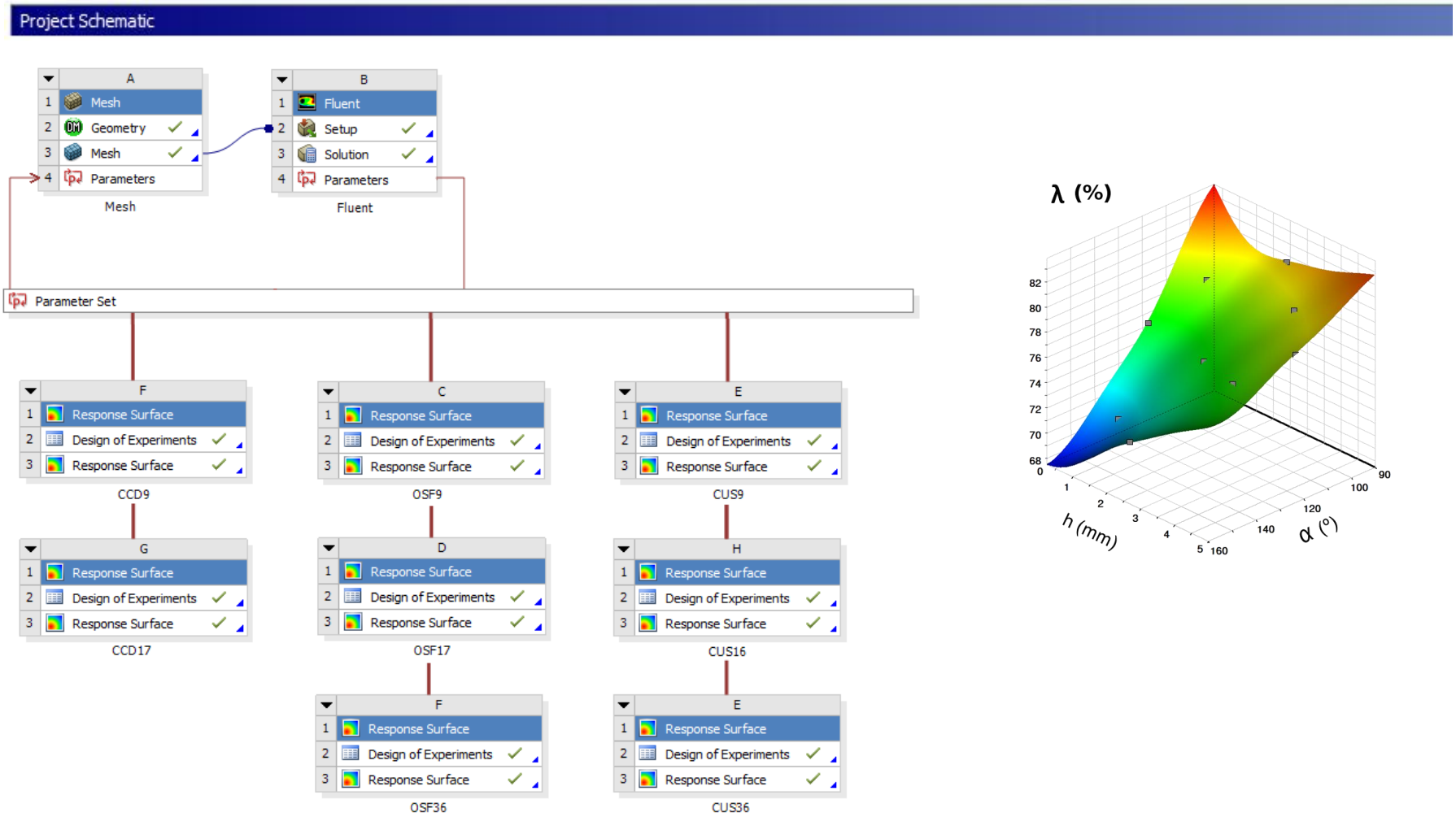
Workflow, Theory & Results

5. DOEs



Workflow, Theory & Results

6. Response Surfaces



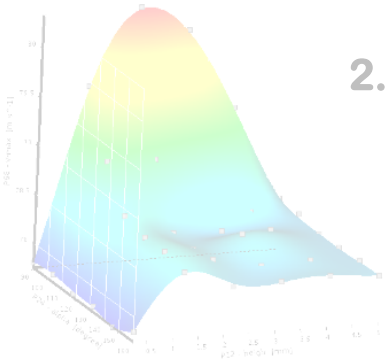
Workflow, Theory & Results

6. Response Surfaces

Project Schematic

ANSYS Algorithms

1. Standard Response Surface



2. Kriging

Genetic Aggregation

3. Non-Parametric Regression

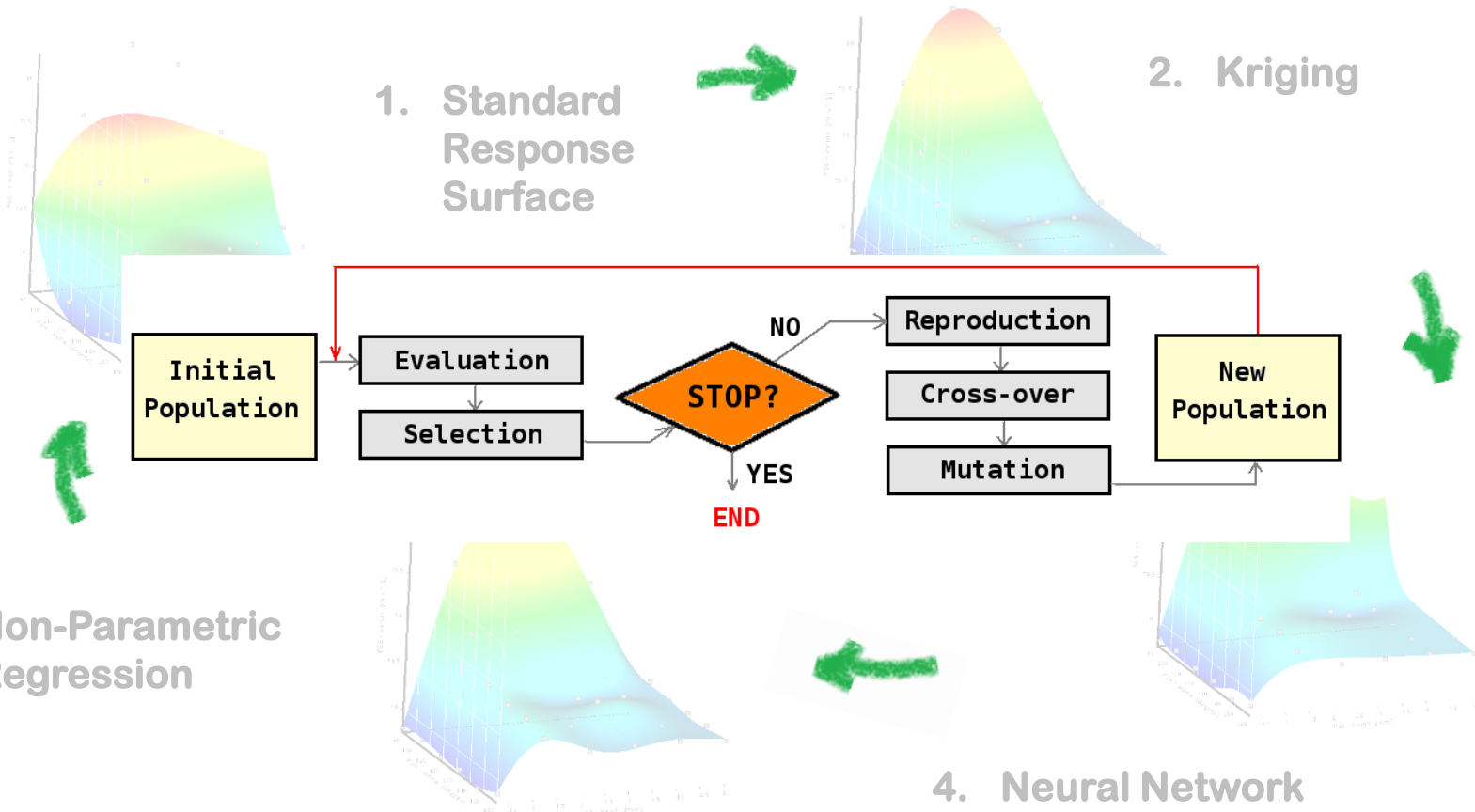
4. Neural Network

Workflow, Theory & Results

6. Response Surfaces

Project Schematic

ANSYS Algorithms



Workflow, Theory & Results

6. Response Surfaces

Project Schematic

Goodness of Fit

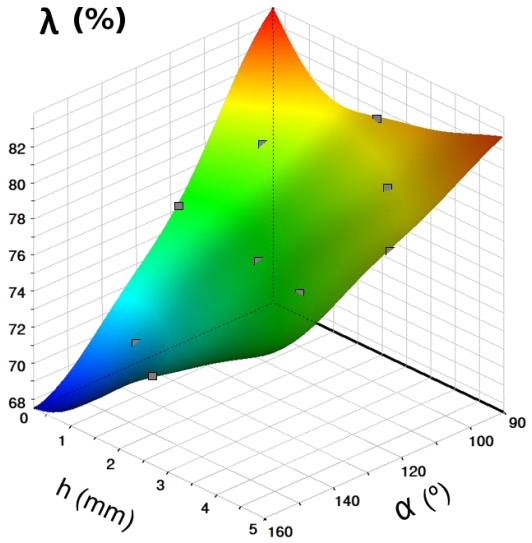
Prediction?

Interpolation?

Reliability?

Approximation?

Stability?



B/S/H/ UC

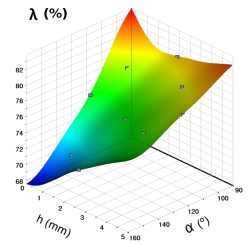
Workflow, Theory & Results

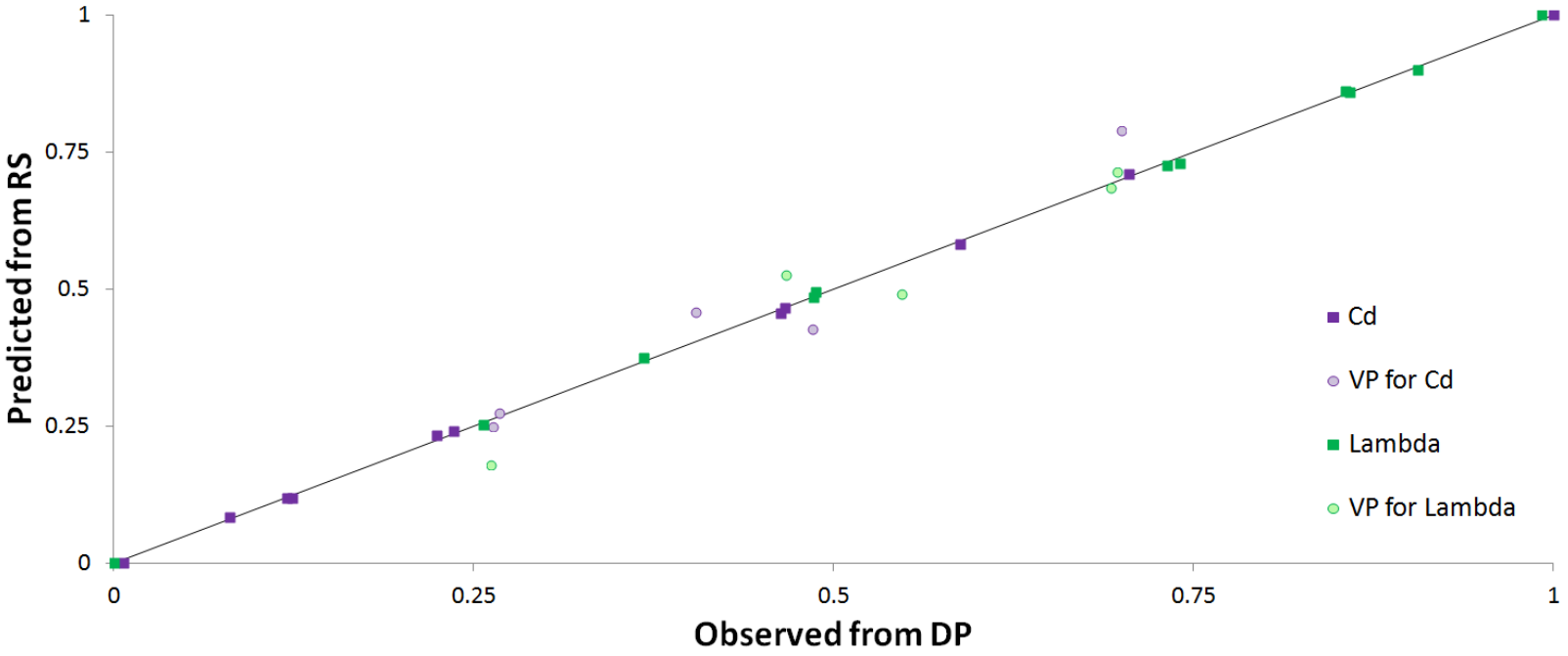
6. Response Surfaces

Project Schematic

Goodness of Fit

1. Verification Points → Prediction



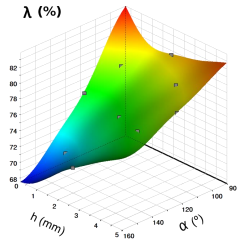


Workflow, Theory & Results

6. Response Surfaces

Project Schematic

Goodness of Fit



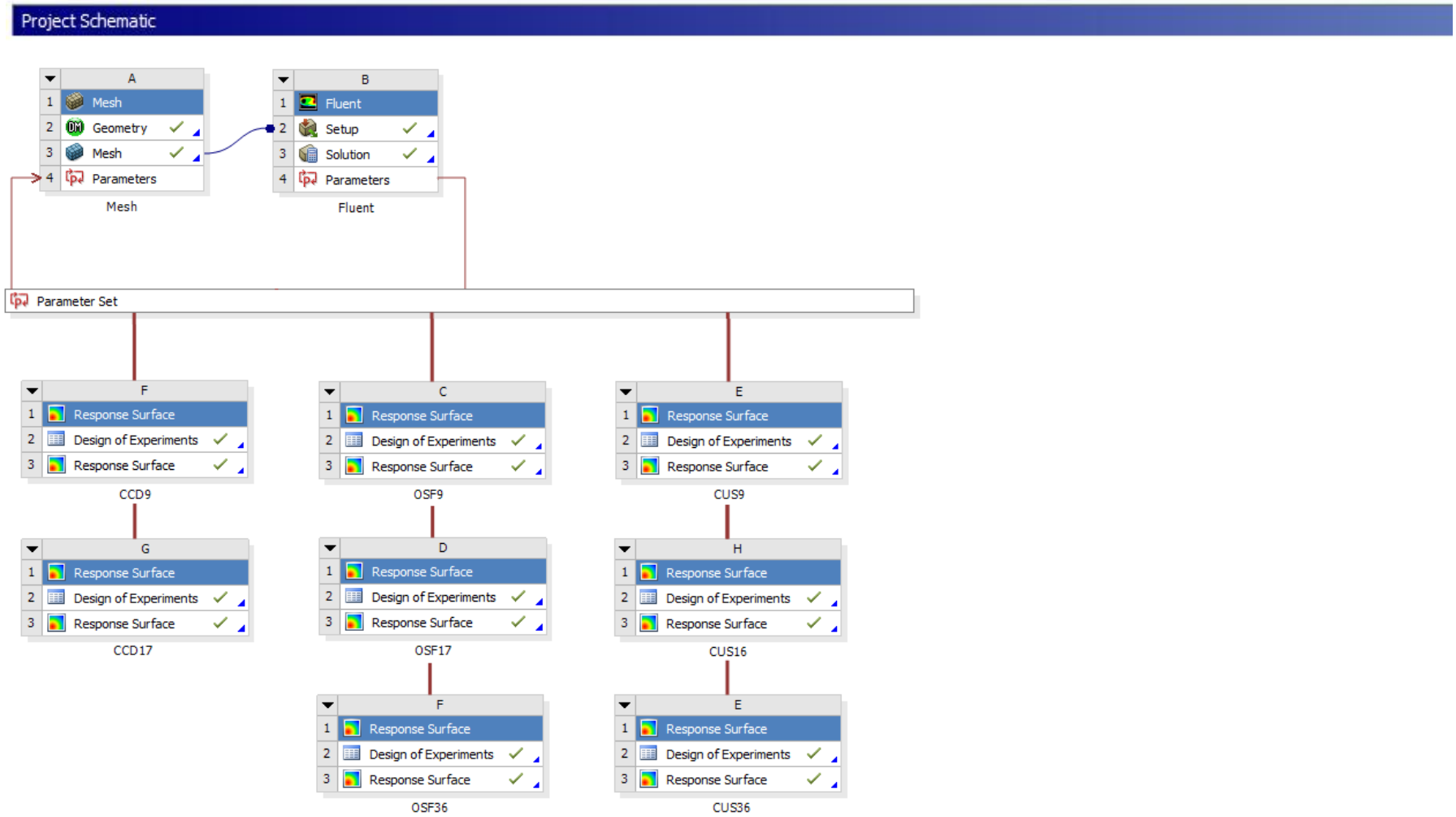
1. Verification Points → Prediction
2. Quality metrics

$$R^2 = 1 - \frac{\sum_{j=1}^{N}(r_j - \tilde{r}_j)^2}{\sum_{j=1}^{N}(r_j - \bar{r})^2} \qquad \text{RMSE} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(r_j - \tilde{r}_j)^2} \qquad \text{RMAE} = \frac{1}{\sigma_r}\max_{j=1:N}|(r_j - \tilde{r}_j)| \qquad \text{RAAE} = \frac{1}{N\,\sigma_r}\sum_{j=1:N}^{N}|(r_j - \tilde{r}_j)|$$

P47- lambda CCD-9			
Coefficient of Determination (Best Value = 1)		**Relative Maximum Absolute Error (Best Value = 0%)**	
Learning Points	0.9999	Learning Points	3.5169
Verification Points	3.5169	Verification Points	15.9997
Cross-Validation on Learning Points	0.9994	Cross-Validation on Learning Points	16.0270
Root Mean Square Error (Best Value = 0)		**Relative Average Absolute Error (Best Value = 0%)**	
Learning Points	6.32E-07	Learning Points	2.1003
Verification Points	8.92E-06	Verification Points	7.4396
Cross-Validation on Learning Points	1.51E-06	Cross-Validation on Learning Points	7.3000

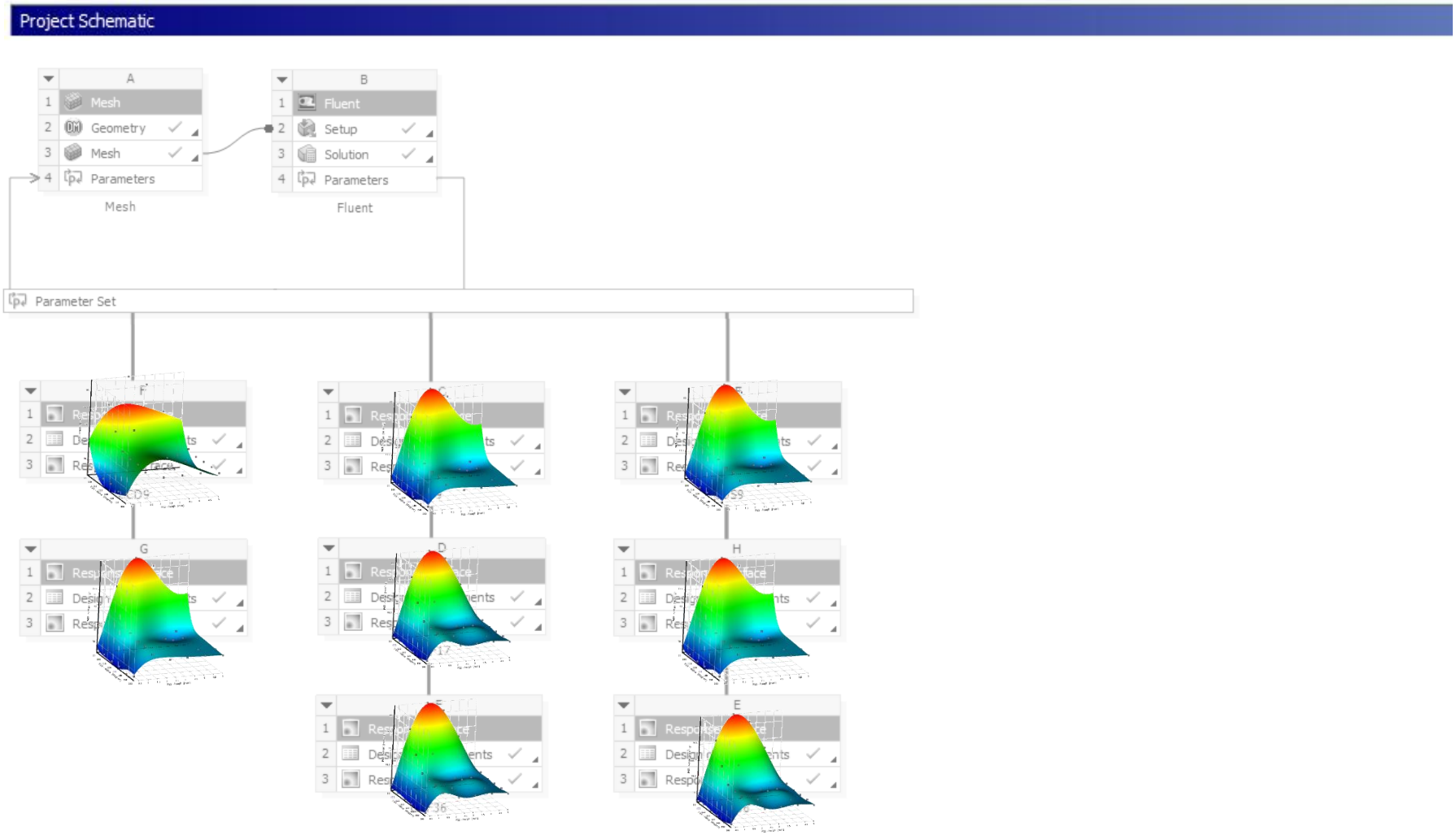
Workflow, Theory & Results

6. Response Surfaces



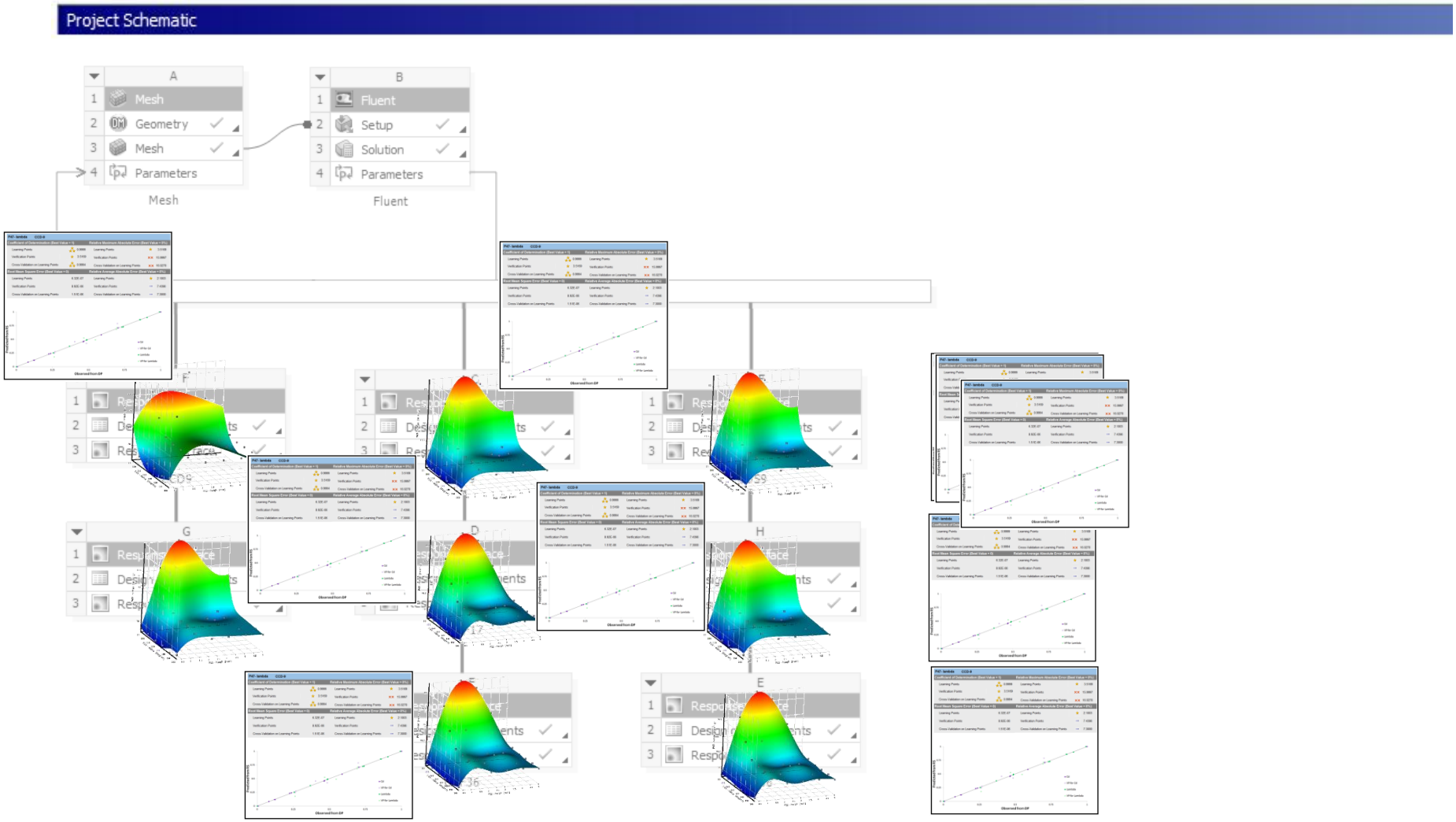
Workflow, Theory & Results

6.1. DOE Analysis results



Workflow, Theory & Results

6.1. DOE Analysis results

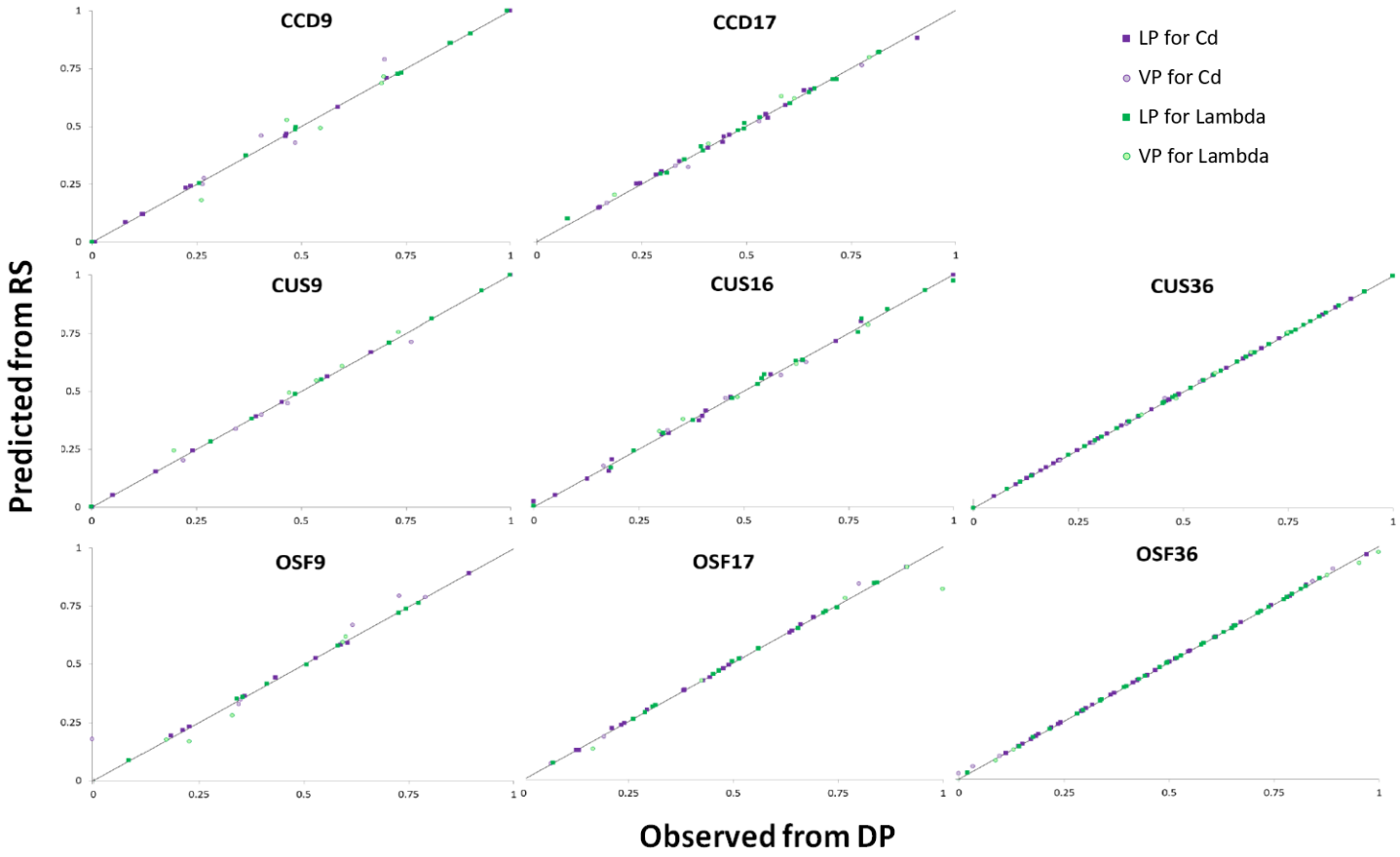


Workflow, Theory & Results

6.1. DOE Analysis results

Project Schematic

5.1.1. Verification Points



Workflow, Theory & Results

6.1. DOE Analysis results

Project Schematic

5.1.2. Statistical Criteria

Lambda	CCD9	OSF9	CUS9	CCD17	OSF17	CUS16	OSF36	CUS36
Coefficient of Determination (Best value = 1)								
Learning Points	0.9996	0.9991	1.0000	0.9972	0.9996	0.9973	0.9999	1.0000
Verification Points	0.8945	0.9608	0.9802	0.9896	0.9460	0.9912	0.9983	0.9973
Cross-Validation	0.9994	0.9941	0.9999	0.9946	0.9949	0.9944	0.9954	0.9962
Root Mean Square Error (Best value = 0)								
Learning Points	3.3E-05	4.2E-05	2.1E-06	1.1E-04	1.9E-05	2.0E-04	3.7E-06	2.8E-08
Verification Points	2.7E-03	1.3E-03	6.6E-04	4.4E-04	1.2E-04	3.0E-04	2.9E-04	7.1E-05
Cross-Validation	1.5E-06	5.1E-06	2.4E-07	3.8E-06	4.1E-06	5.3E-06	3.2E-06	4.1E-06
Relative Maximum Absolute Error (Best value = 0%)								
Learning Points	4.09	5.18	0.83	12.86	4.96	10.40	2.51	0.13
Verification Points	50.81	33.25	25.87	20.58	29.54	13.74	6.40	9.18
Cross-Validation	16.03	12.86	0.44	15.00	13.84	14.27	13.71	5.69
Relative Average Absolute Error (Best value = 0%)								
Learning Points	1.65	2.67	0.40	4.03	1.44	4.07	0.66	0.06
Verification Points	15.20	8.17	6.51	2.10	4.96	2.76	0.46	0.61
Cross-Validation	7.30	6.71	0.28	5.99	6.82	6.39	4.52	4.21

Workflow, Theory & Results

6.1. DOE Analysis results

Project Schematic

5.1.2. Statistical Criteria

Cd	CCD9	OSF9	CUS9	CCD17	OSF17	CUS16	OSF36	CUS36
Coefficient of Determination (Best value = 1)								
Learning Points	0.9996	0.9991	1.0000	0.9969	0.9987	0.9979	0.9999	1.0000
Verification Points	0.8833	0.9556	0.9785	0.9905	0.9272	0.9904	0.9987	0.9984
Cross-Validation	0.9987	0.9994	0.9994	0.9923	0.9957	0.9917	0.9971	0.9971
Root Mean Square Error (Best value = 0)								
Learning Points	6.4E-07	1.3E-06	6.0E-08	3.6E-06	5.4E-08	4.6E-06	1.2E-07	1.1E-08
Verification Points	6.6E-05	4.6E-05	2.2E-05	1.2E-05	5.0E-05	9.0E-06	6.1E-06	1.1E-06
Cross-Validation	6.3E-08	1.5E-07	5.2E-04	1.2E-03	9.7E-07	1.7E-03	8.8E-05	5.4E-08
Relative Maximum Absolute Error (Best value = 0%)								
Learning Points	3.63	5.48	0.78	15.09	4.32	8.60	3.10	1.32
Verification Points	56.22	36.79	28.36	19.07	24.84	14.77	5.61	6.53
Cross-Validation	5.71	18.37	4.50	16.32	13.89	21.45	14.80	8.63
Relative Average Absolute Error (Best value = 0%)								
Learning Points	1.52	2.62	0.41	4.06	3.08	3.78	0.67	0.08
Verification Points	15.66	8.44	6.48	2.08	8.09	2.83	0.41	0.49
Cross-Validation	2.81	6.31	2.06	6.91	5.43	6.50	3.44	1.99

better

worst

Workflow, Theory & Results

6.1. DOE Analysis results

Project Schematic

5.1.2. Statistical Criteria

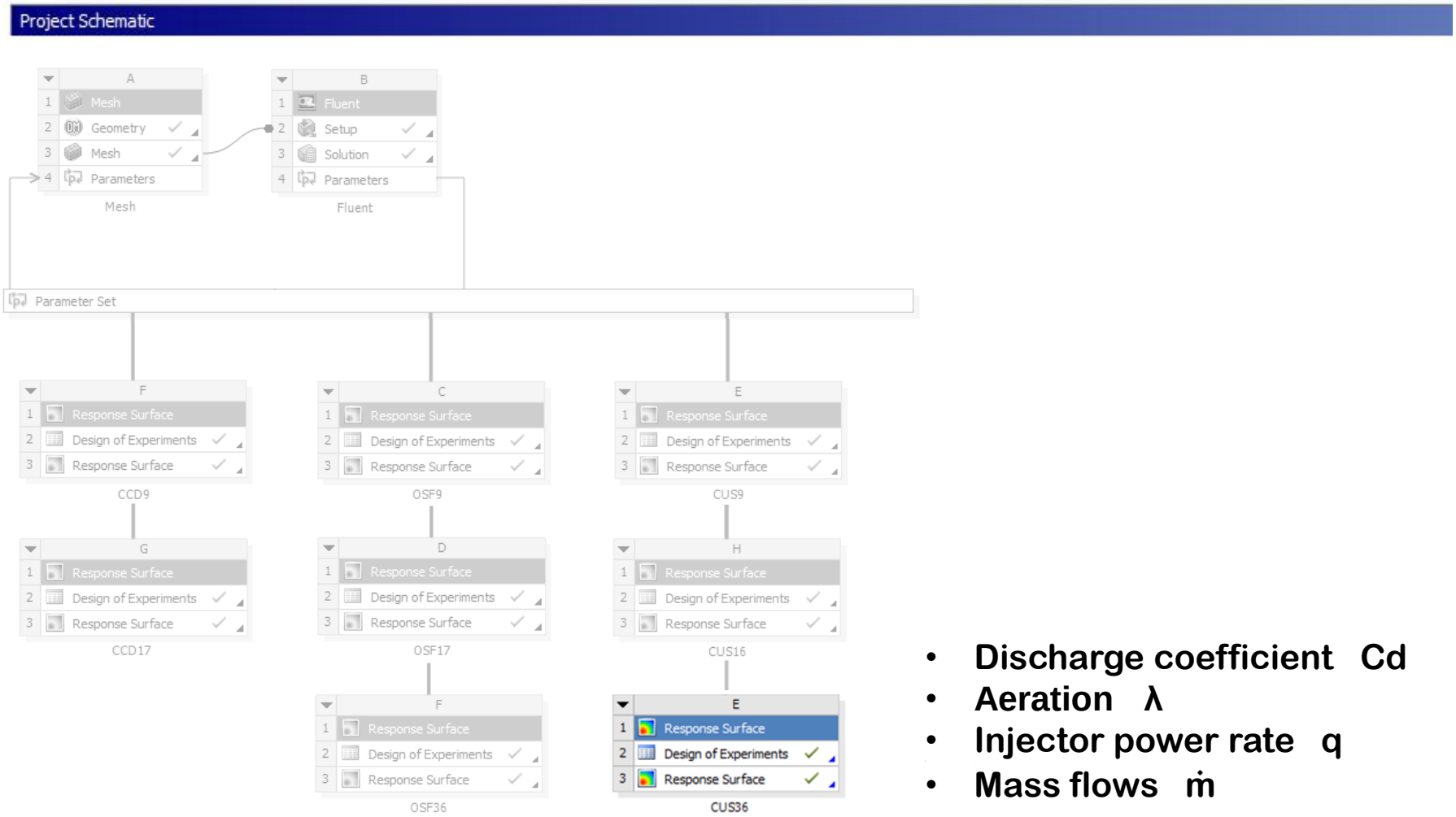
Cd	CCD9	OSF9	CUS9	CCD17	OSF17	CUS16	OSF36	CUS36
Coefficient of Determination (Best value = 1)								
Learning Points	0.9996	0.9991	1.0000	0.9969	0.9987	0.9979	0.9999	1.0000
Verification Points	0.8833	0.9556	0.9785	0.9905	0.9272	0.9904	0.9987	0.9984
Cross-Validation	0.9987	0.9994	0.9994	0.9923	0.9957	0.9917	0.9971	0.9971
Root Mean Square Error (Best value = 0)								
Learning Points	6.4E-07	1.3E-06	6.0E-08	3.6E-06	5.4E-08	4.6E-06	1.2E-07	1.1E-08
Verification Points	6.6E-05	4.6E-05	2.2E-05	1.2E-05	5.0E-05	9.0E-06	6.1E-06	1.1E-06
Cross-Validation	6.3E-08	1.5E-07	5.2E-04	1.2E-03	9.7E-07	1.7E-03	8.8E-05	5.4E-08
Relative Maximum Absolute Error (Best value = 0%)								
Learning Points	3.63	5.48	0.78	15.09	4.32	8.60	3.10	1.32
Verification Points	56.22	36.79	28.36	19.07	24.84	14.77	5.61	6.53
Cross-Validation	5.71	18.37	4.50	16.32	13.89	21.45	14.80	8.63
Relative Average Absolute Error (Best value = 0%)								
Learning Points	1.52	2.62	0.41	4.06	3.08	3.78	0.67	0.08
Verification Points	15.66	8.44	6.48	2.08	8.09	2.83	0.41	0.49
Cross-Validation	2.81	6.31	2.06	6.91	5.43	6.50	3.44	1.99

better

worst

Workflow, Theory & Results

6.2. CUS 36 Results



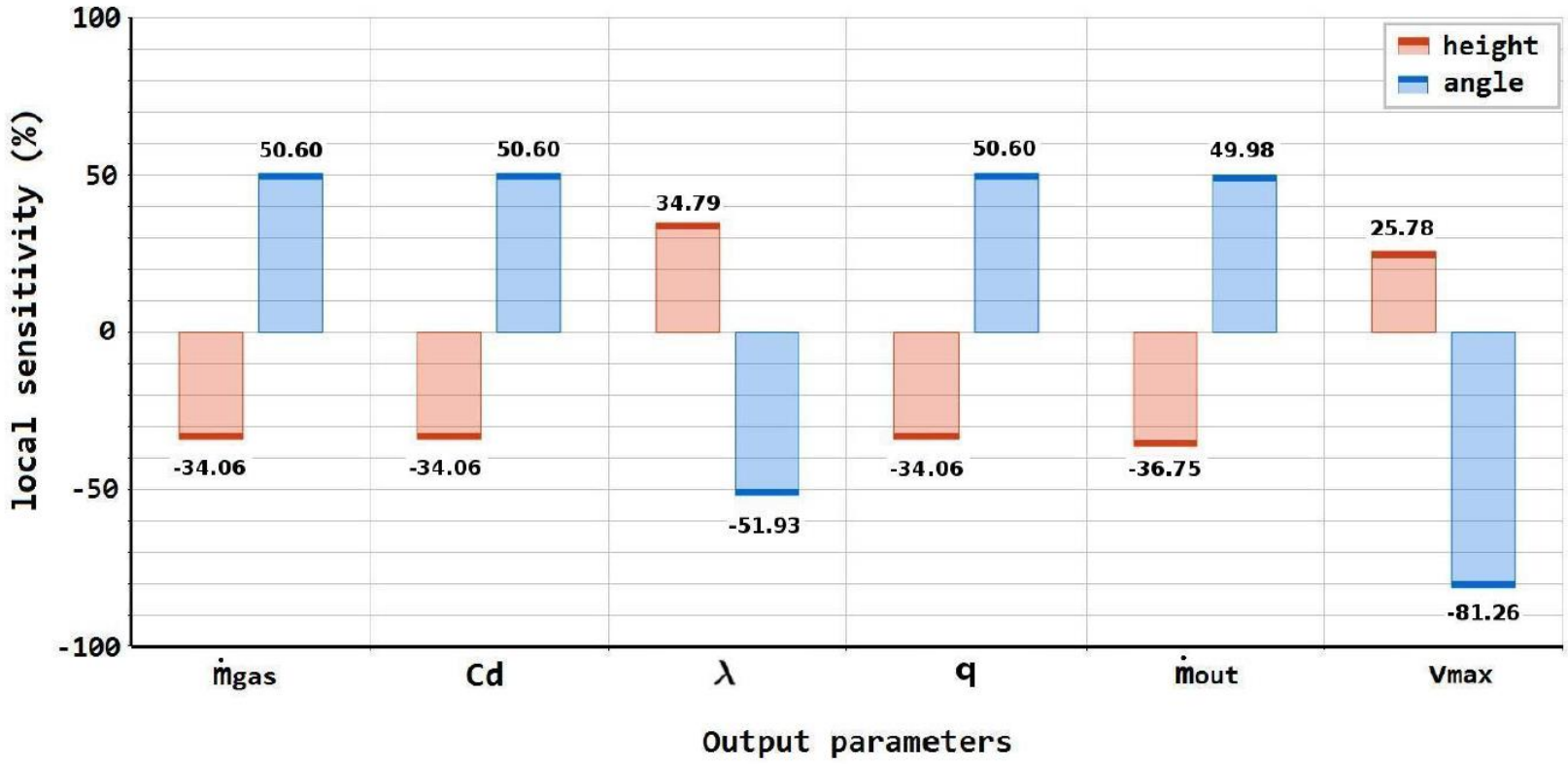
- Discharge coefficient Cd
- Aeration λ
- Injector power rate q
- Mass flows $\dot{m}$

Workflow, Theory & Results

6.2. CUS 36 Results

Project Schematic

6.2.1. Local sensitivities

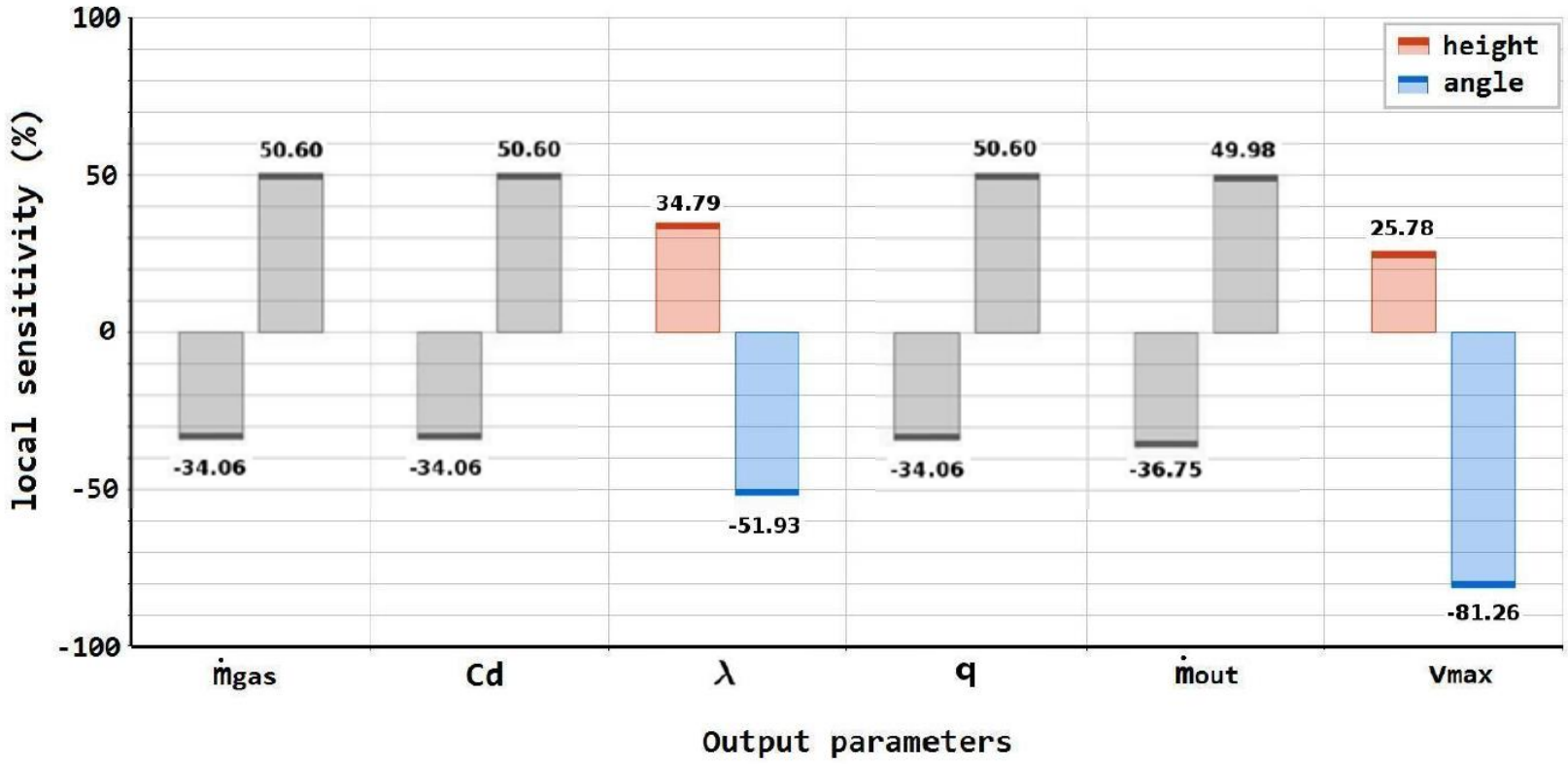


Workflow, Theory & Results

6.2. CUS 36 Results

Project Schematic

6.2.1. Local sensitivities

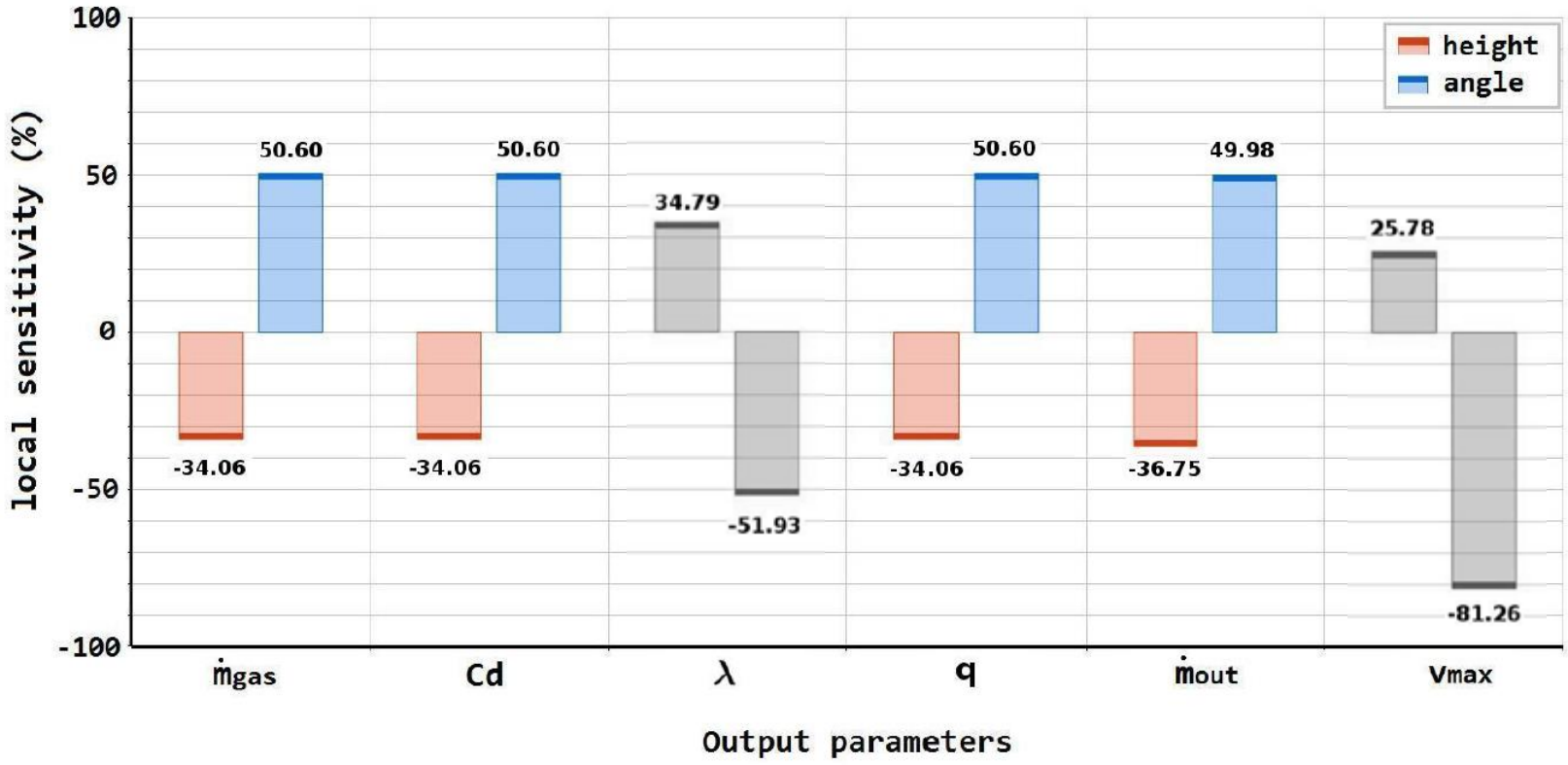


Workflow, Theory & Results

6.2. CUS 36 Results

Project Schematic

6.2.1. Local sensitivities

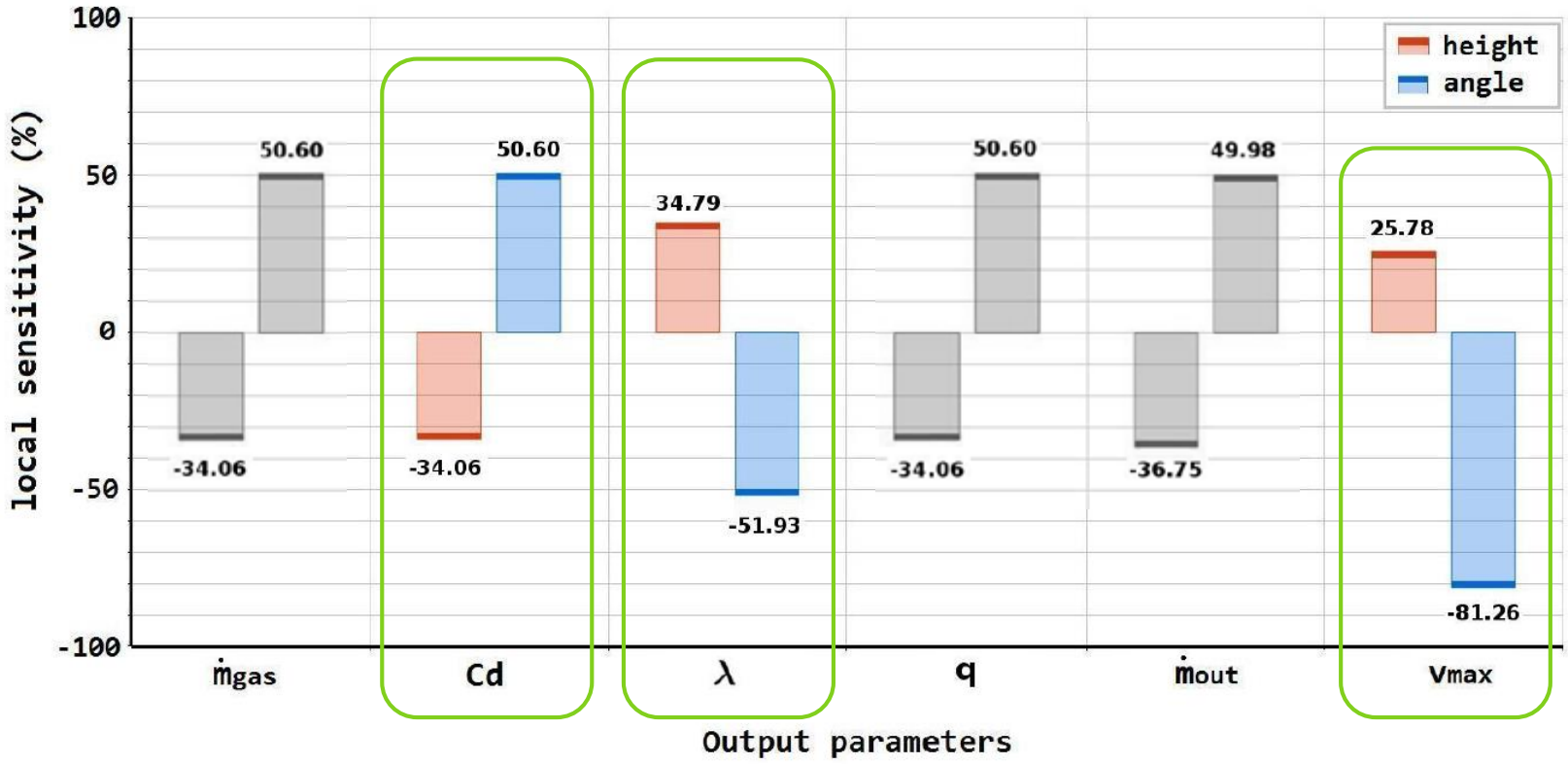


Workflow, Theory & Results

6.2. CUS 36 Results

Project Schematic

6.2.1. Local sensitivities



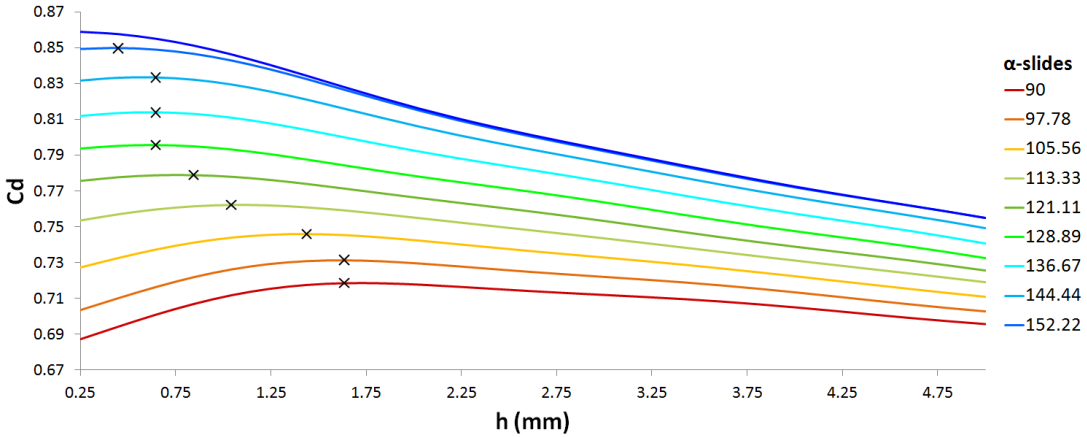
Workflow, Theory & Results

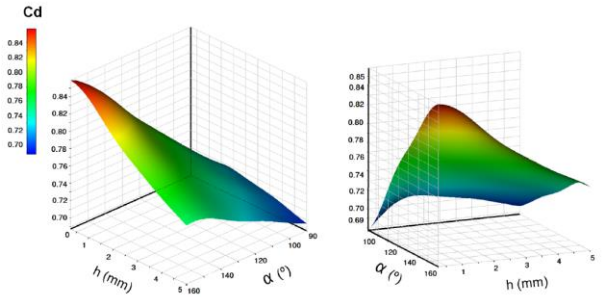
6.2. CUS 36 Results

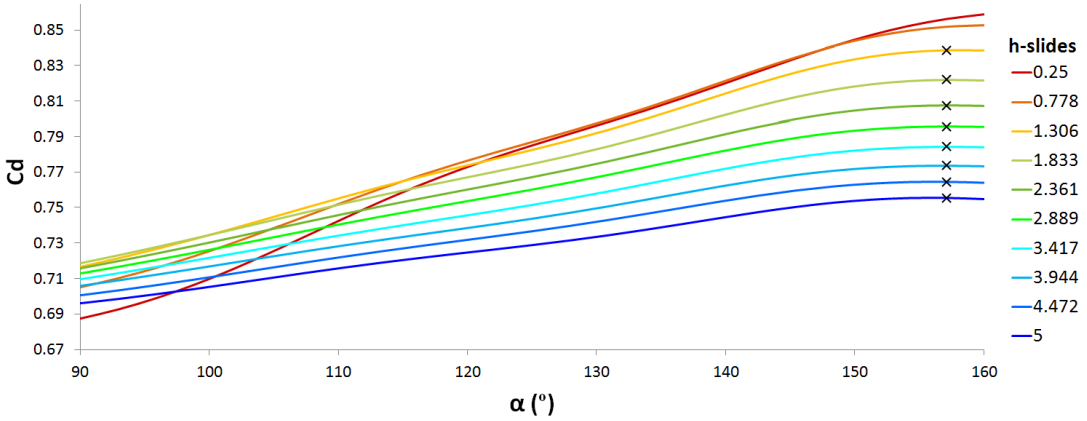
Project Schematic

6.2.2. Discharge coefficient

$Cd_{max} = 0.859 \quad Cd_{min} = 0.687$







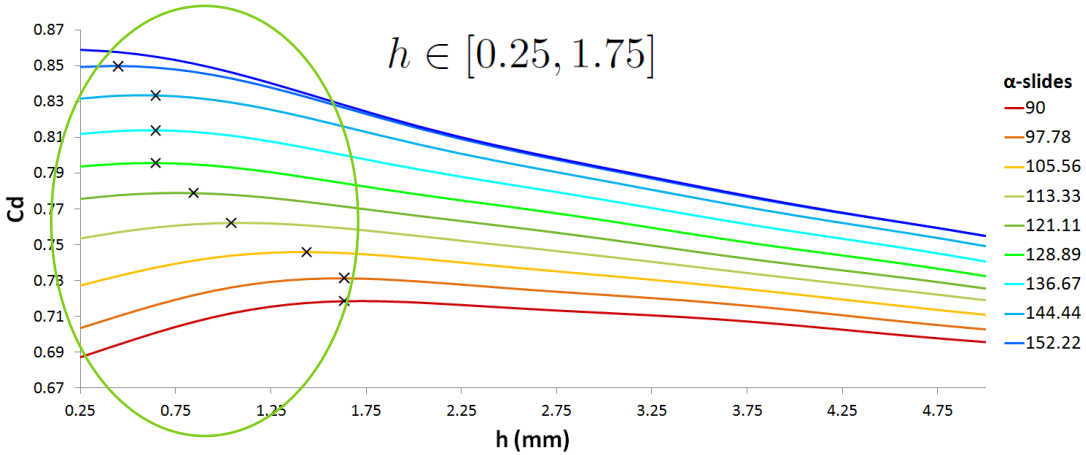
Workflow, Theory & Results

6.2. CUS 36 Results

Project Schematic

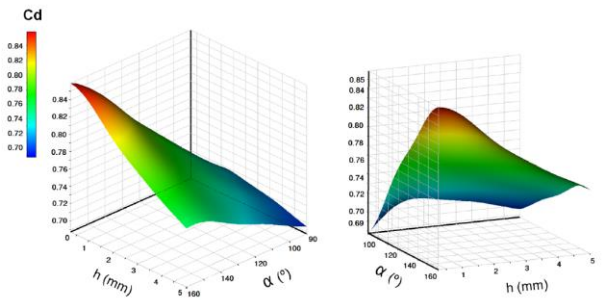
6.2.2. Discharge coefficient

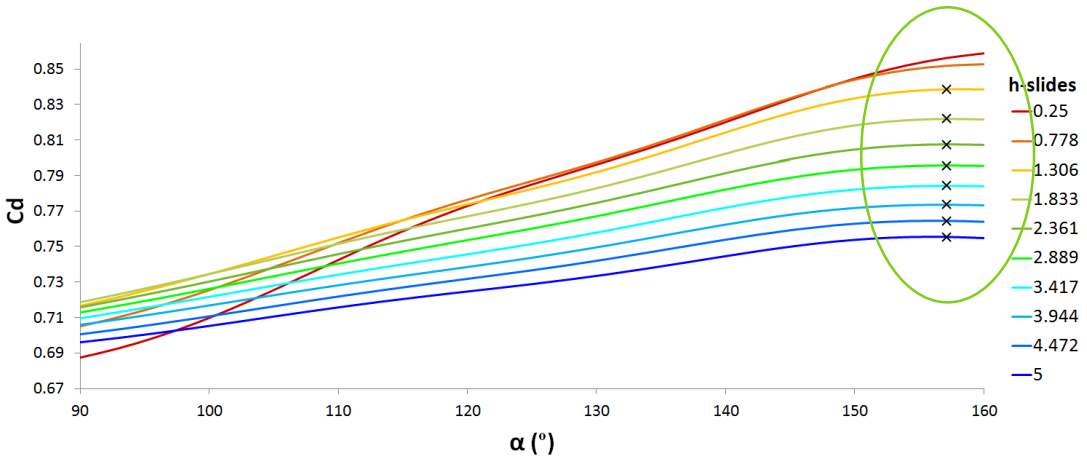
$Cd_{max} = 0.859 \quad Cd_{min} = 0.687$



Lower heights
&
larger angles

$\alpha \in [155, 160]^{o}$





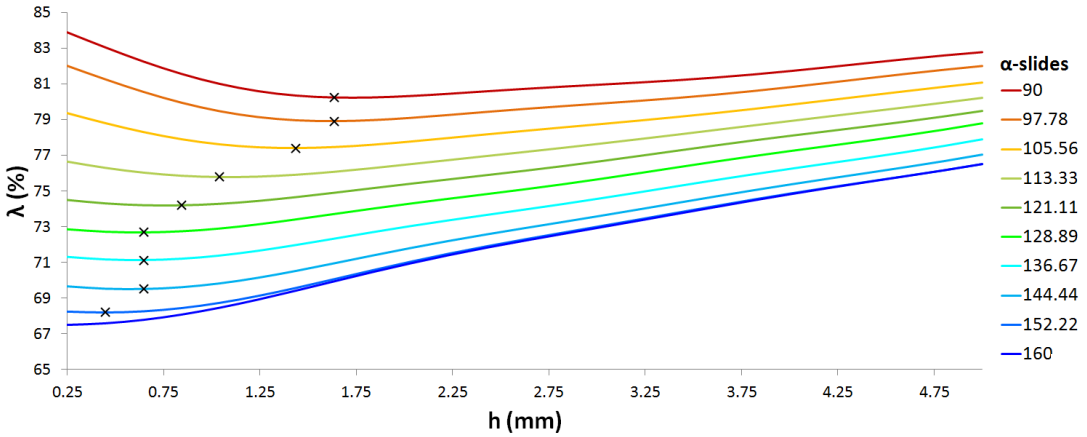
Workflow, Theory & Results

6.2. CUS 36 Results

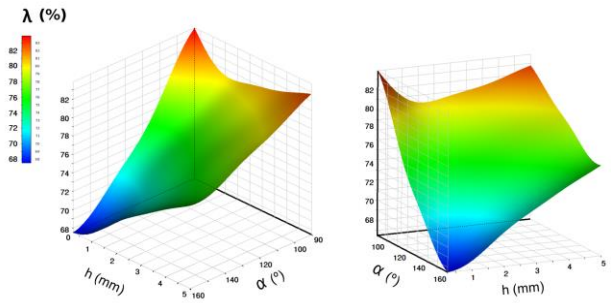
Project Schematic

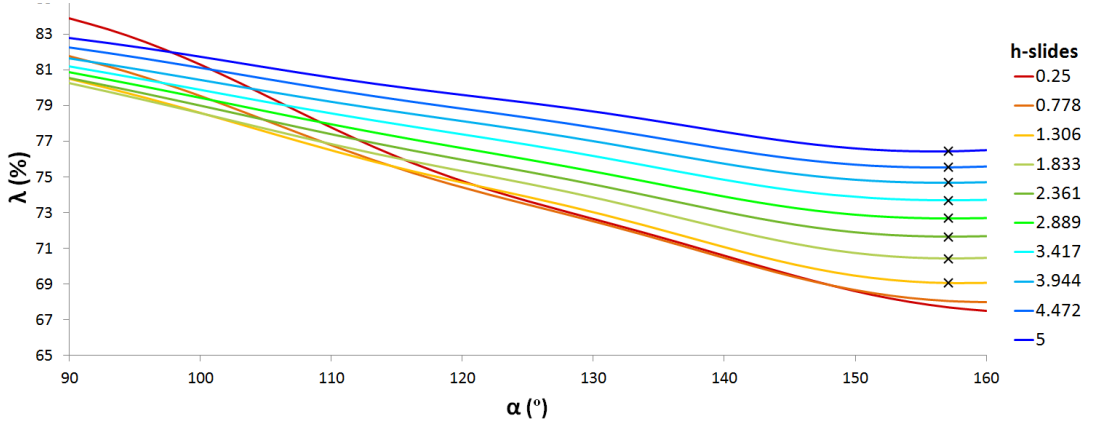
6.2.3. Aeration

$\lambda_{max} = 83.88\%$ $\lambda_{min} = 67.50\%$



Lower angles



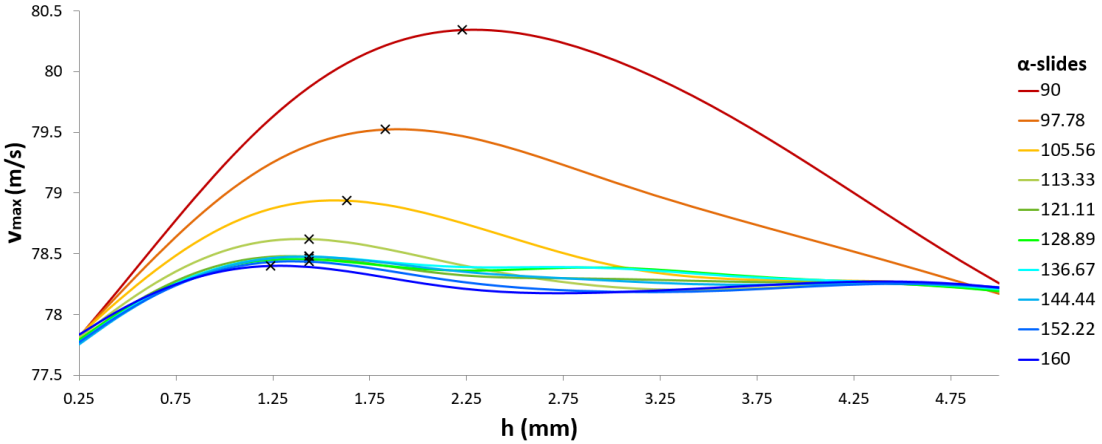


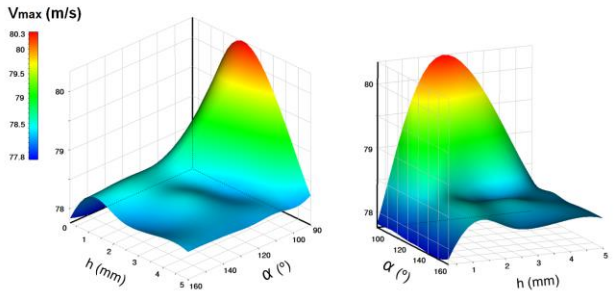
Workflow, Theory & Results

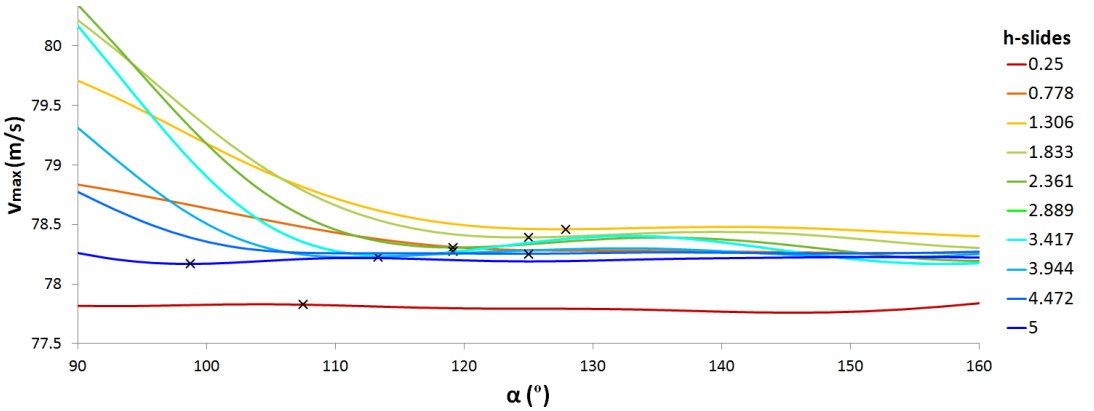
6.2. CUS 36 Results

Project Schematic

6.2.4. Maximum velocity of gas

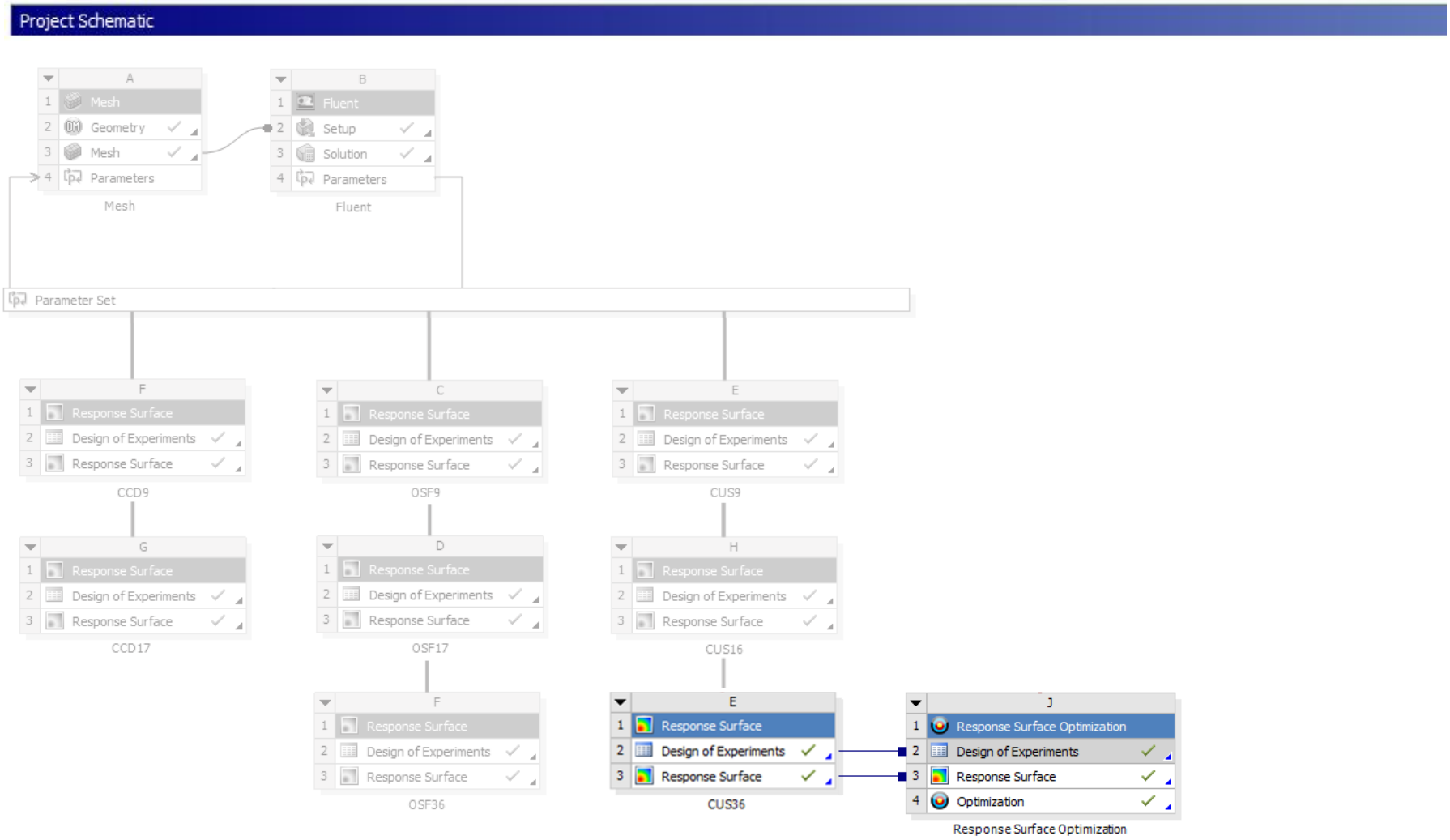






Workflow, Theory & Results

7. Optimization

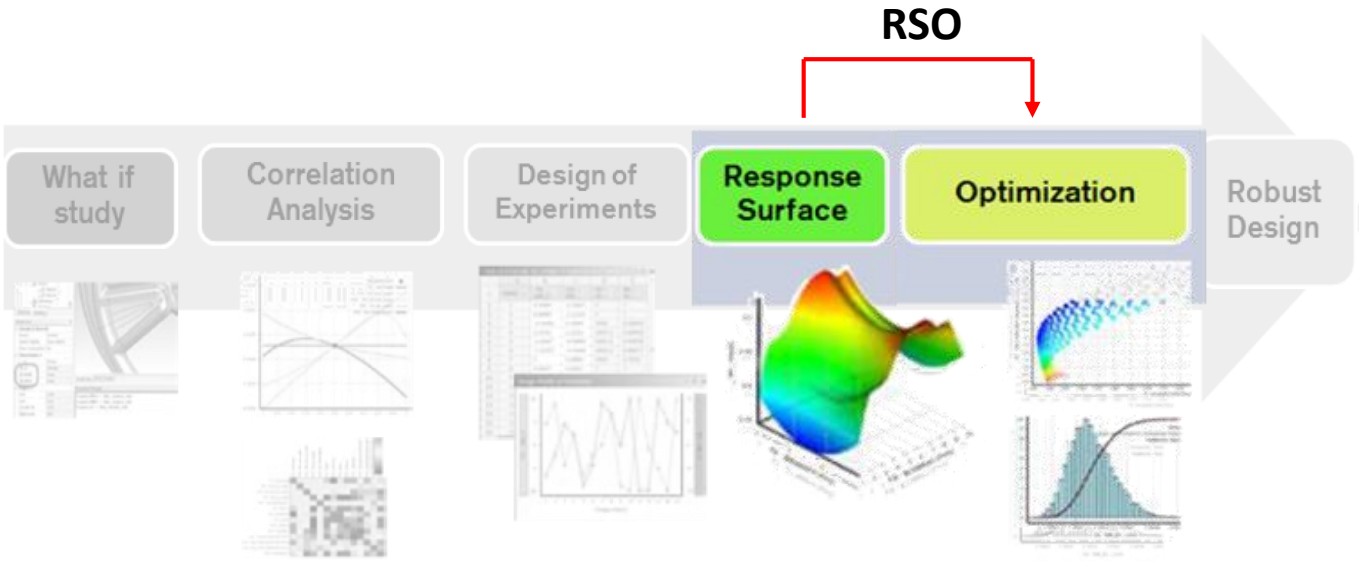


Workflow, Theory & Results

7. Optimization

Project Schematic

Response Surface Optimization



Multi Objective Genetic Algorithm (MOGA) → Pareto Fronts
Multi Objective Genetic Algorithm (MOGA) → Candidate Points

Workflow, Theory & Results

7. Optimization

Project Schematic

7.1. λ – Cd maximization

Base Case

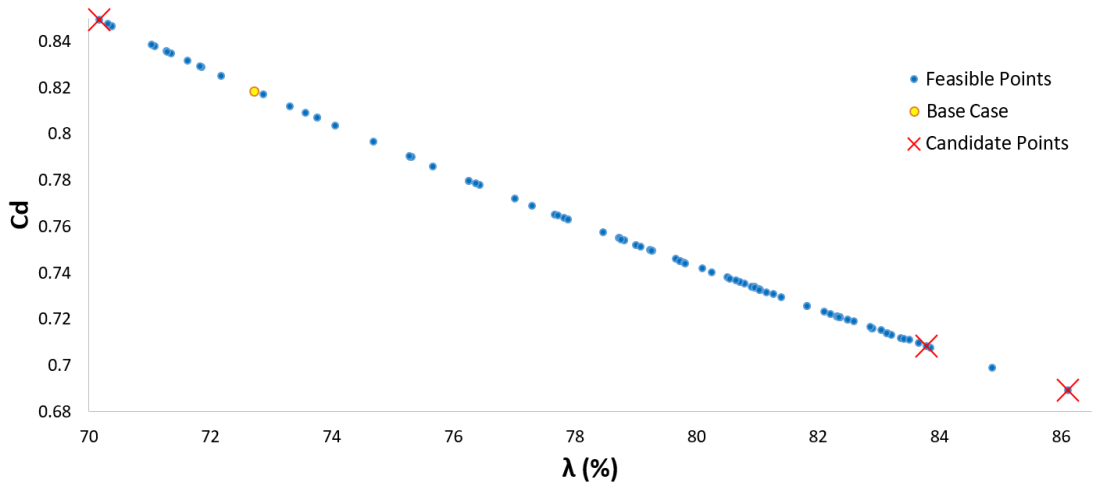
q = 1864 W
λ = 72.7 %
Cd = 0.818

Workflow, Theory & Results

7. Optimization

Project Schematic

7.1. λ – Cd maximization



Base Case

q = 1864 W
λ = 72.7 %
Cd = 0.818

	h (mm)	α (º)	λ (%)		Cd	
			Parameter value	Variation from reference	Parameter value	Variation from reference
Candidate Point 1	0.27	90.3	★★ 86.1	2.8%	×× 0.689	-2.7%
Candidate Point 2	0.61	152.9	×× 70.2	16.3%	★★ 0.850	19.9%
Candidate Point 3	4.45	97.5	★★ 83.8	**0.0%**	×× 0.708	**0.0%**

Workflow, Theory & Results

7. Optimization

Project Schematic

7.2. λ – Cd maximization with $q > q_{BaseCase}$

Base Case

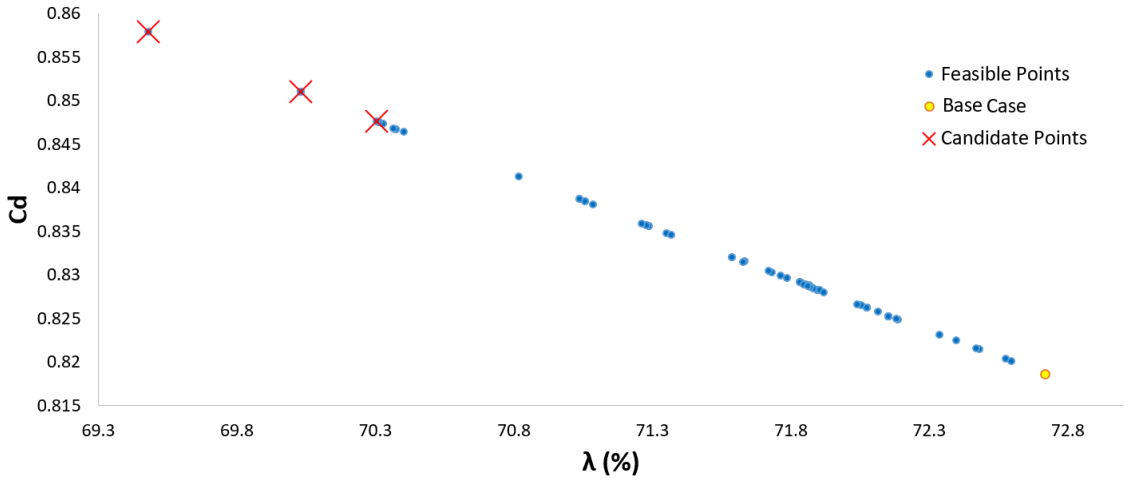
q = 1864 W
λ = 72.7 %
Cd = 0.818

Workflow, Theory & Results

7. Optimization

Project Schematic

7.2. λ – Cd maximization with q > $q_{BaseCase}$



Base Case

q = 1864 W
λ = 72.7 %
Cd = 0.818

	h (mm)	α (º)	λ (%)		Cd		q (W)	
			Parameter value	Variation from reference	Parameter value	Variation from reference	Parameter value	Variation from reference
Candidate Point 1	0.42	159.4	69.5	-1.2%	0.858	1.2%	1953.3	1.2%
Candidate Point 2	0.61	154.2	70.0	-0.4%	0.851	0.4%	1937.5	0.4%
Candidate Point 3	0.60	151.2	70.3	0.0%	0.848	0.0%	1929.9	0.0%

Workflow, Theory & Results

7. Optimization

Project Schematic

7.3. $\lambda - v_{max}$ maximization

Base Case

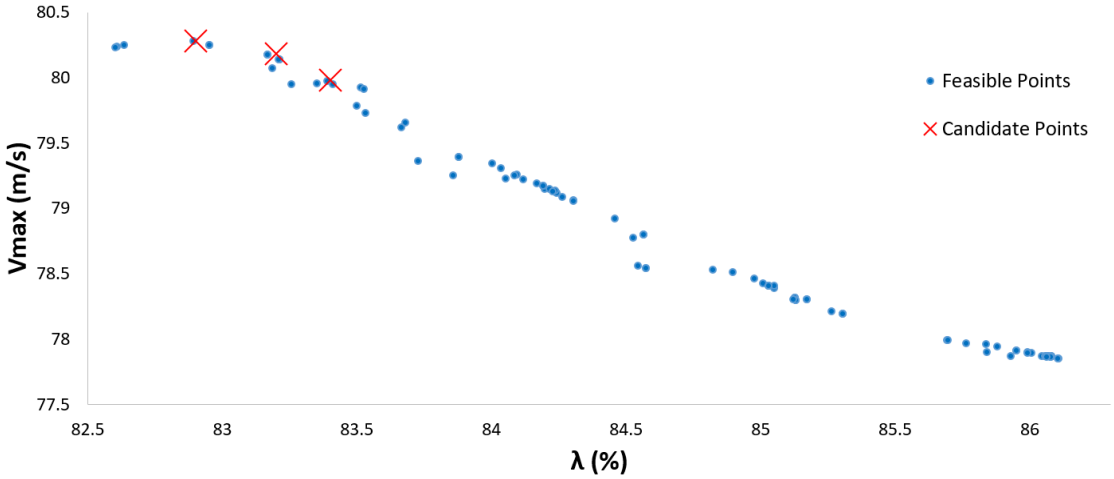
q = 1864 W
λ = 72.7 %
Cd = 0.818

Workflow, Theory & Results

7. Optimization

Project Schematic

7.3. $\lambda - v_{max}$ maximization



Base Case

q = 1864 W
λ = 72.7 %
Cd = 0.818

	h (mm)	α (º)	λ (%)		Vmax (m/s)		Cd
			Parameter value	Variation from reference	Parameter value	Variation from reference	
Candidate Point 1	2.39	90.4	82.9	-0.6%	80.28	0.4%	0.716
Candidate Point 2	2.78	90.4	83.2	-0.3%	80.18	0.3%	0.713
Candidate Point 3	3.15	90.4	83.4	0.0%	79.98	0.0%	0.711

Concluding remarks

Conclusions

1. **Design Exploration Process**
   - Number of simulations influences the most
   - Random distribution is a good choice
   - Genetic Agreggation is the recommended option despite being slower

2. **Physics & Optimization**
   - m_{gas}, q, Cd and m_{out} increases with the angle
   - λ and v_{max} increases with the height
   - Multi-objective optimization of q and λ only achievable compromising one of the variables

Concluding remarks

Conclusions

3. Geometric

- Small heights with larger angles give better results
- Larger discharge coefficients

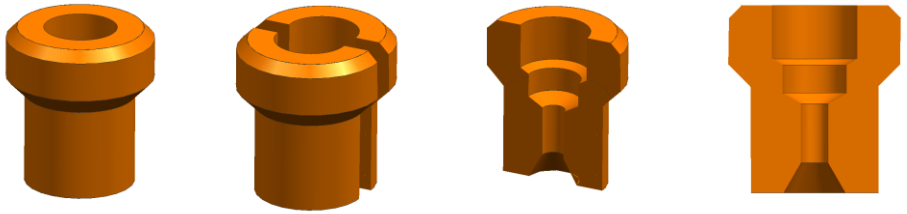
$$\alpha \in [155, 160]^{\circ}$$

$$h \in [0.25, 1.75]$$

Concluding remarks

Future work

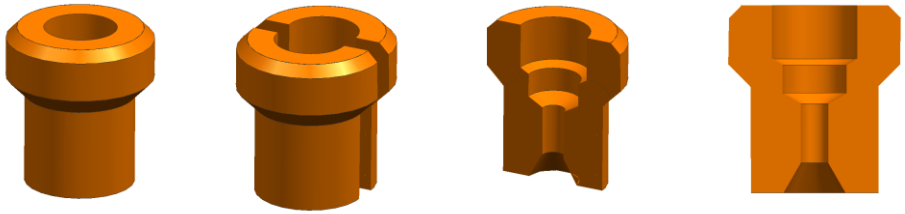
- Counter-bored injectors



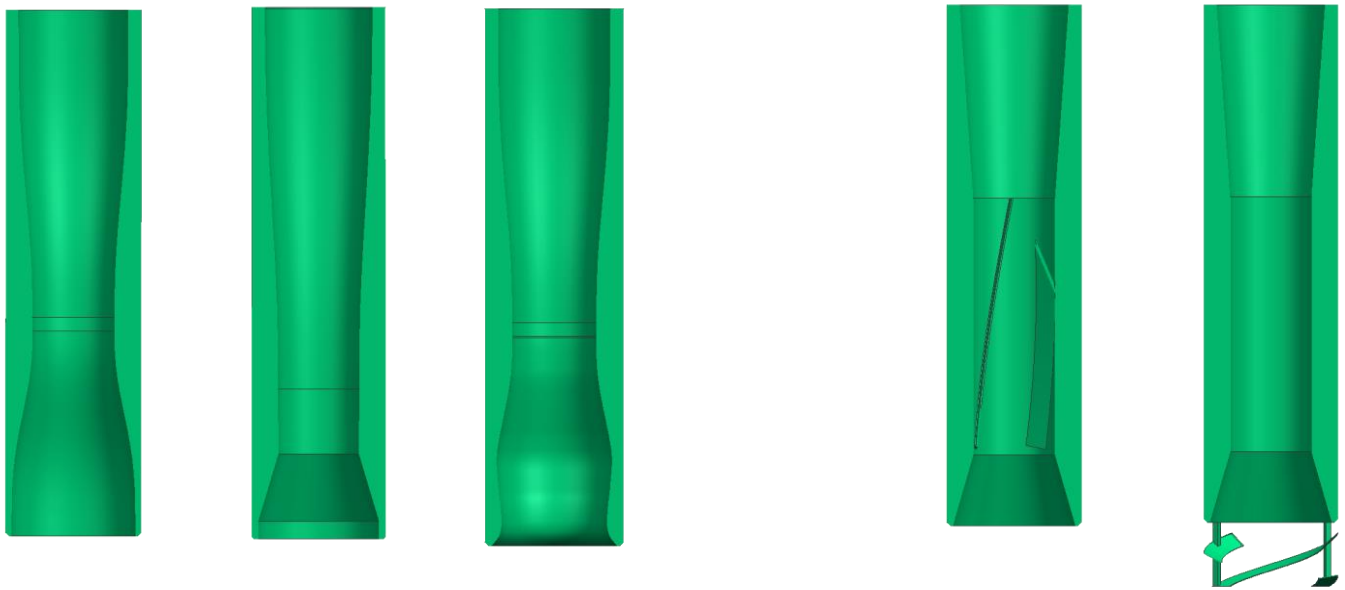
Concluding remarks

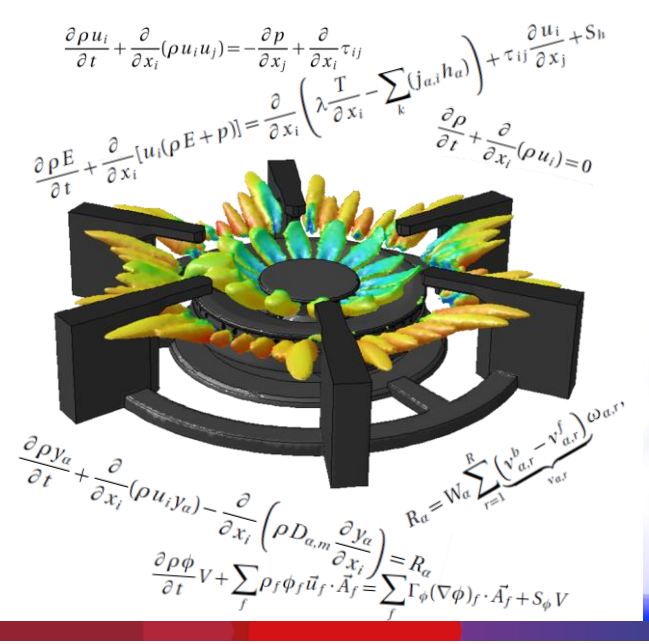
Future work

- Counter-bored injectors



- Include other burner elements in the study (Venturi tube, spreader…)





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