Numerical performance comparison of different tube cross-sections for heat recovery from particle-laden exhaust gas streams

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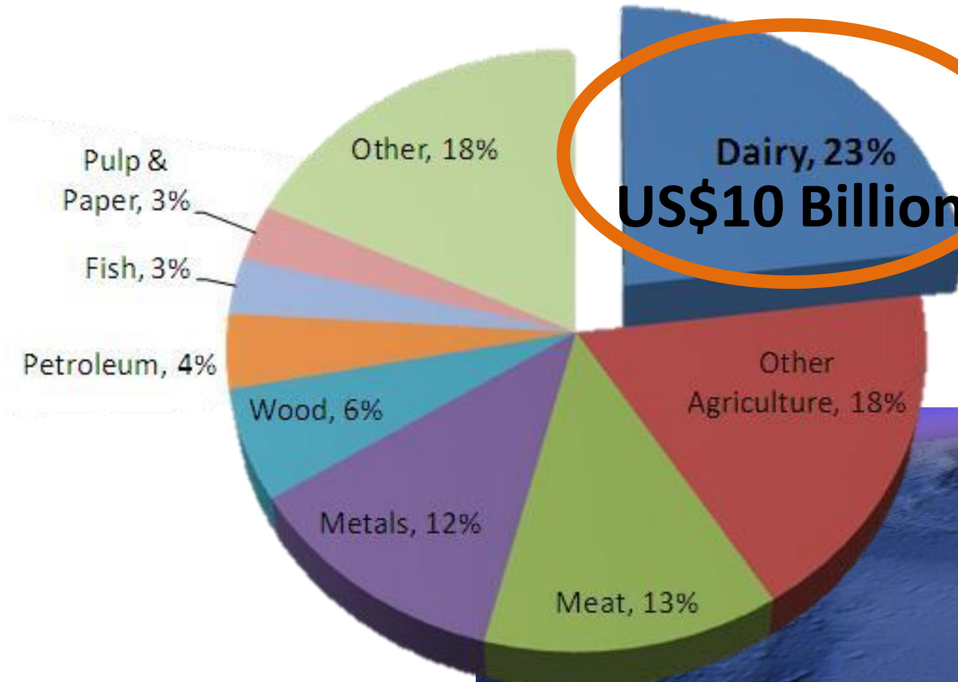
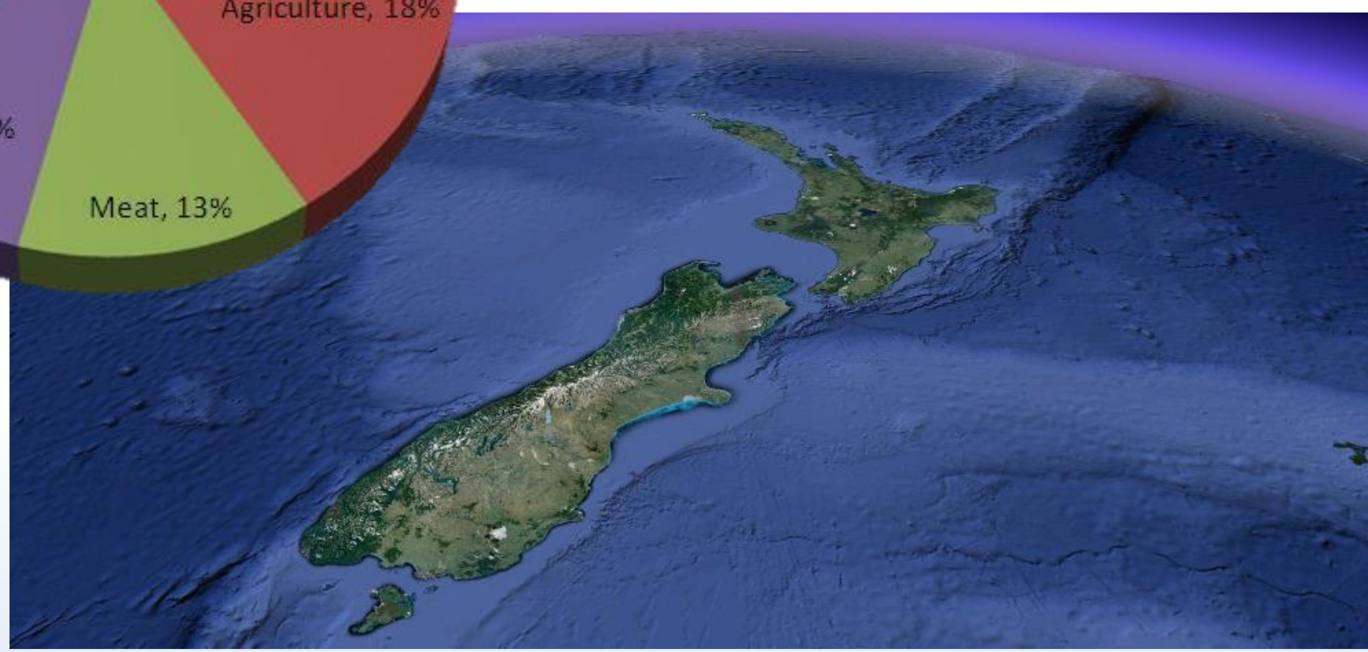
Outline

- Background
- Challenges facing heat recovery from air
- Methodology
- Numerical Results
- Experimental Work
- Summary

New Zealand Exports

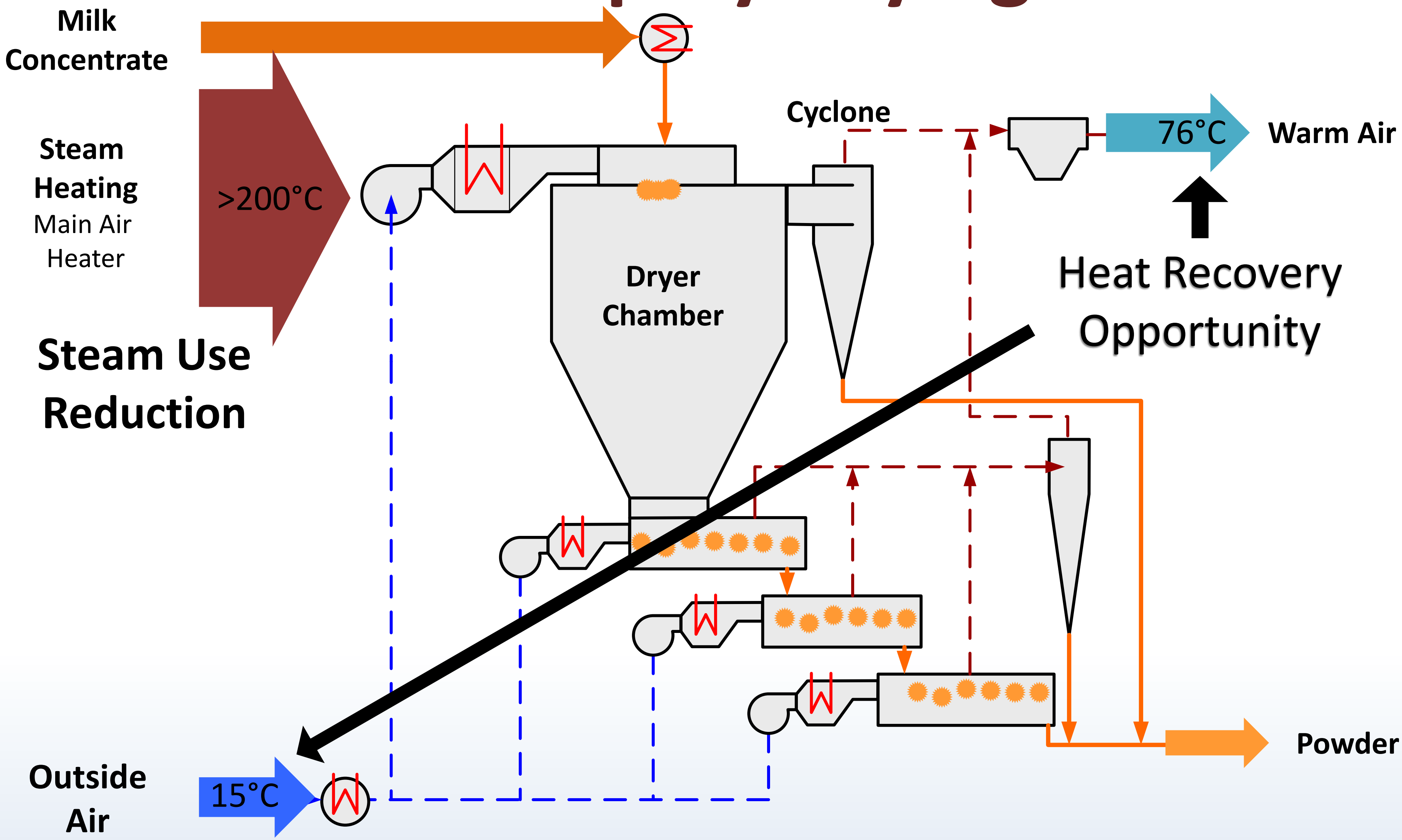


Milk Powder
≈85%



New Zealand Dairy

Milk Spray Drying



Challenges

1) Expensive to recover heat from air
2) Distance between exhaust and inlet ducts
3) Particulate fouling
4) High heat transfer resistance and lots of area

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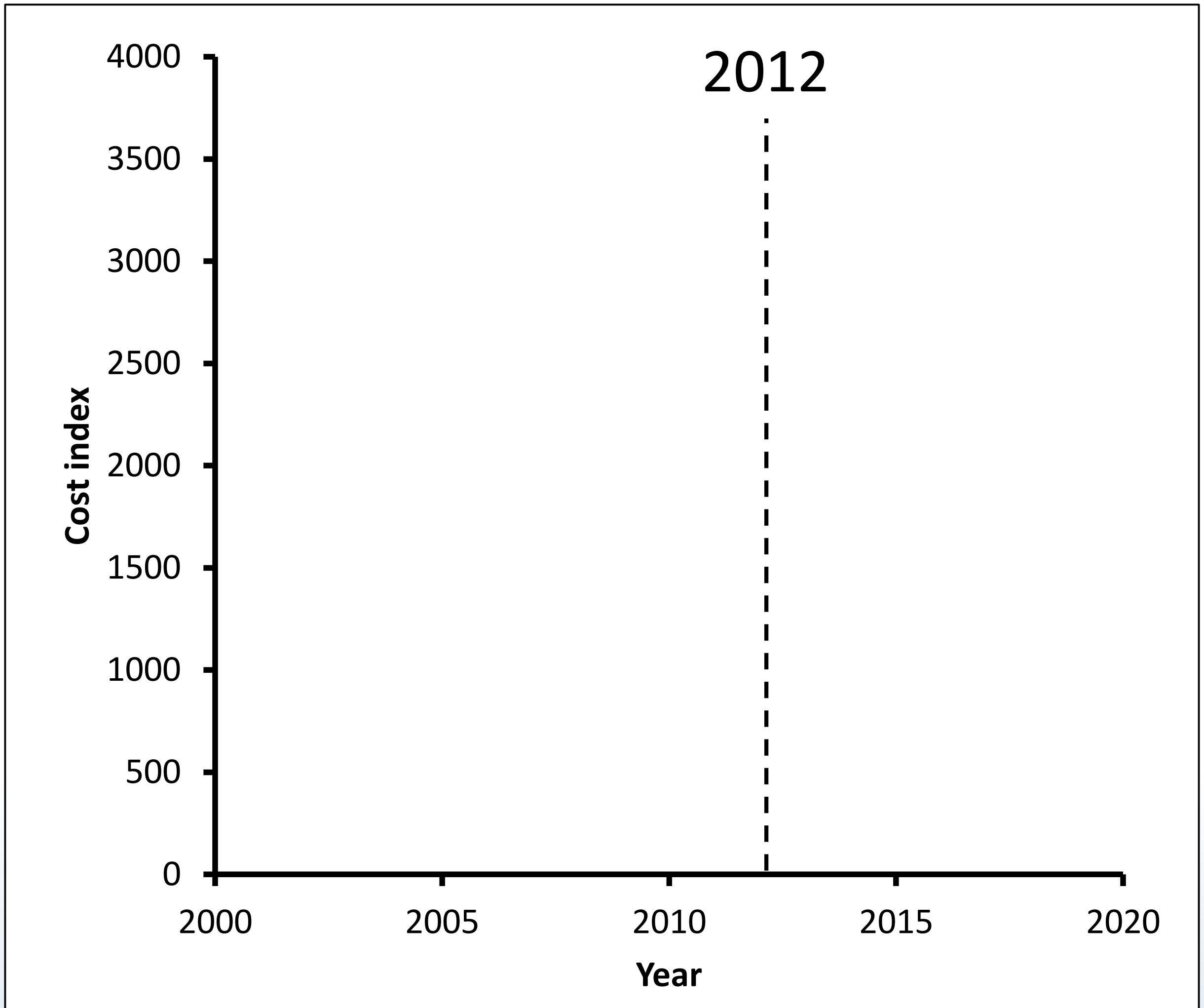
How Fast are Steam Prices Rising?



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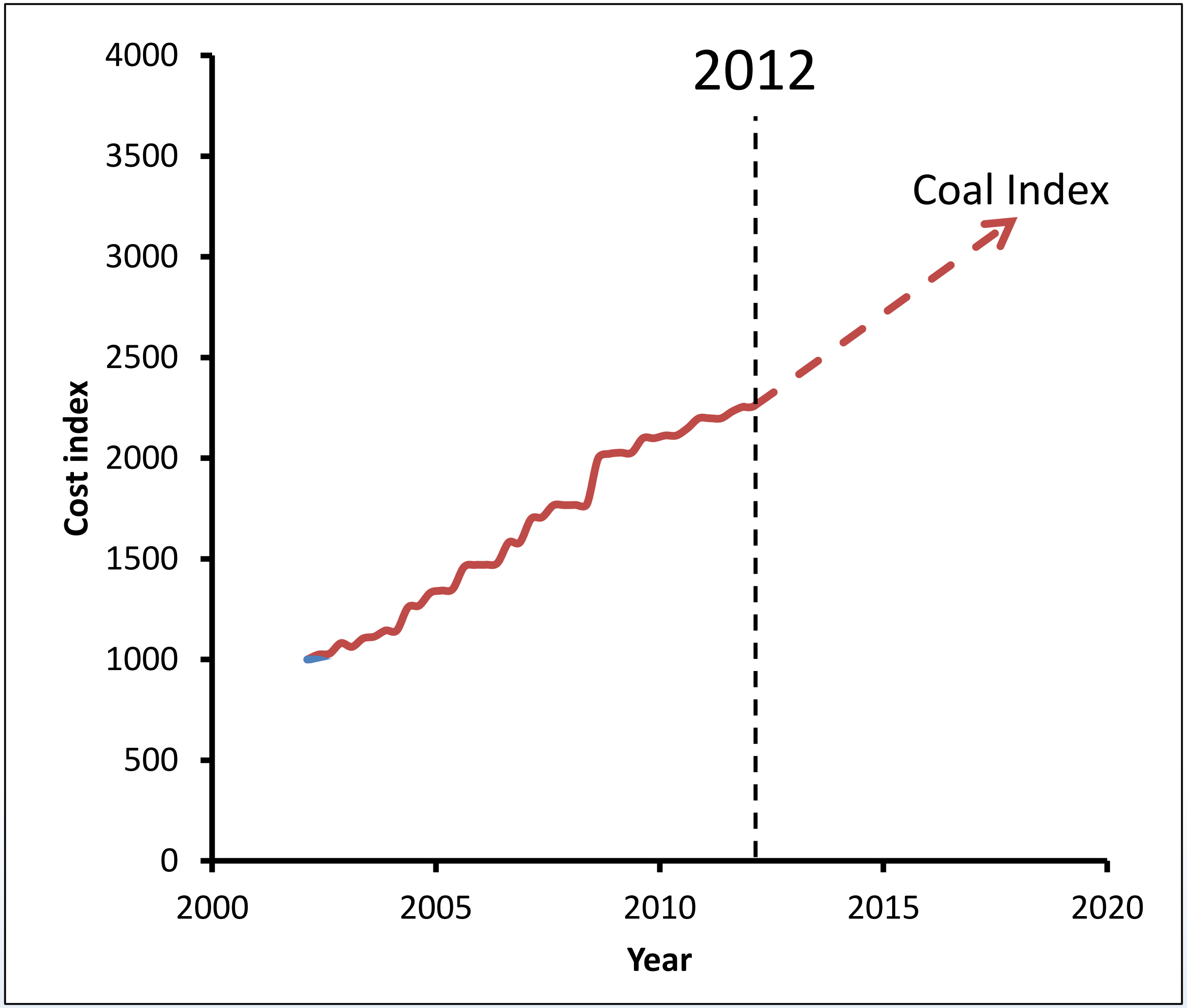

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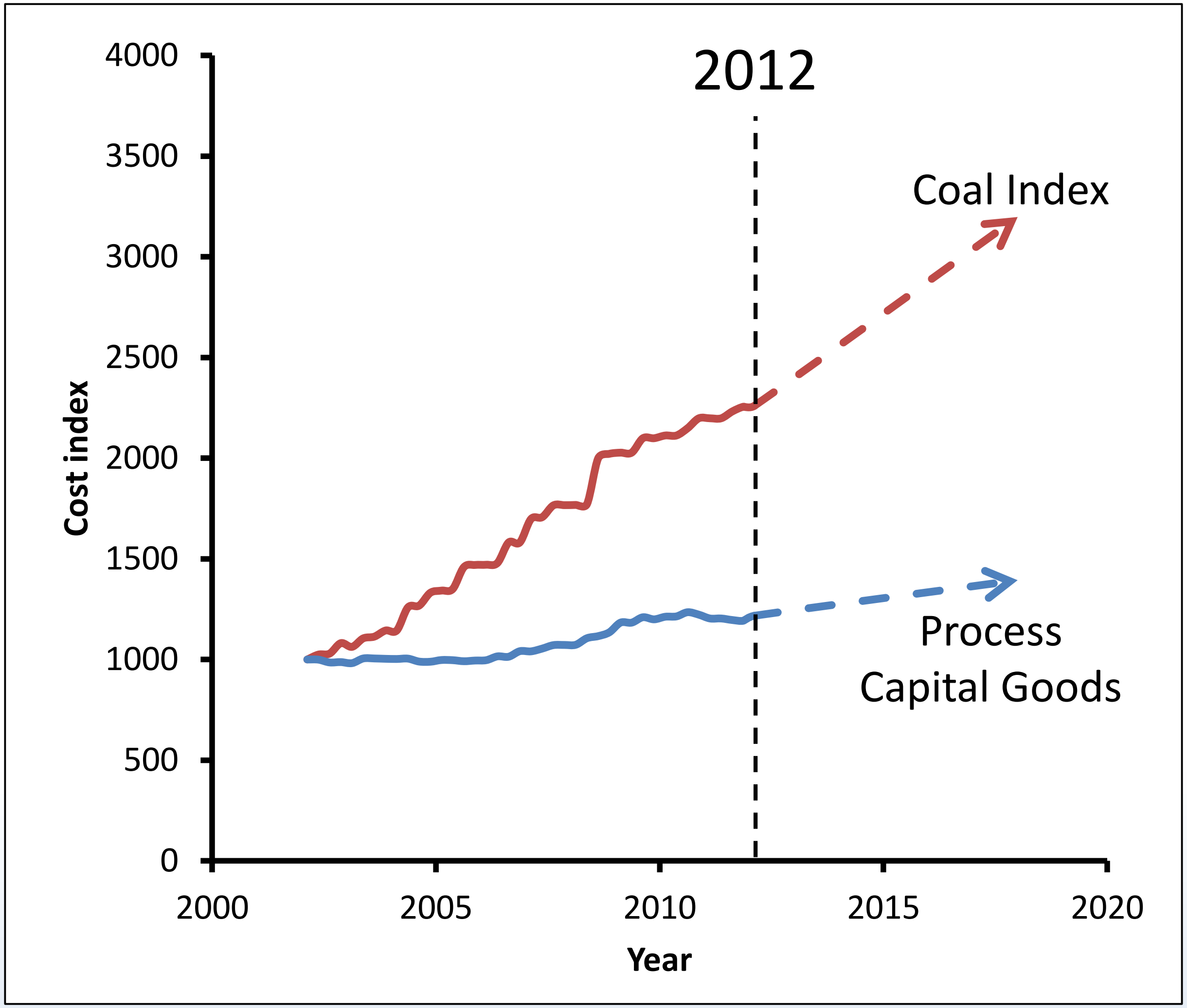

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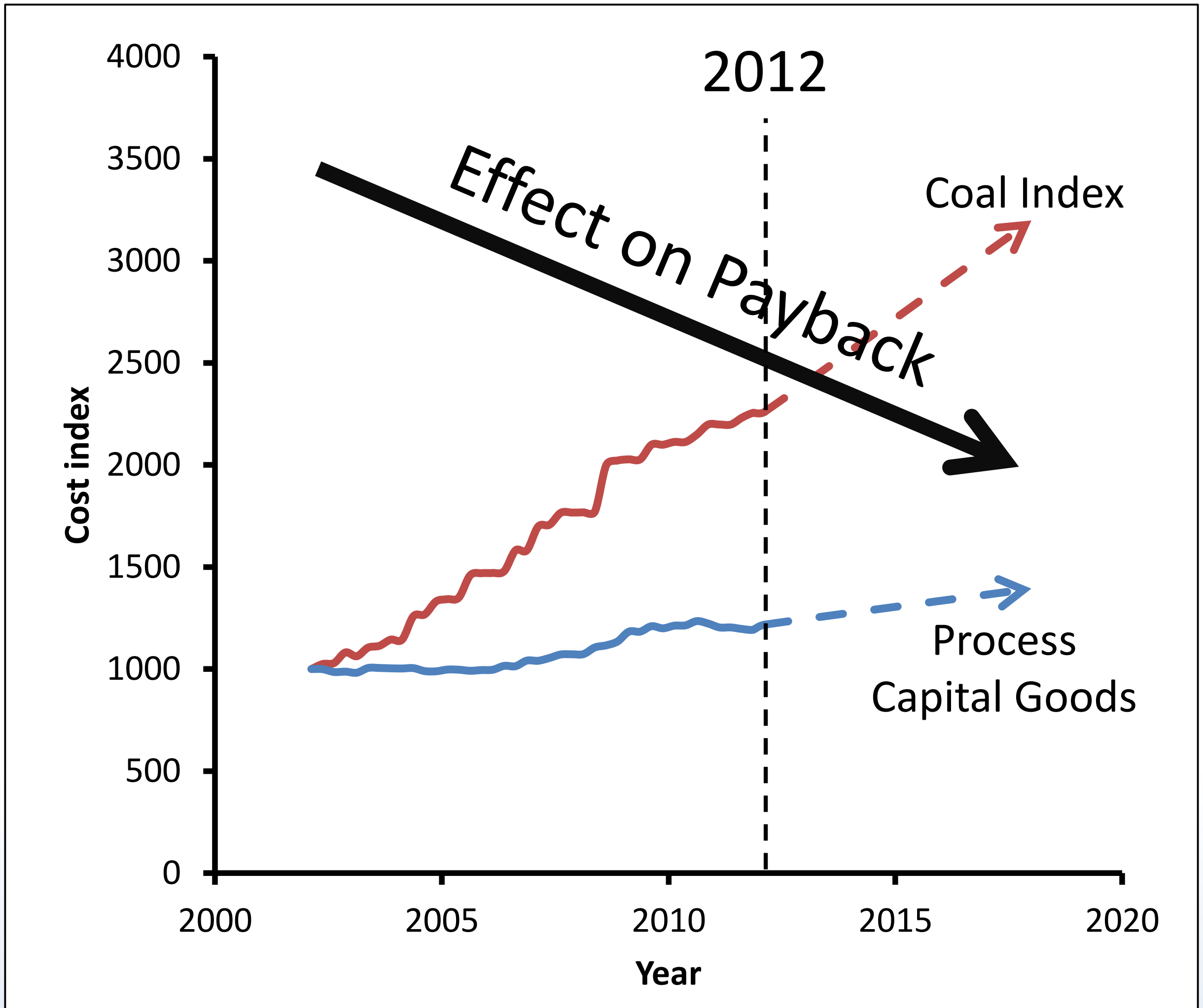

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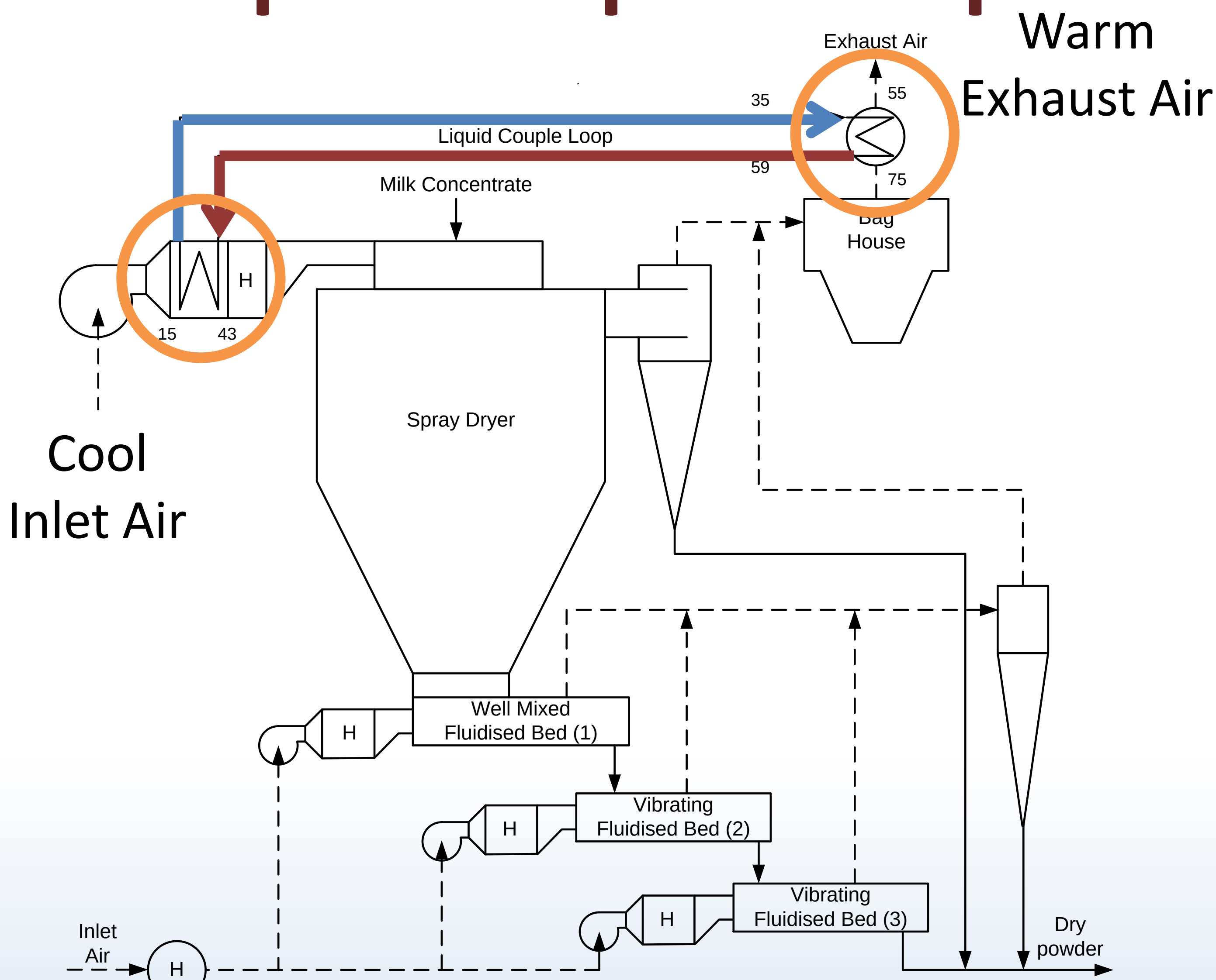
Liquid Coupled Loop



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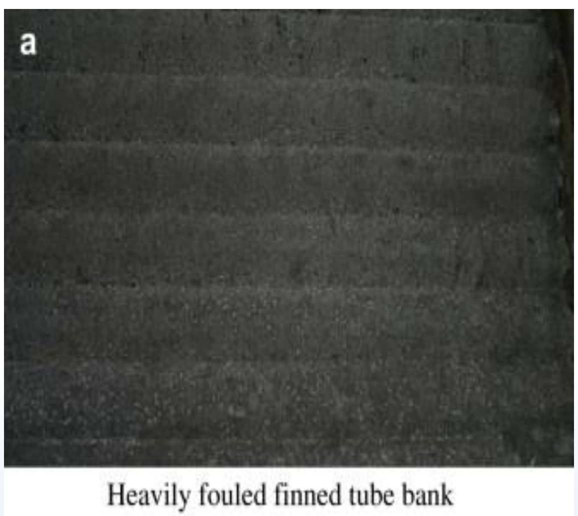
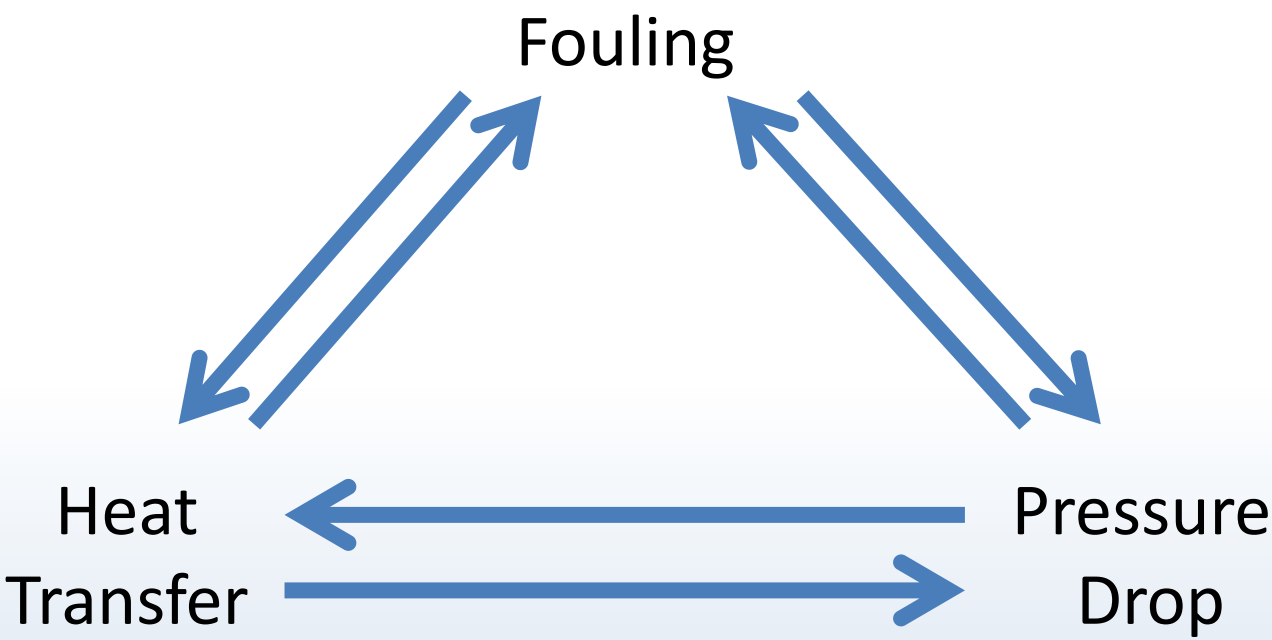


Finned Tube Boiler Recuperator

Inside a Dairy Plant

Challenges

1) Expensive to recover heat from air
2) Distance between exhaust and inlet ducts
3) Particulates
4) **High heat transfer resistance and lots of area**



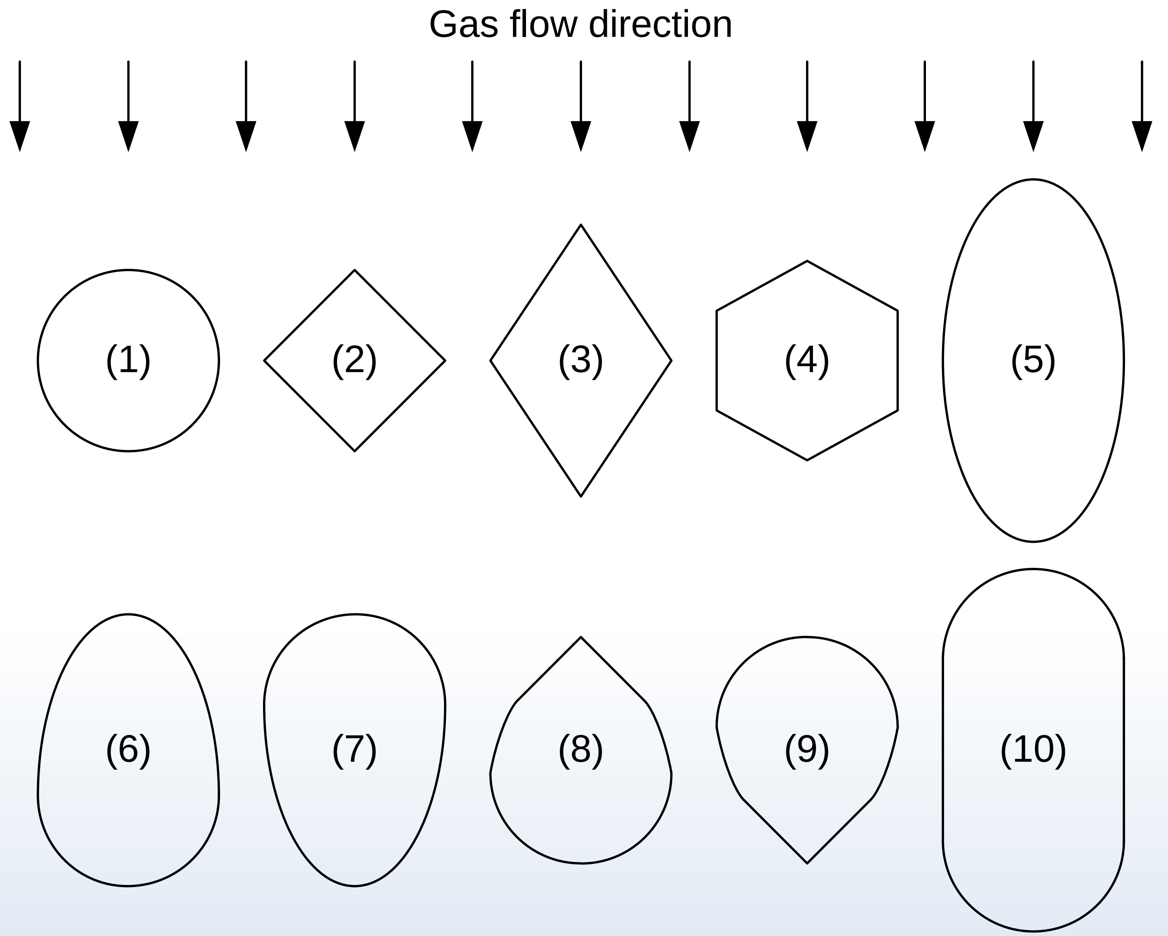
What is the General Solution?

- Liquid coupled loop of compact HX
- Inlet exchanger can use finned tube compact HX
- Exhaust exchanger needs to be low fouling – no extended surface fins
  - Bare tube
  - Plain plate HX (not considered in this paper)

THEREFORE, WHAT IS THE BEST TUBE SHAPE?

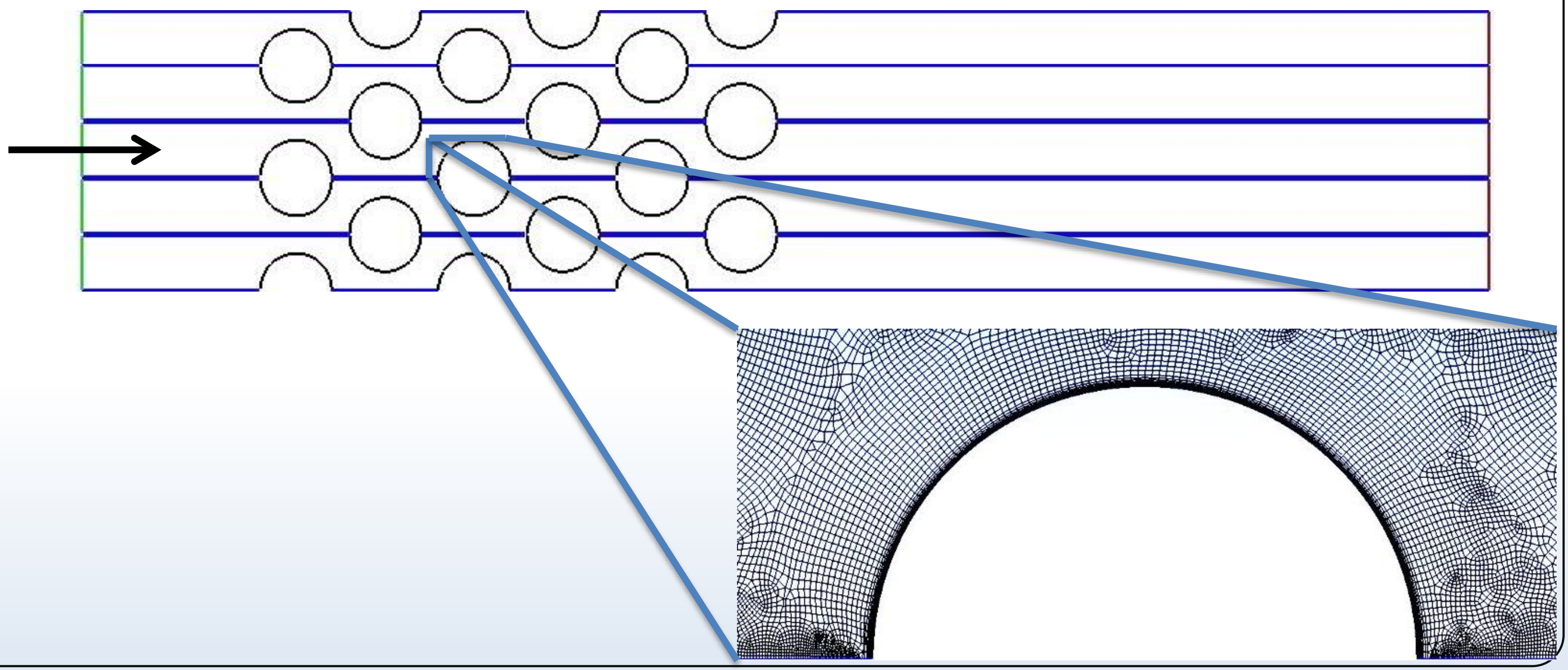
Methodology

- Selected 10 common shapes



Methodology

- Constructed CFD models in Fluent 13.0, 6 rows
  - Constant free-flow, σ
  - Constant HT area / volume, α, (changing length spacing)

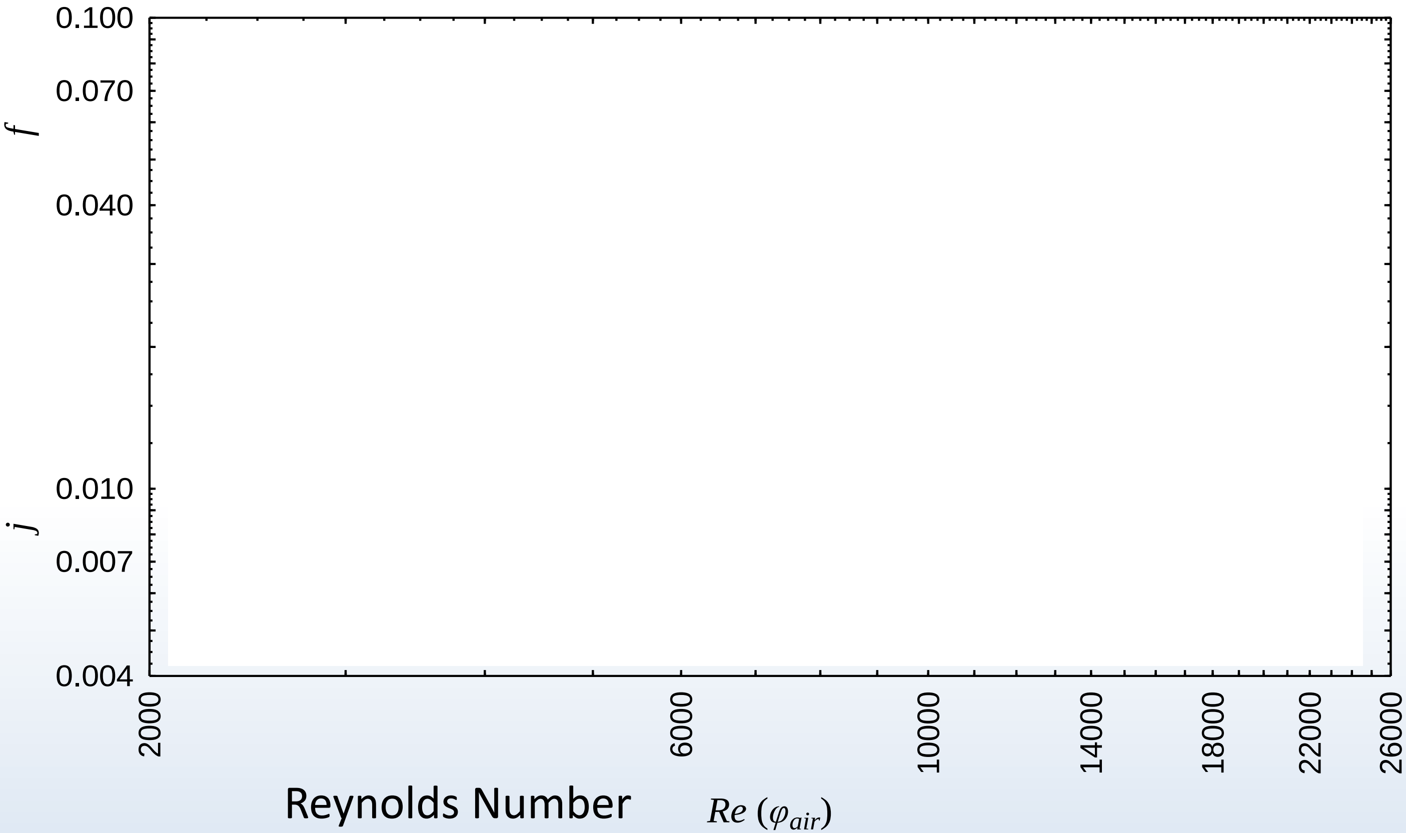


Methodology

- Compared models to experimental correlations (if available)
  - Round tube

Pressure Drop, ΔP

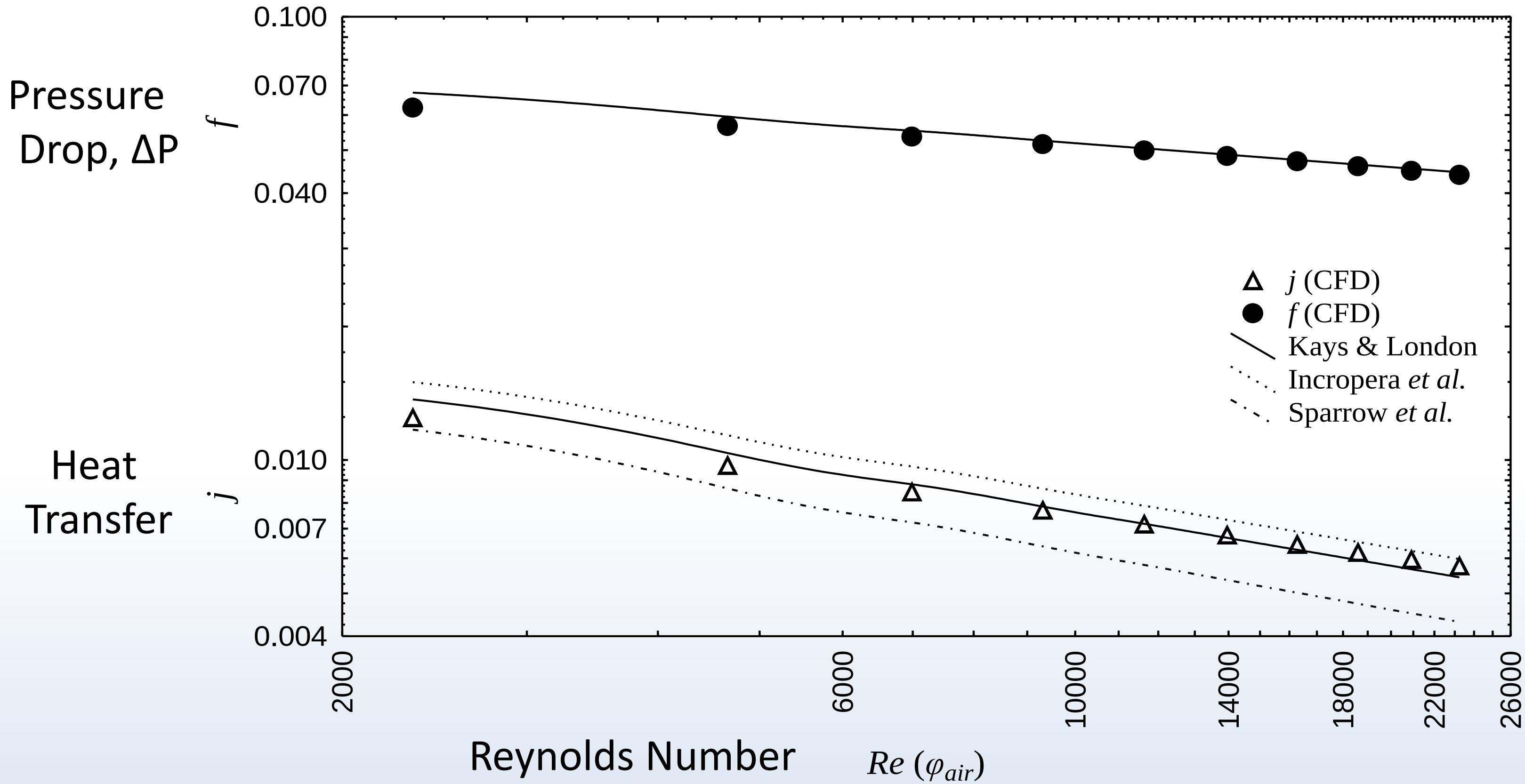
Heat Transfer



Reynolds Number

Methodology

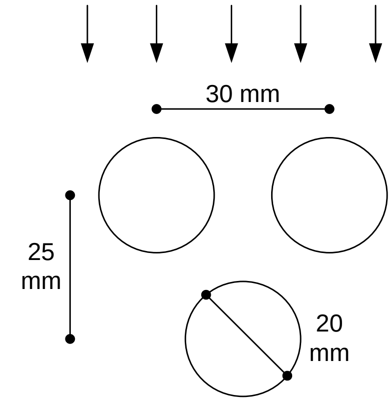
- Compared models to experimental correlations (if available)
  - Round tube

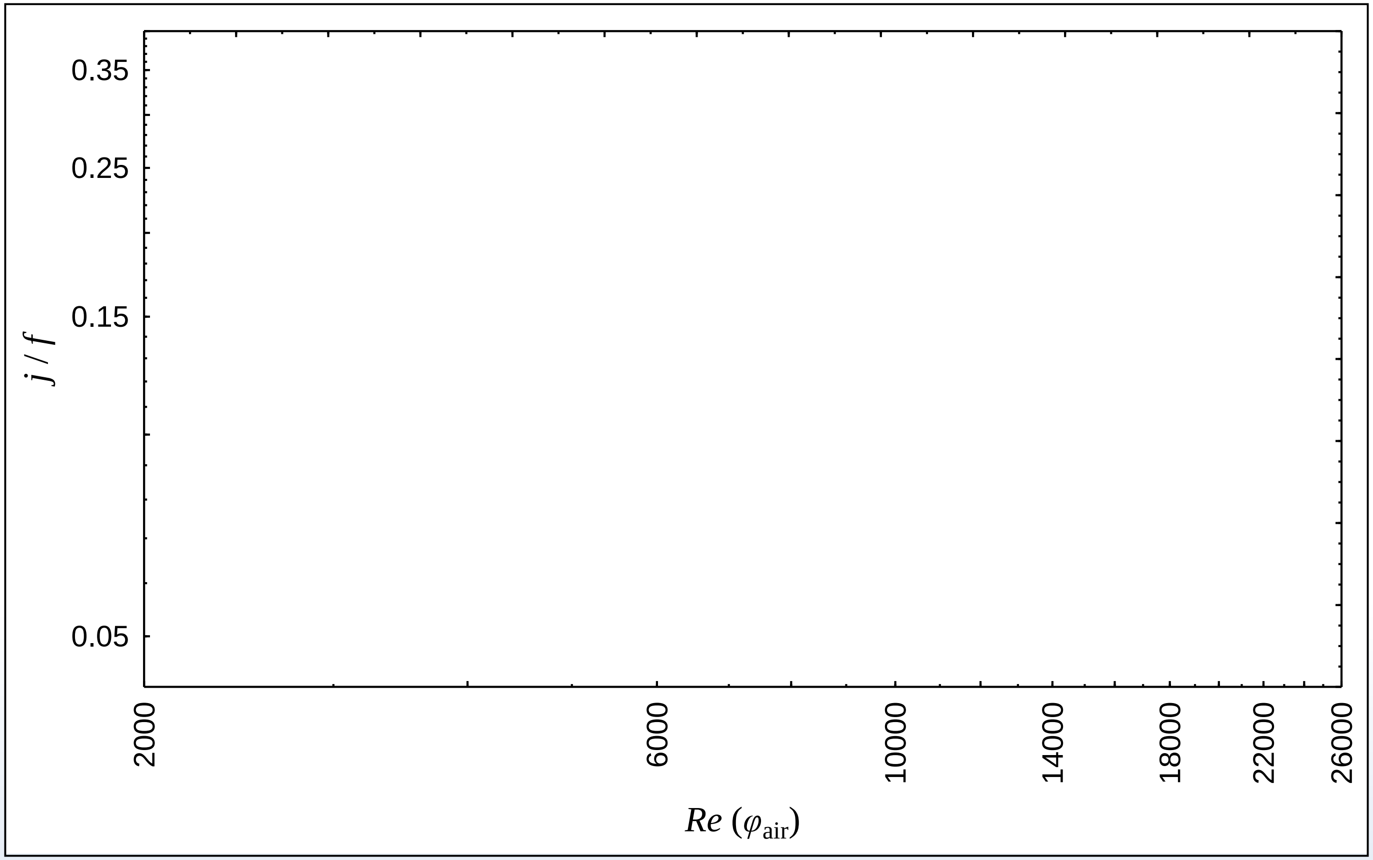


Basis for Comparison

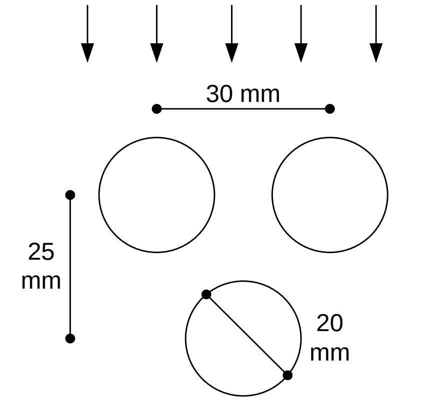
1. Heat transfer coefficient per unit fan power (Kays & London, 1998)
   - $h/E \propto \sigma^2 j/f$
   - Compare tubes with the same σ and α

Results


30 mm
25 mm
20 mm
Arrangement A - 1.50:1.25


0.35
0.25
0.15
0.05
j / f
2000
6000
10000
14000
18000
22000
26000
Re (φair)

Results



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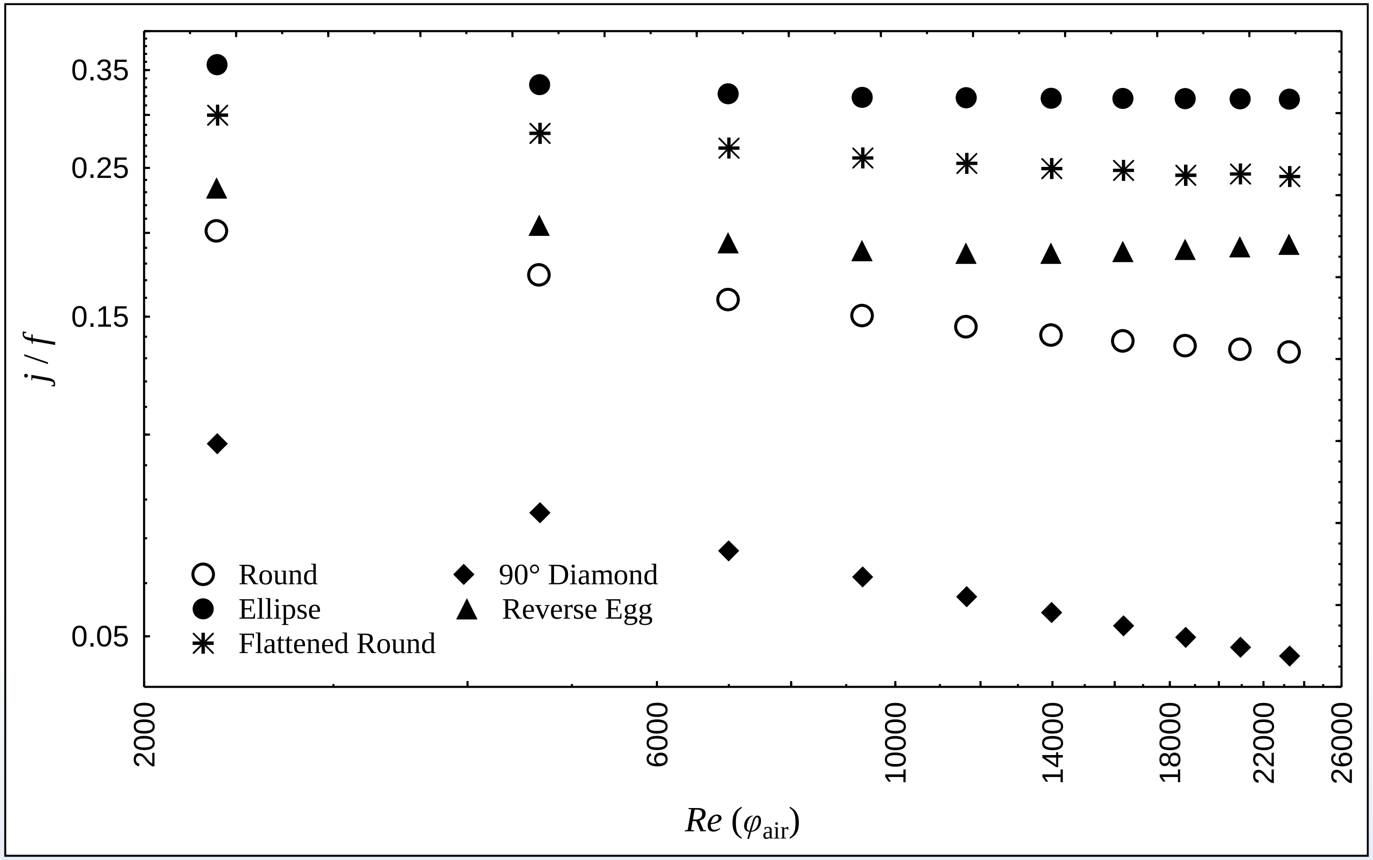
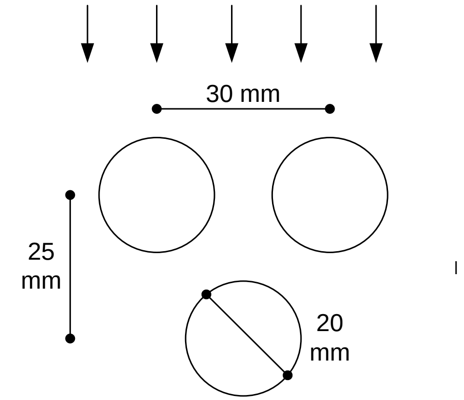


Results

Efficiency Ranking

1. Elliptical
2. Flattened round
3. Reverse egg



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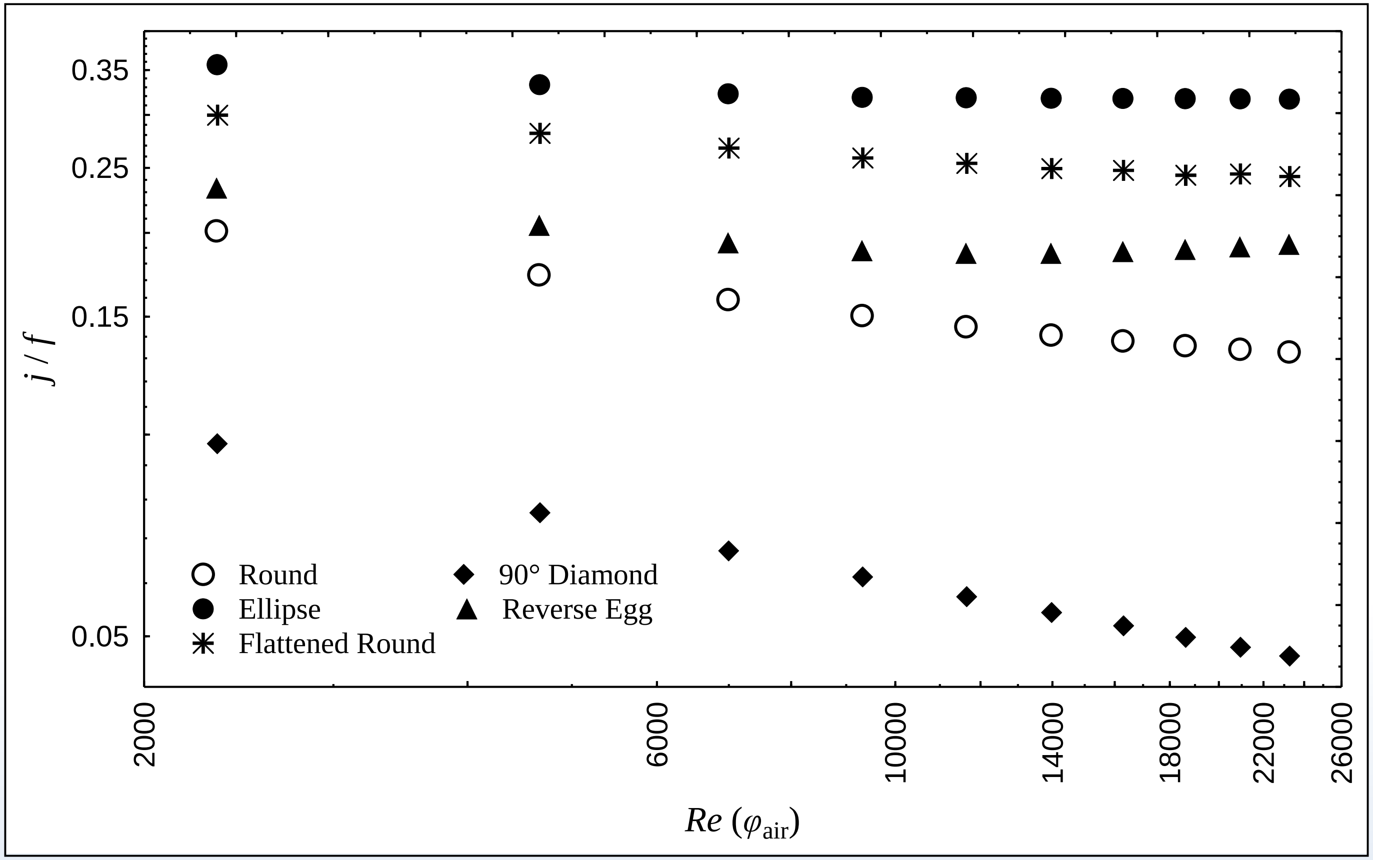

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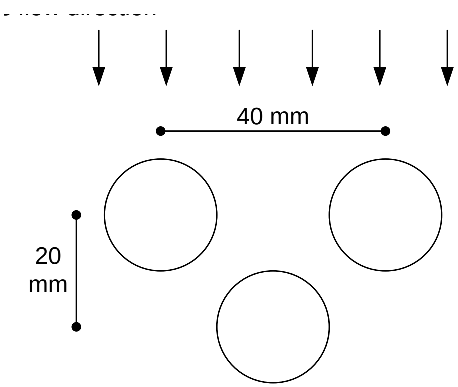
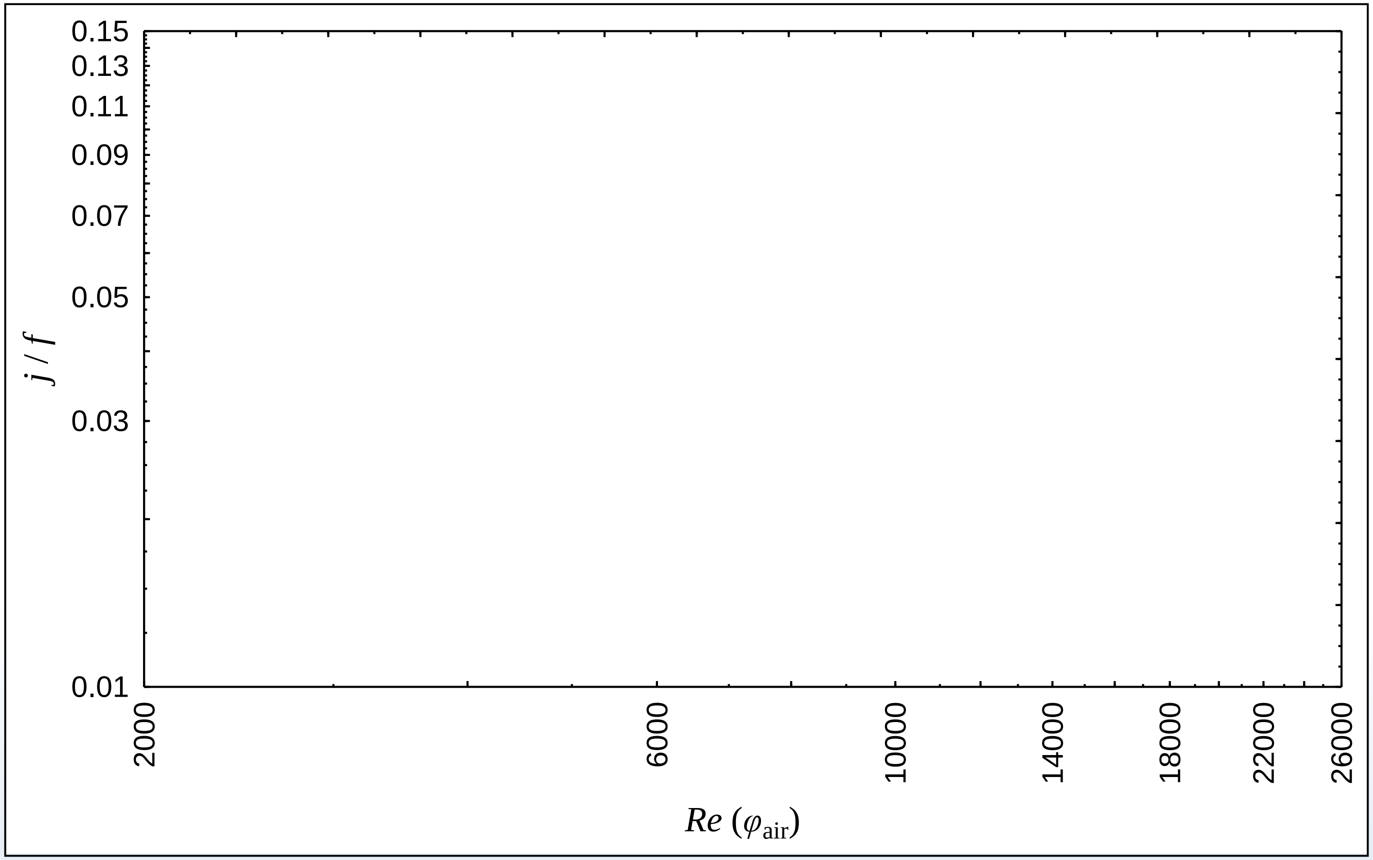
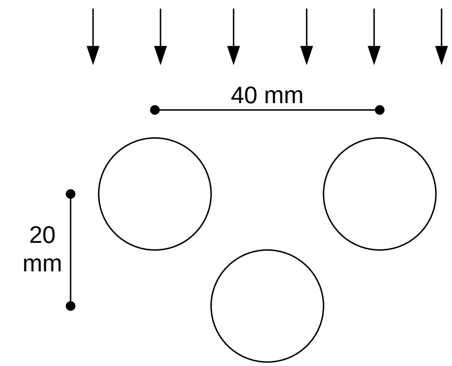


Arrangement B - 2.00:1.00



Results



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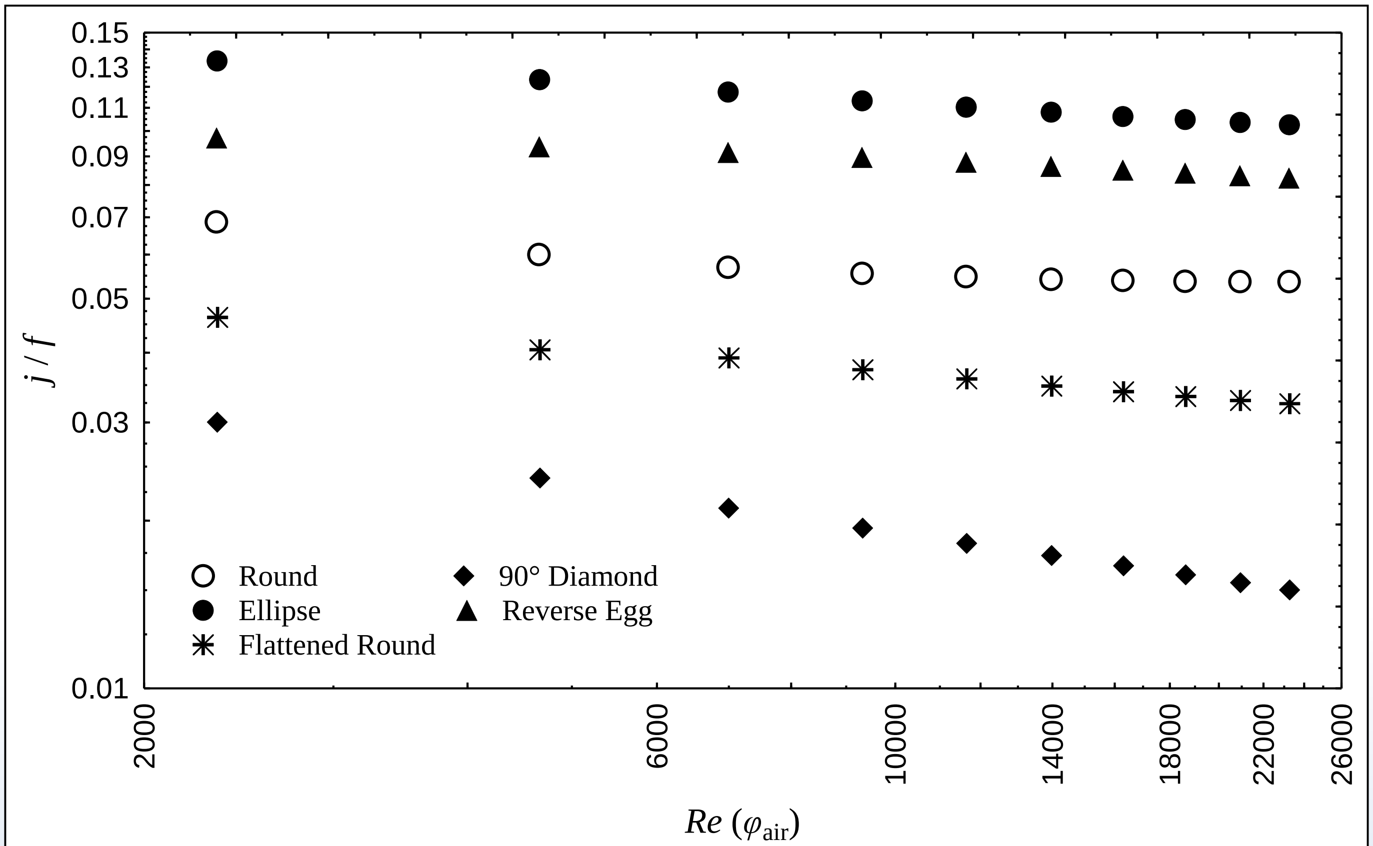

Results

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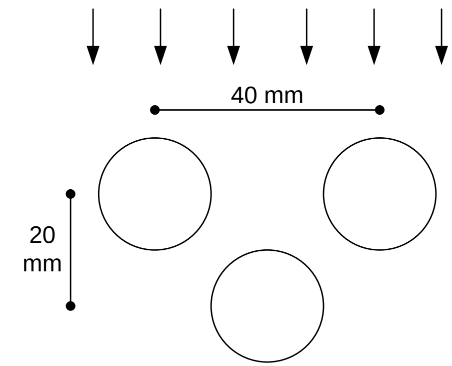
2. Reverse egg
3. Round



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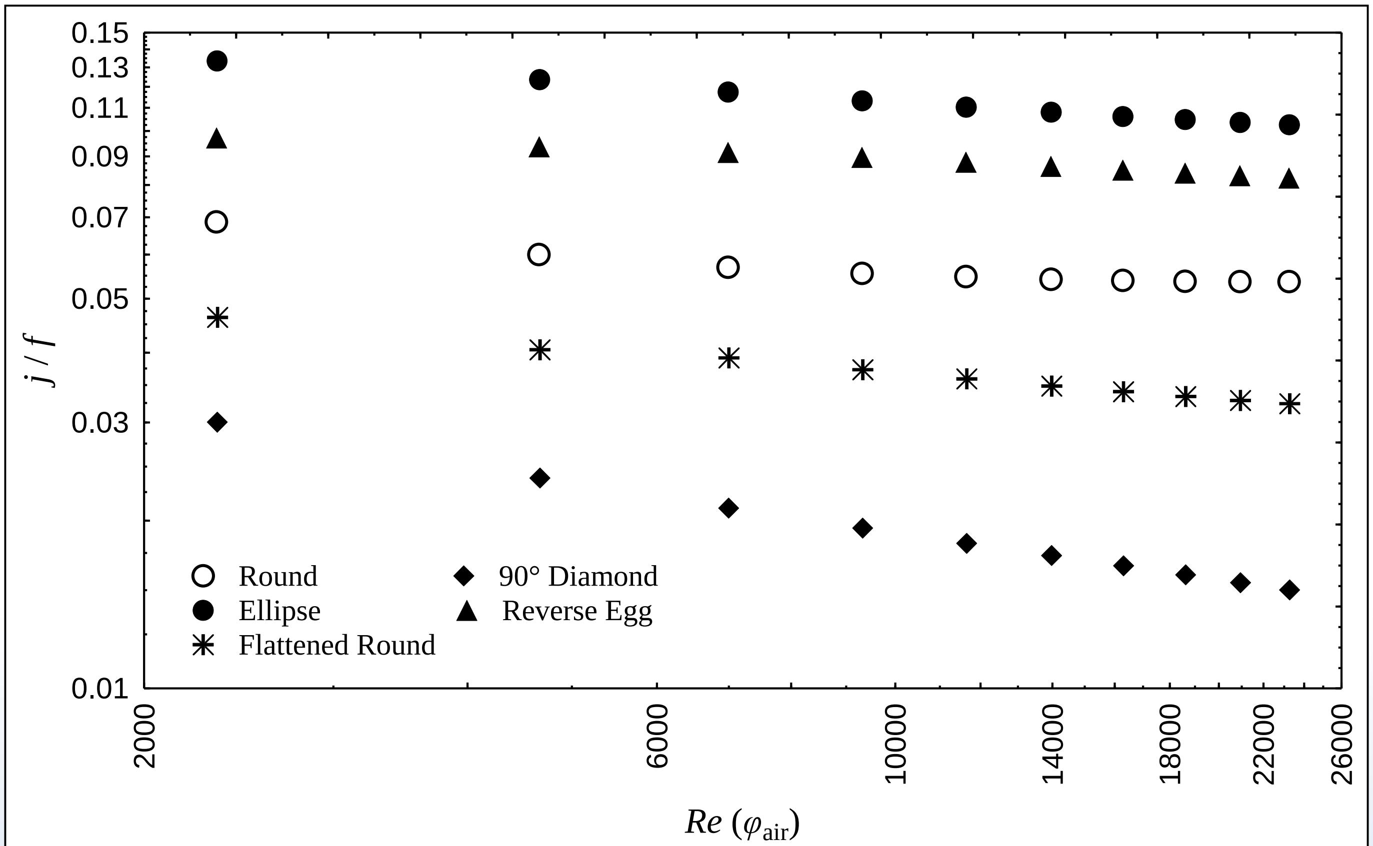

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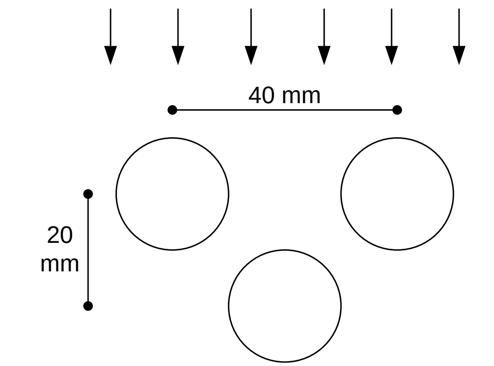

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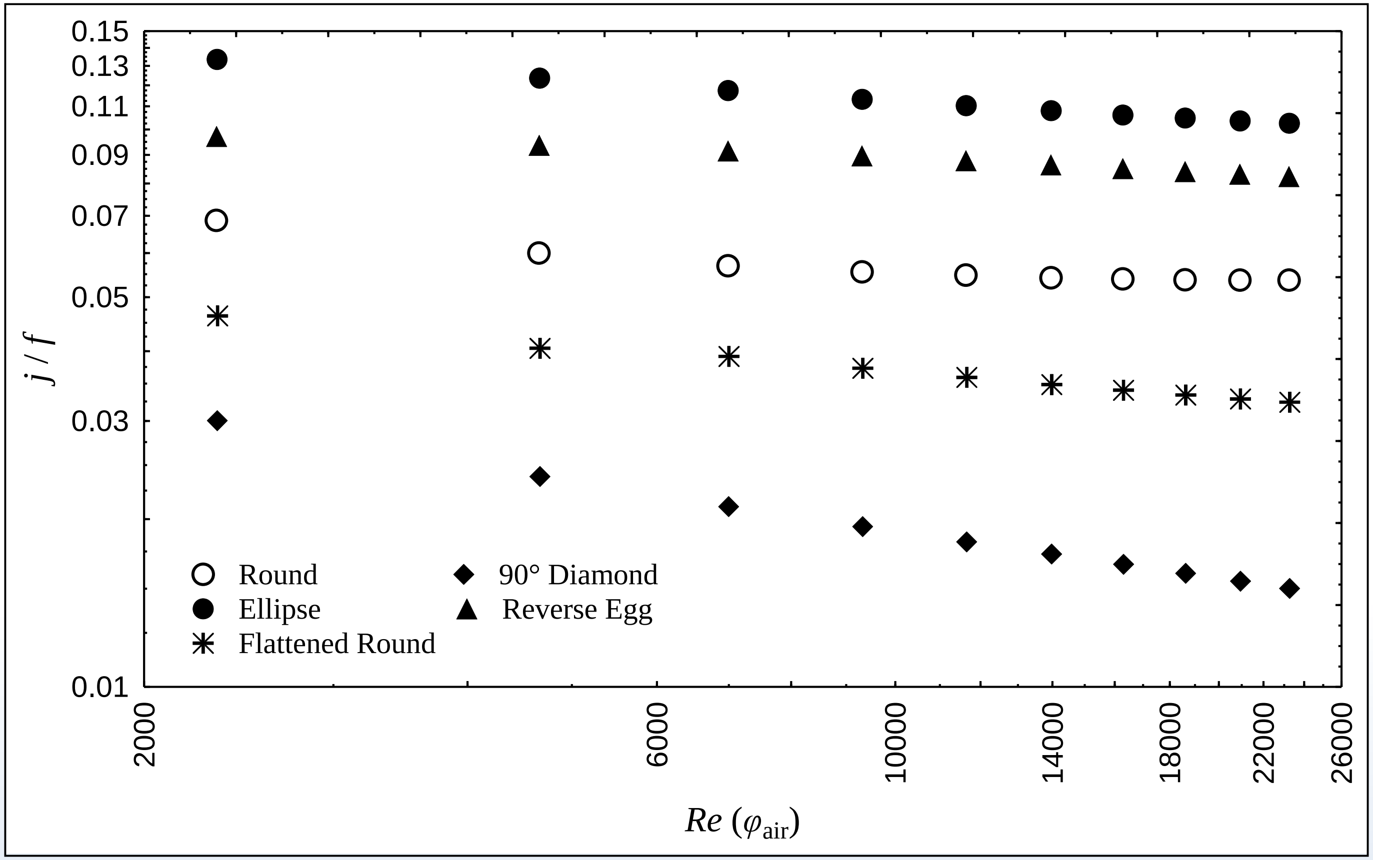
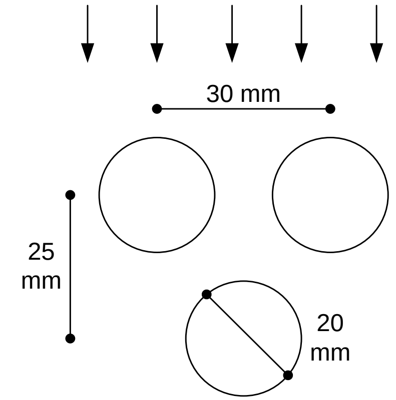


Flattened Round

Efficiency Ranking

1. Elliptical
2. Flattened round
3. Reverse egg

Results



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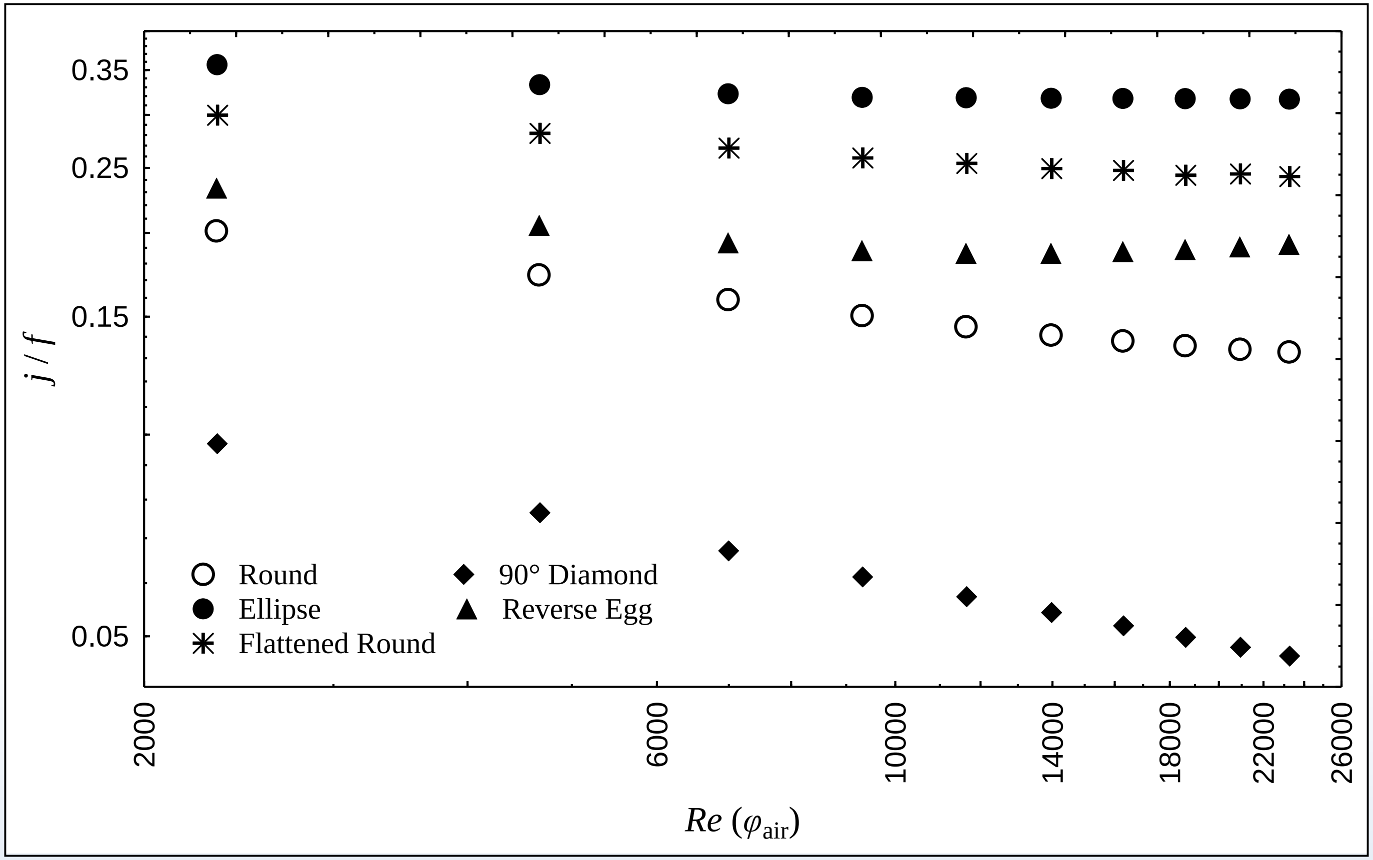
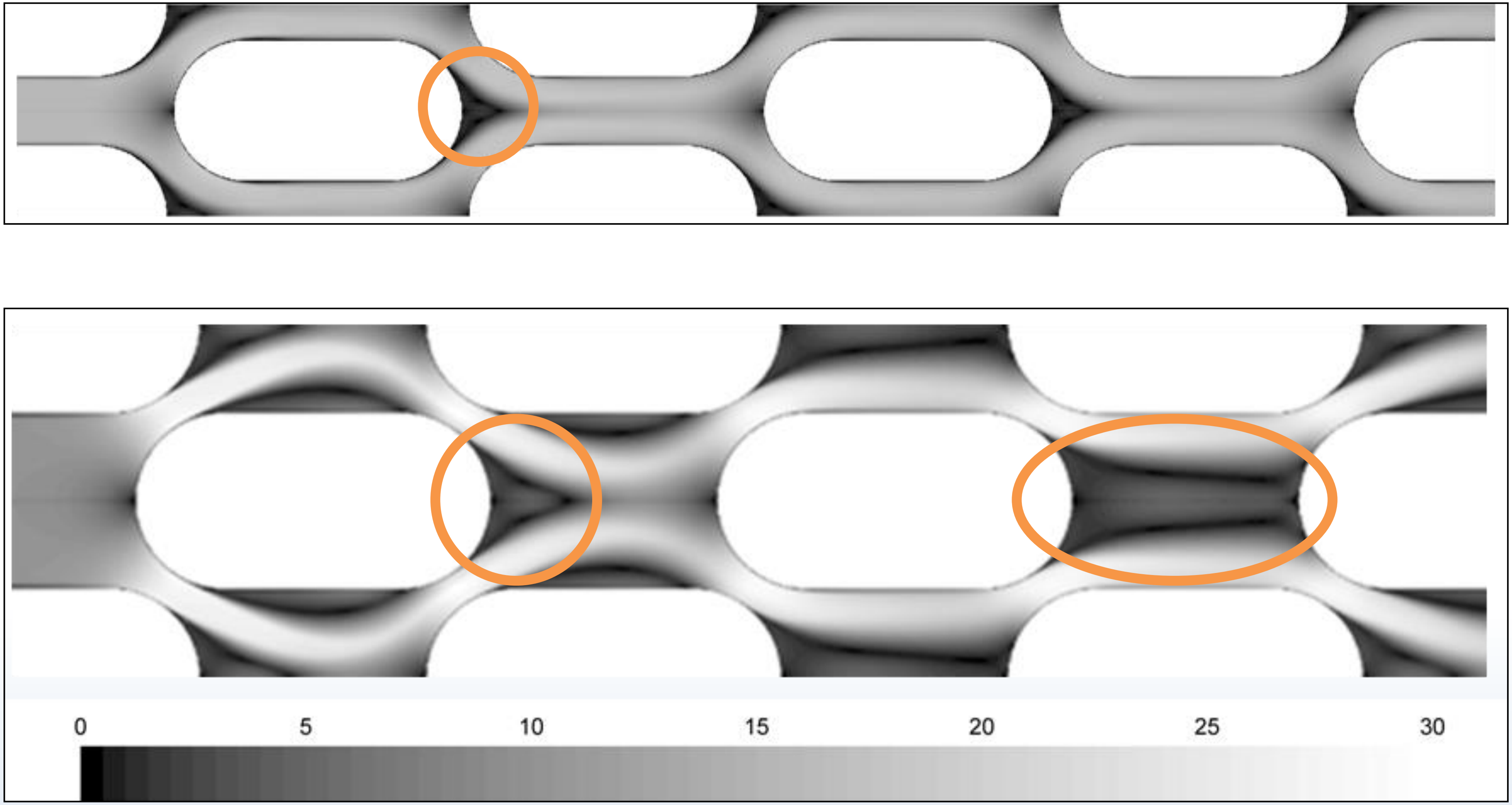


Flattened Round

Optimal Spacing is Important

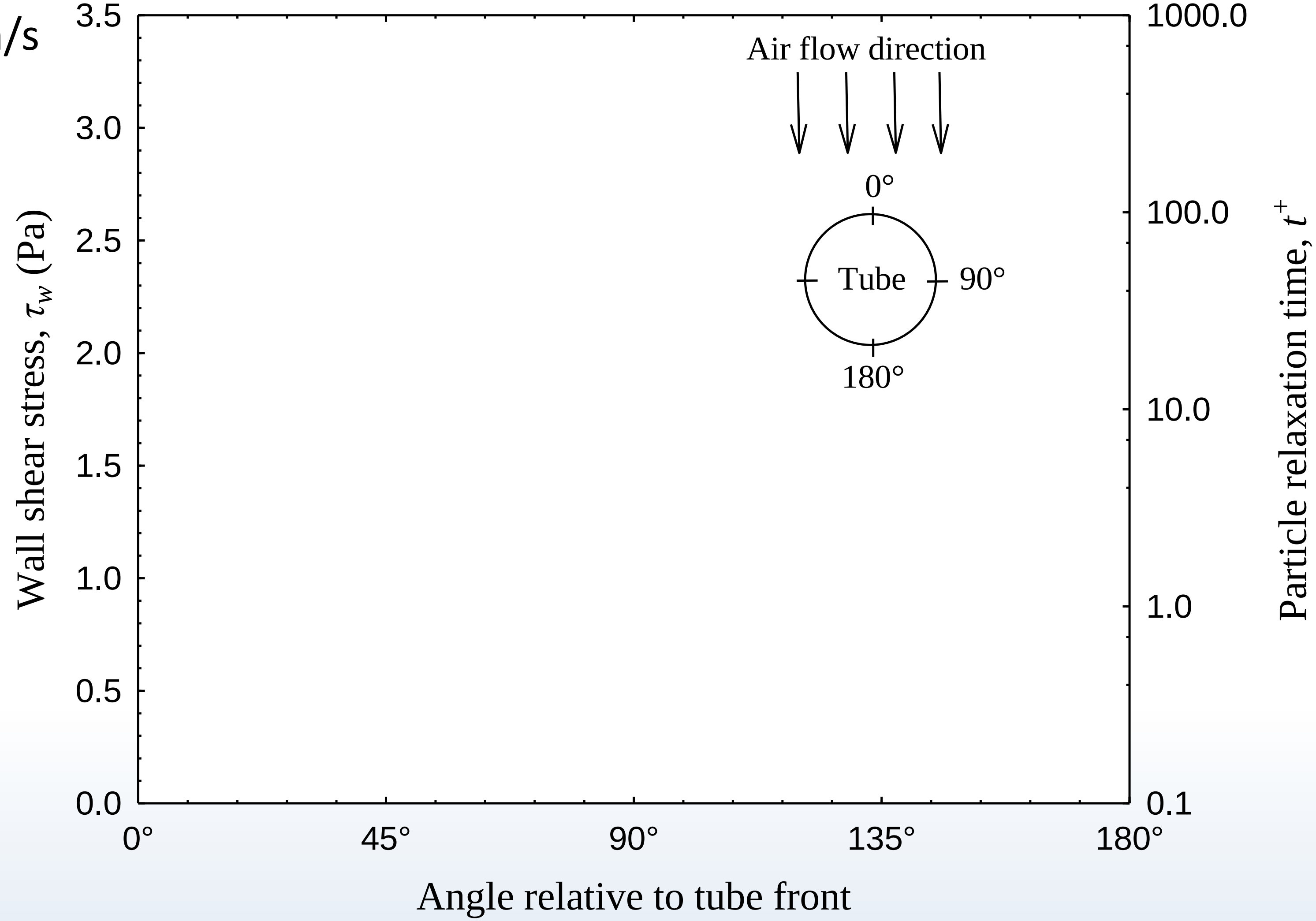


Basis for Comparison

2. Low fouling
   - High wall shear stress (related to tube geometry, arrangement and gas flow velocity)
   - $R_f \propto {}^{1}/_{\tau_w}$
   - Adhesion/stickiness properties are important
   - These are assumed constant between shapes

Wall Shear Stress and Deposition

U = 4m/s



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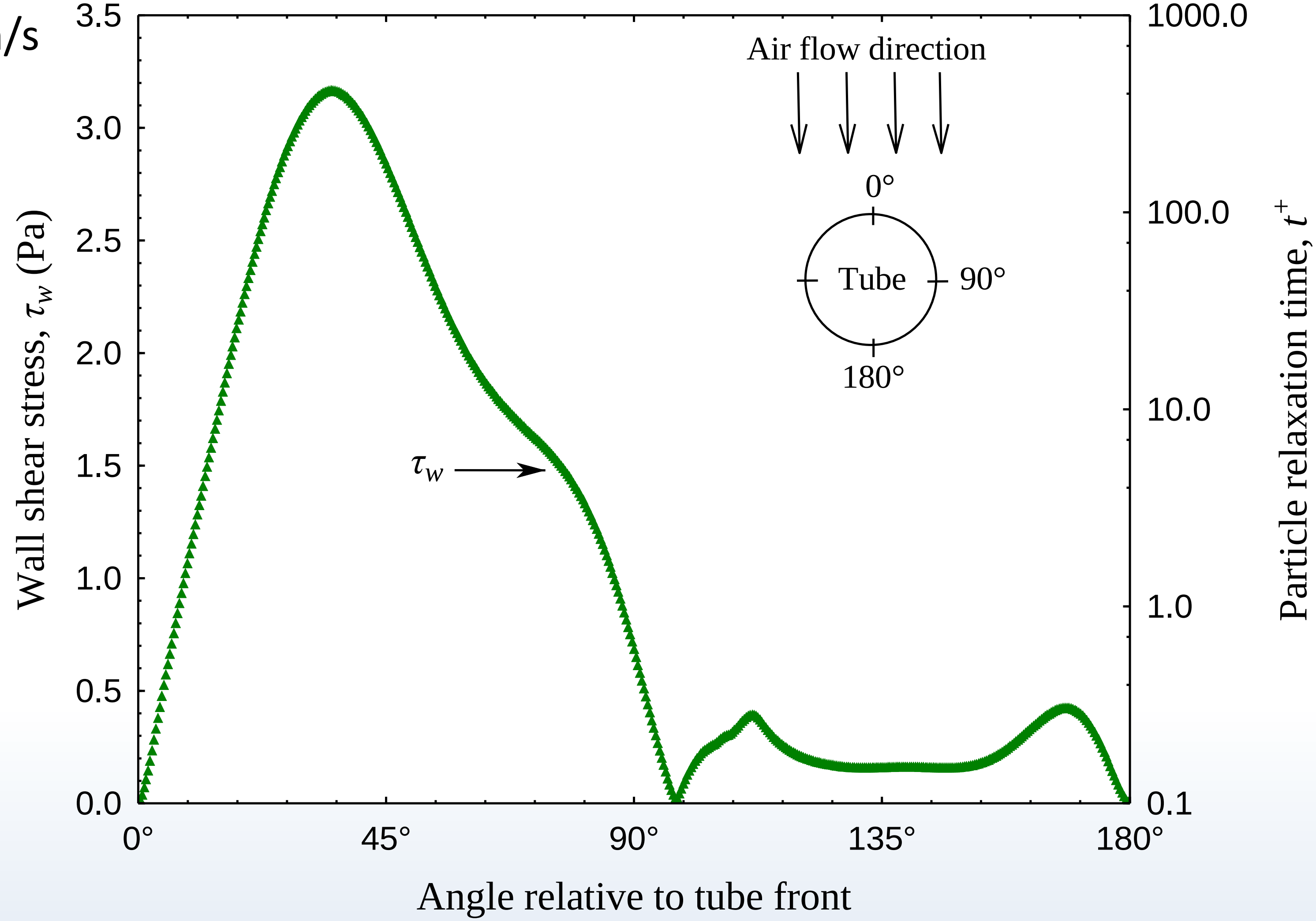

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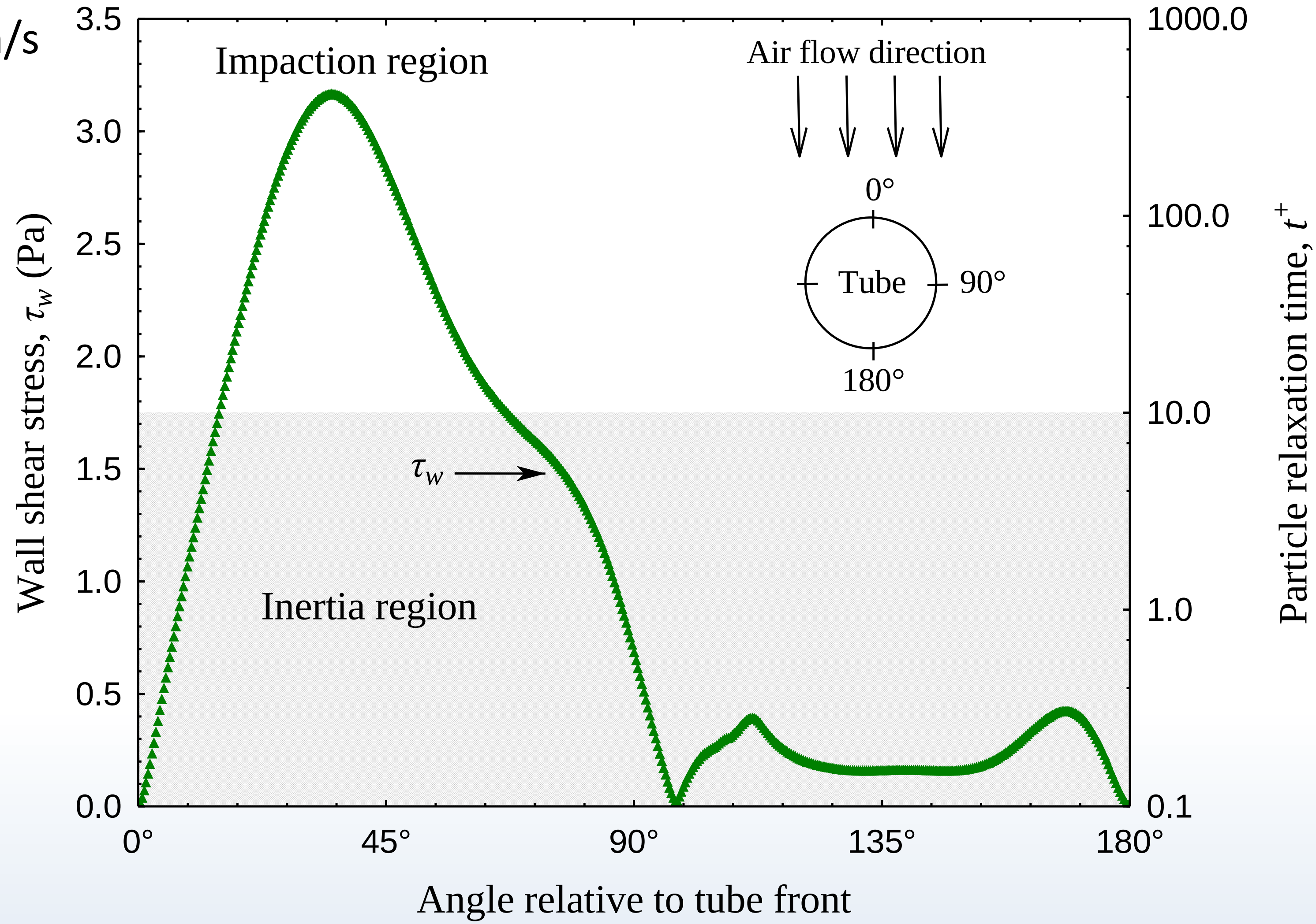

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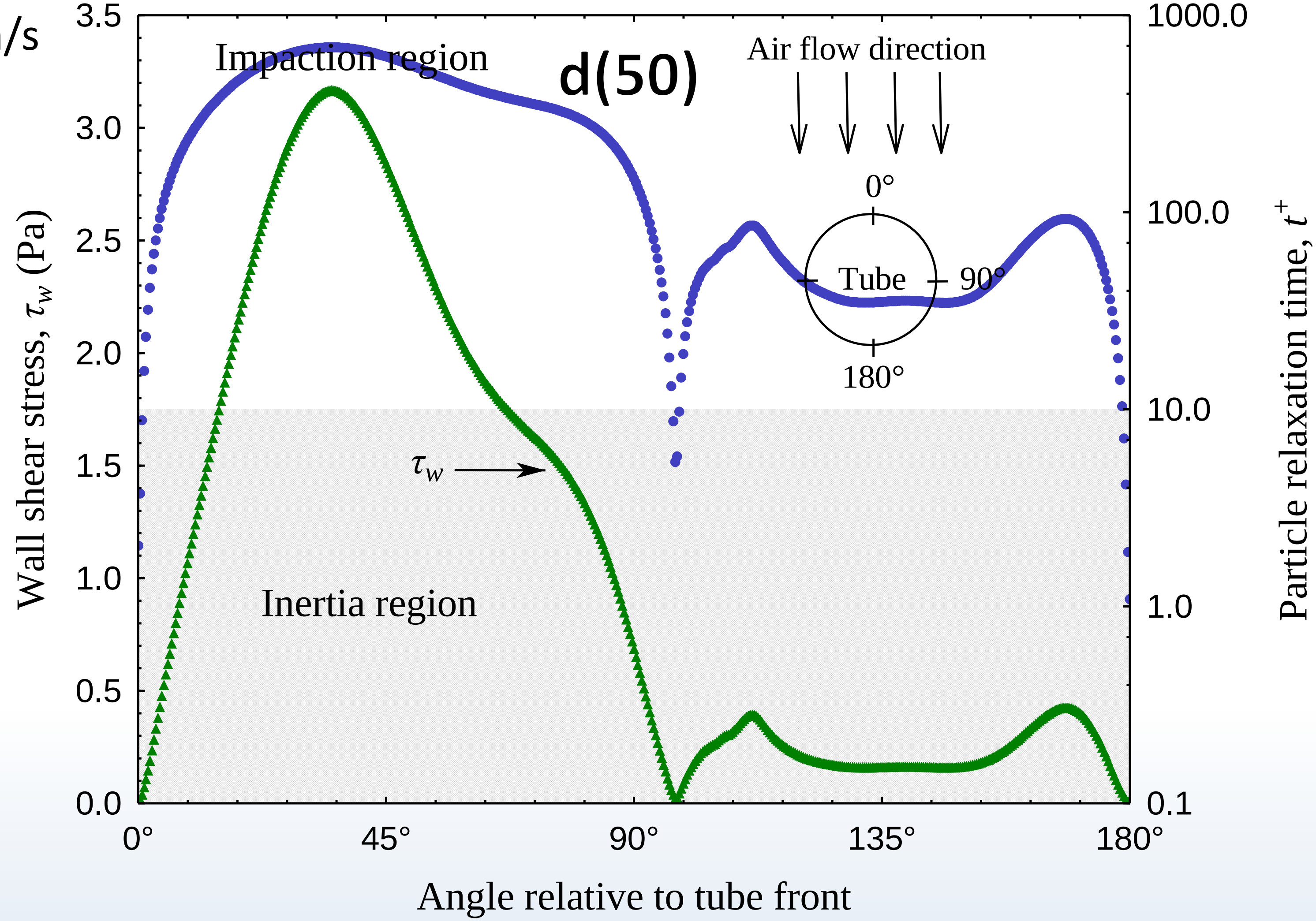


Formulation of $j_{foul}(^1/\tau_w)$

$$\frac{1}{h_{foul}} = \frac{1}{h_{clean}} + R_f \qquad \text{where} \qquad h_{clean} = \left(\frac{c_p \rho}{Pr^{2/3}} \frac{u_\infty}{\sigma}\right) j$$

$$\frac{1}{h_f} = \frac{1}{\left(\frac{c_p \rho}{Pr^{2/3}} \frac{u_\infty}{\sigma}\right) j} + \frac{A}{\tau_w}$$

Dependent on stickiness, Particle size, etc.

$$\frac{1}{j_f} = \frac{1}{j} + \left(\frac{c_p \rho}{Pr^{2/3}} \frac{u_\infty}{\sigma}\right) \frac{A}{\tau_w}$$

Since it varies around the tube, an average was taken

- Front facing
- Rear facing

What is the Best Shape?

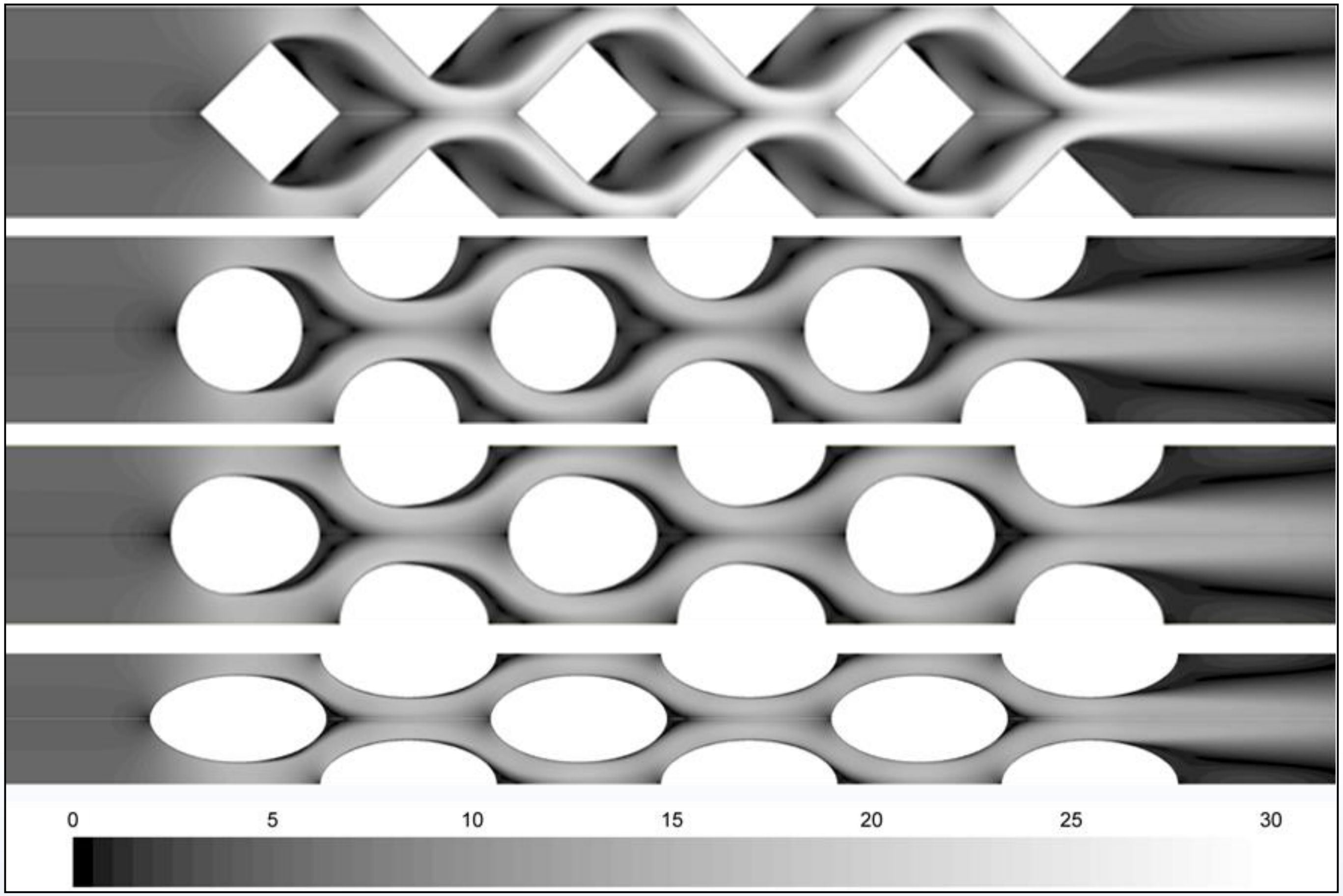
j_f/f^*

0.4

1.0

1.3

2.2



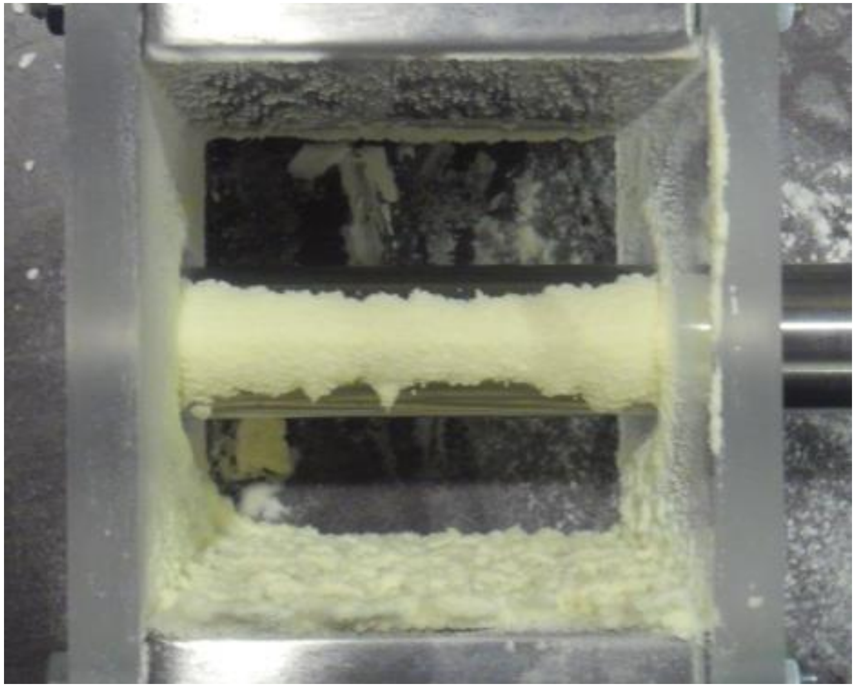
Round vs Elliptical

- On average, for the same Reynolds number
  - Round tube has 37% higher j_f
  - Ellipse has 65% reduction in f
  - So the better performing elliptical tube results from a very low pressure drop -> but larger volume HX
  - Ellipse is expected to have less fouling/deposition due to a smaller stagnation zone

- Limitation: the effect of fouling on the pressure drop has not been included -> experimental work

Preliminary Experimental Results

Round Tube



Elliptical Tube

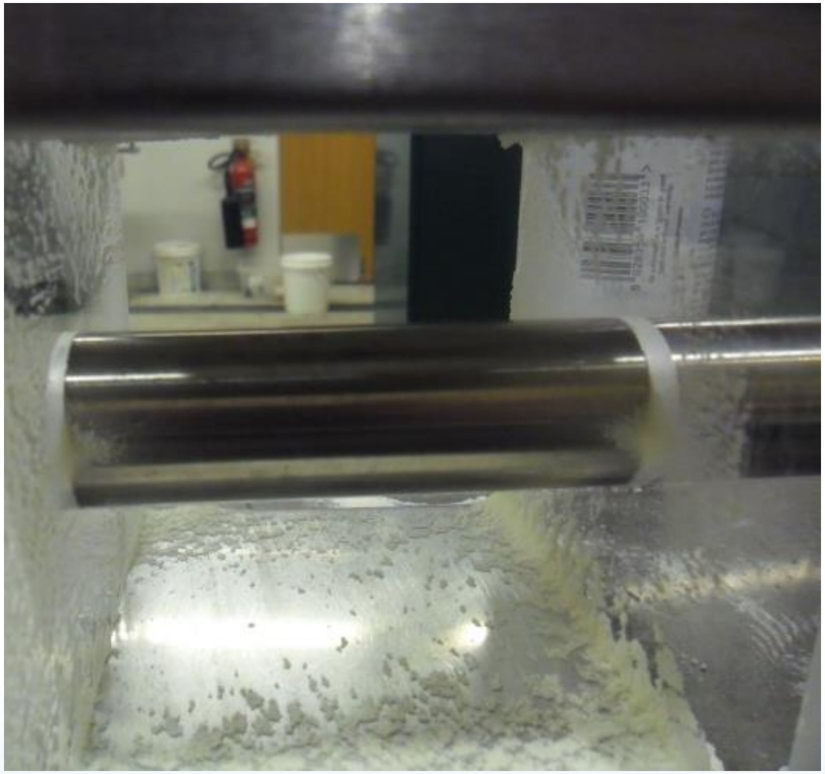
Same air velocity, temperature and relative humidity

- Air temp / RH determine particulate surface stickiness
- Similar particle loading and time (equilibrium)

Round: Front vs Back

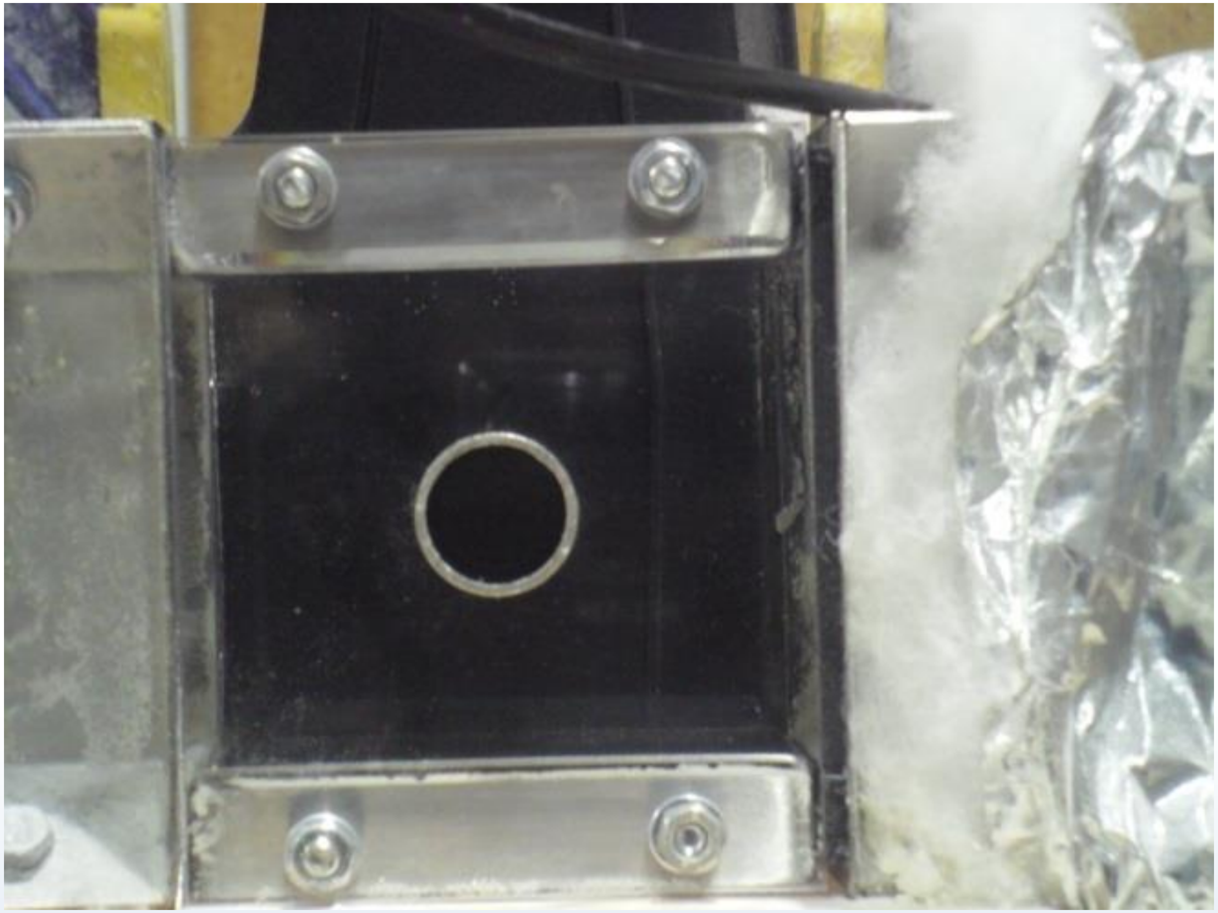
Front

Back



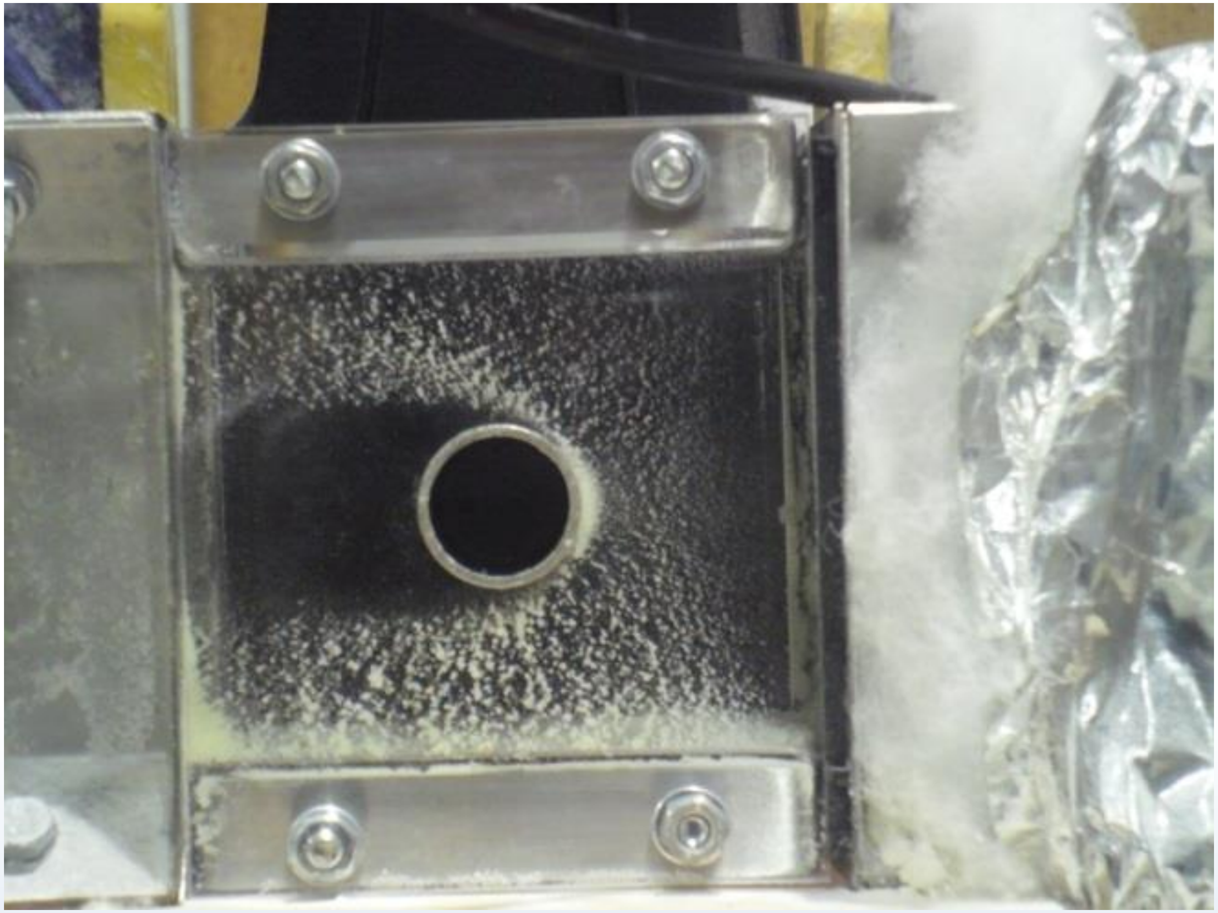
Start

Testing in Fastforward



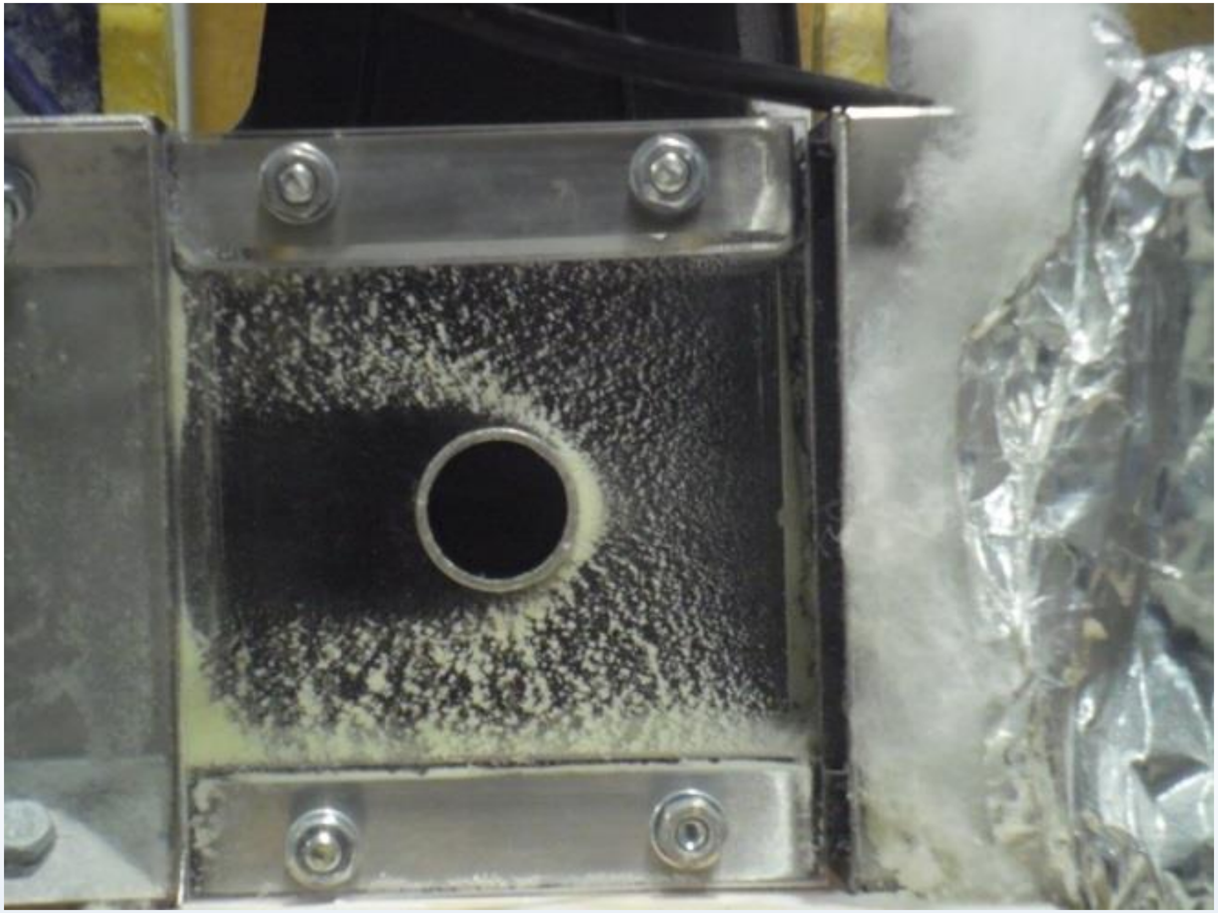
5 mins

Testing in Fastforward



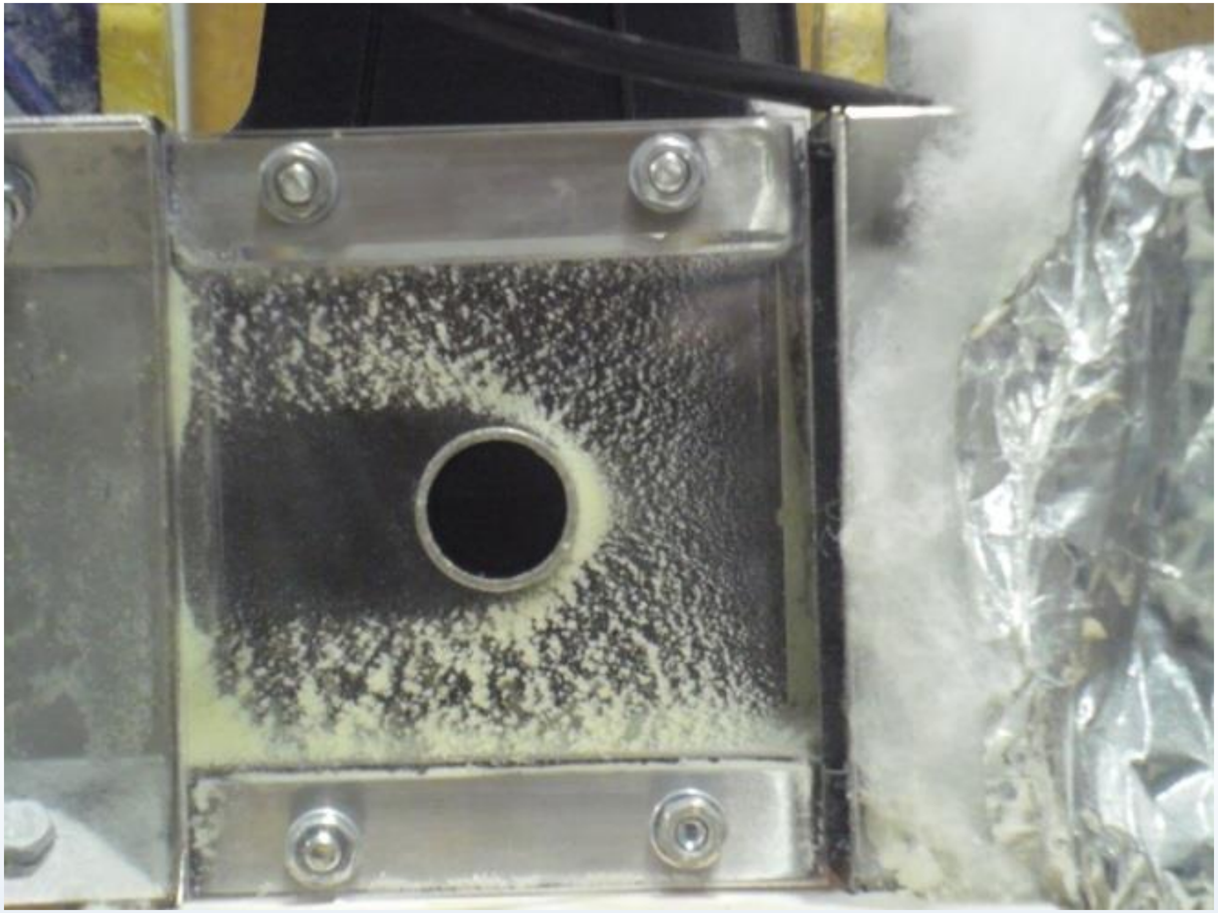
Testing in Fastforward

10 mins



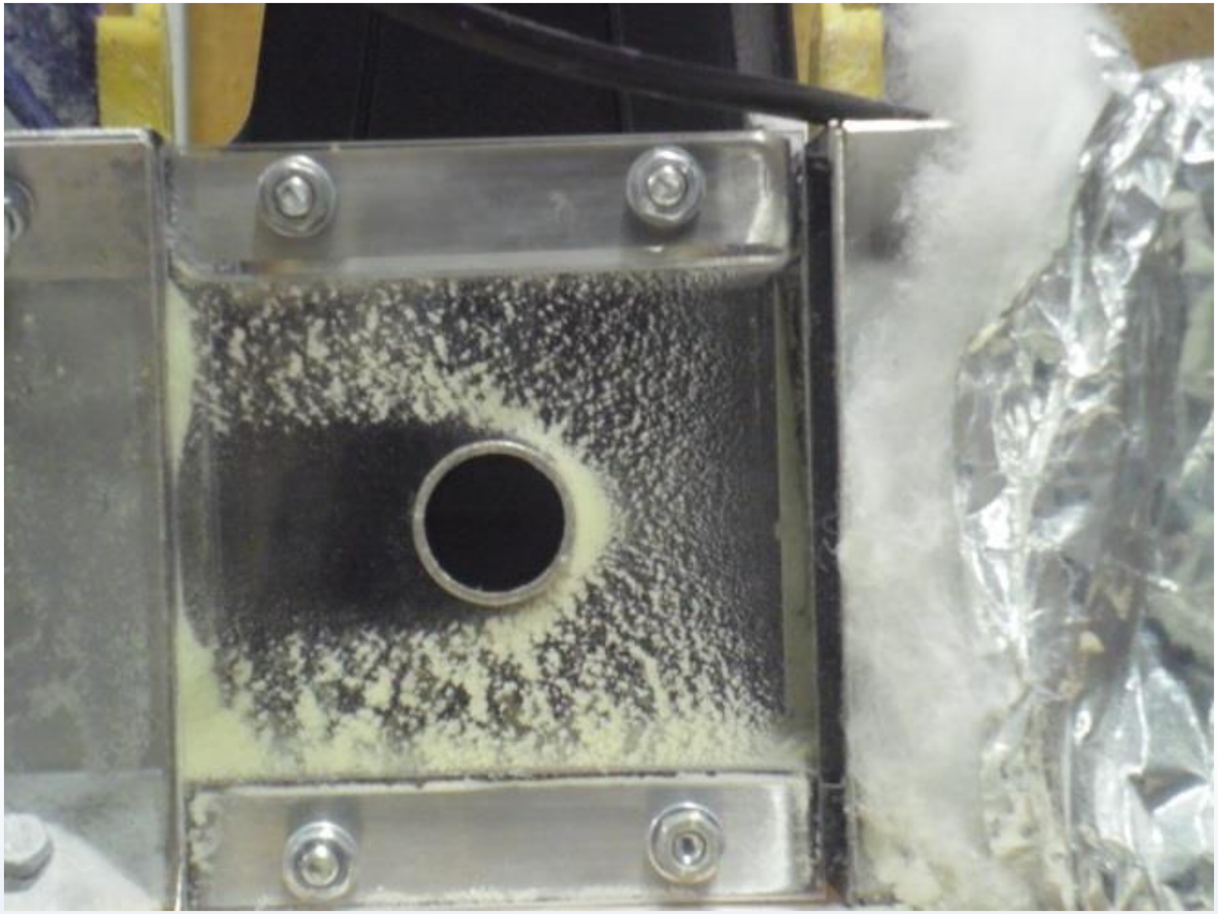
15 mins

Testing in Fastforward



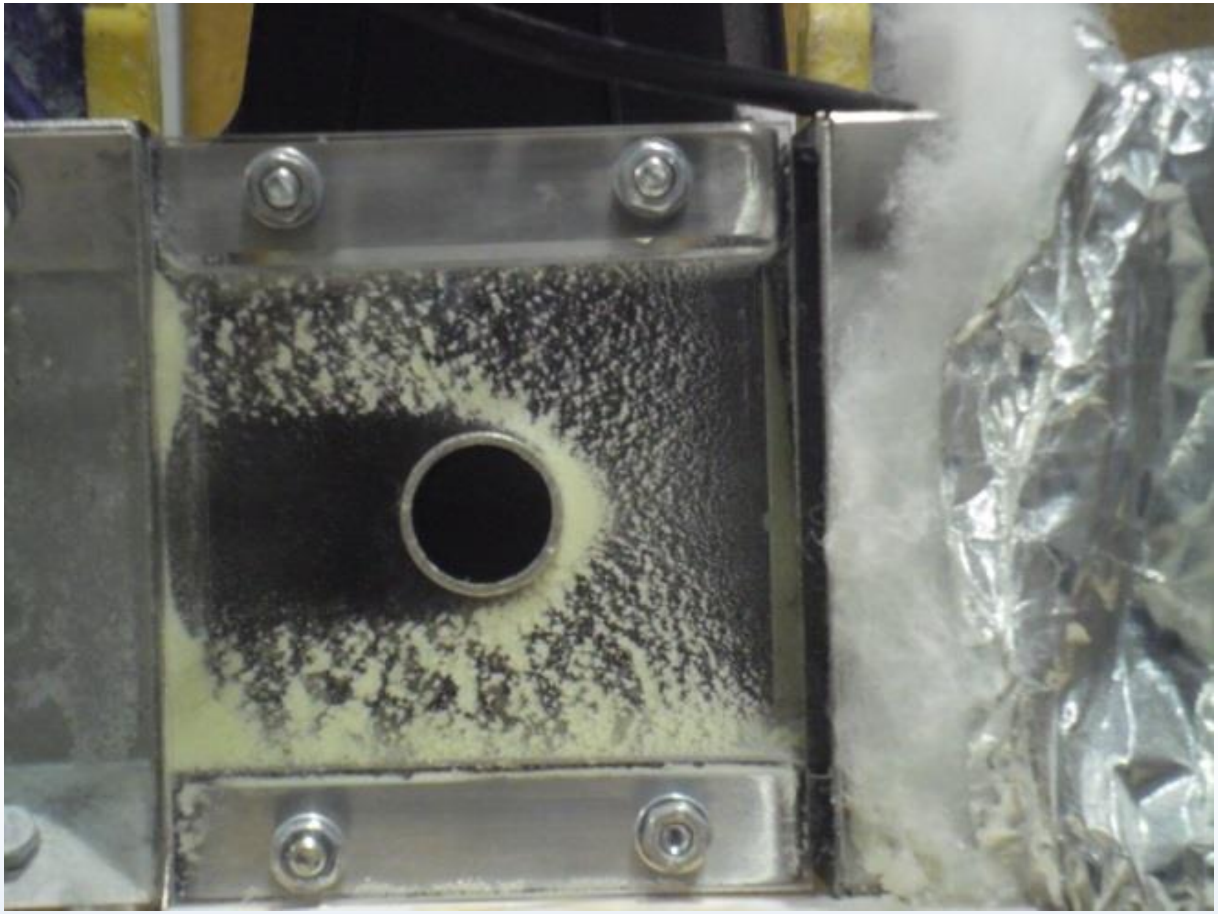
Testing in Fastforward

20 mins



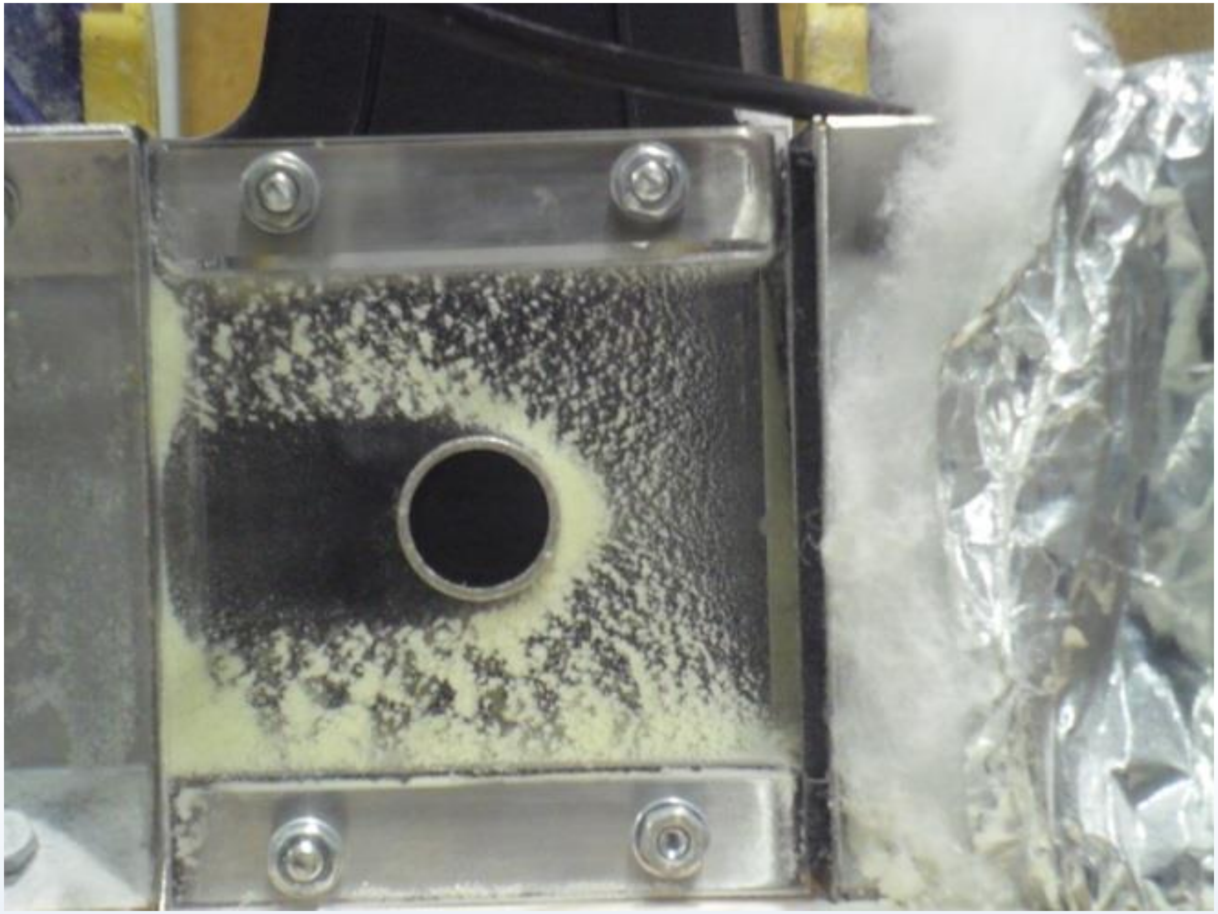
Testing in Fastforward

25 mins



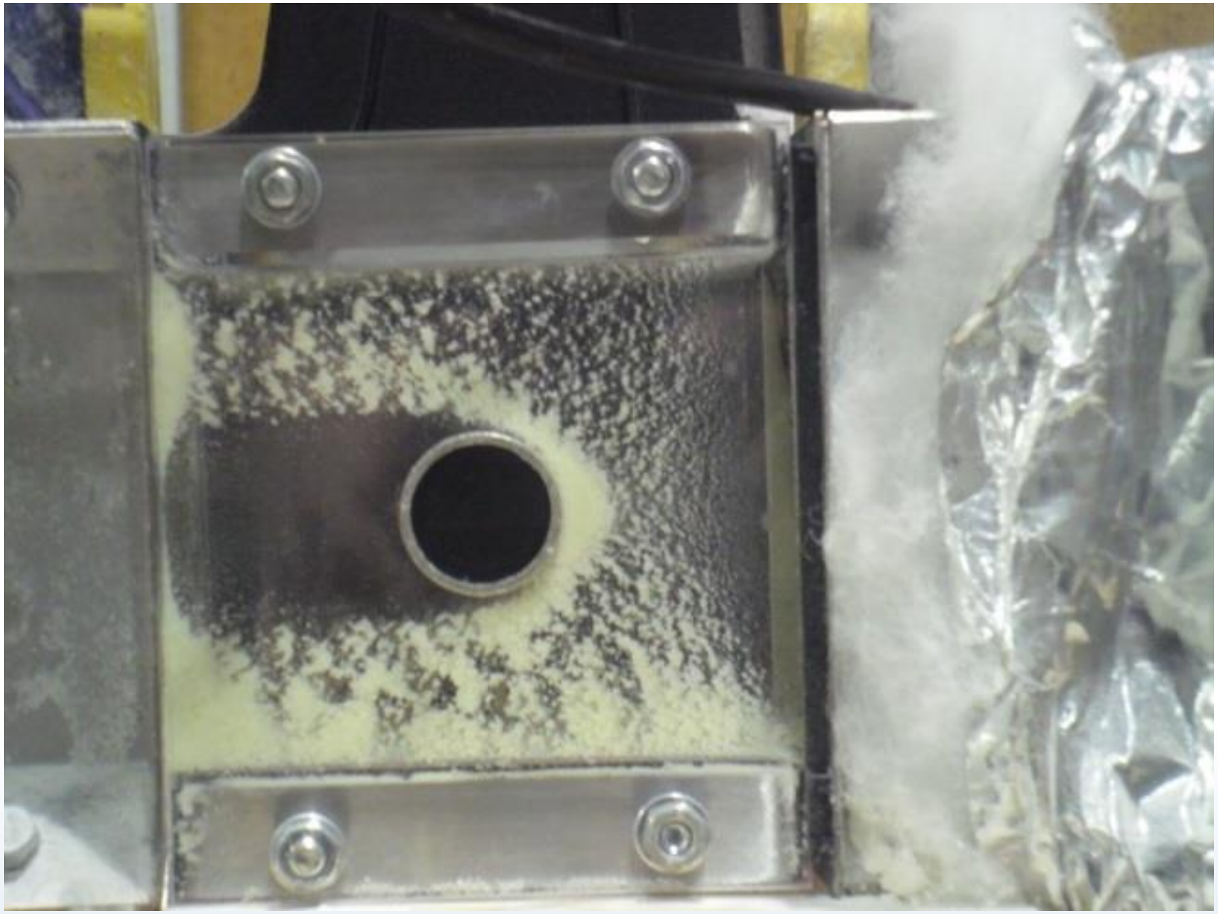
Testing in Fastforward

30 mins



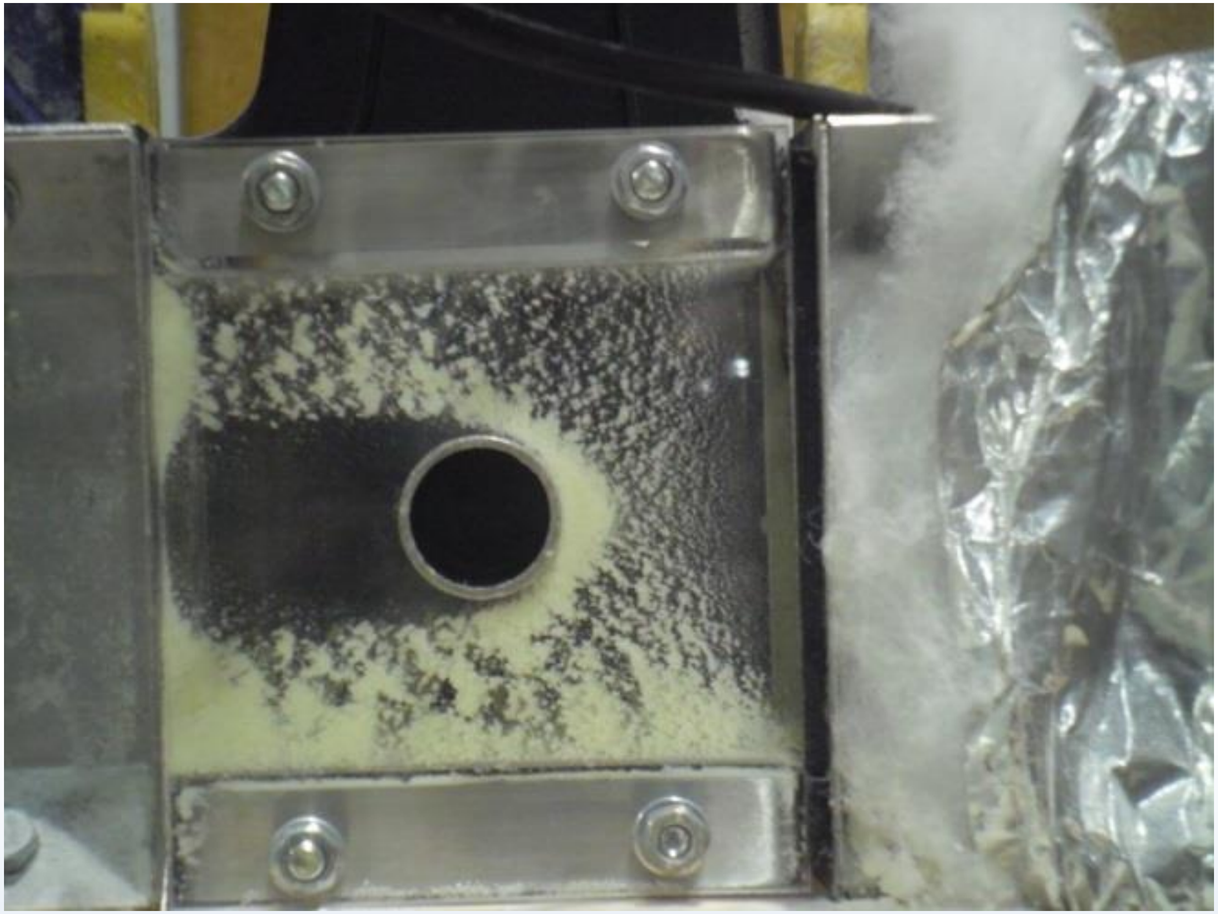
Testing in Fastforward

35 mins

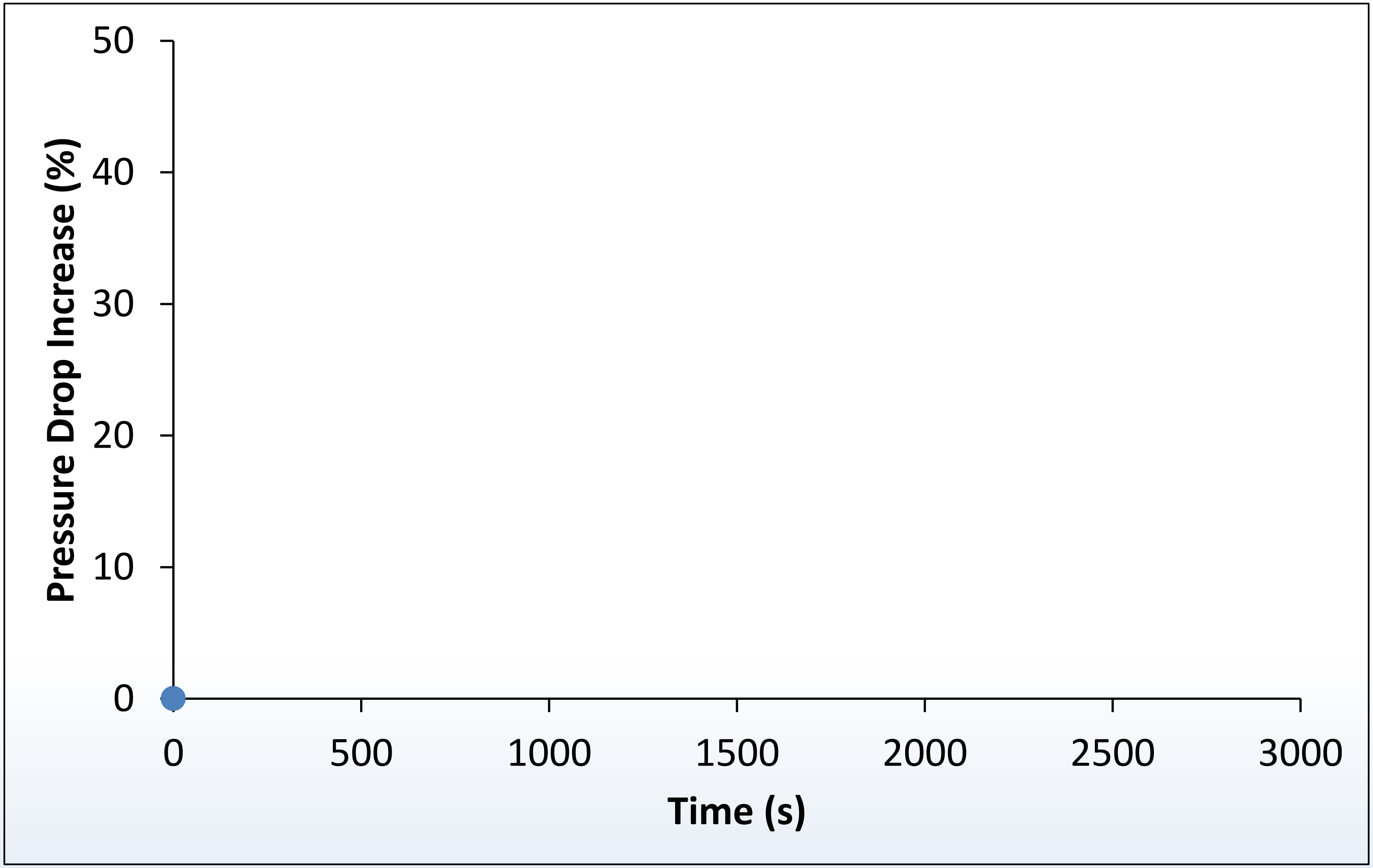


Testing in Fastforward

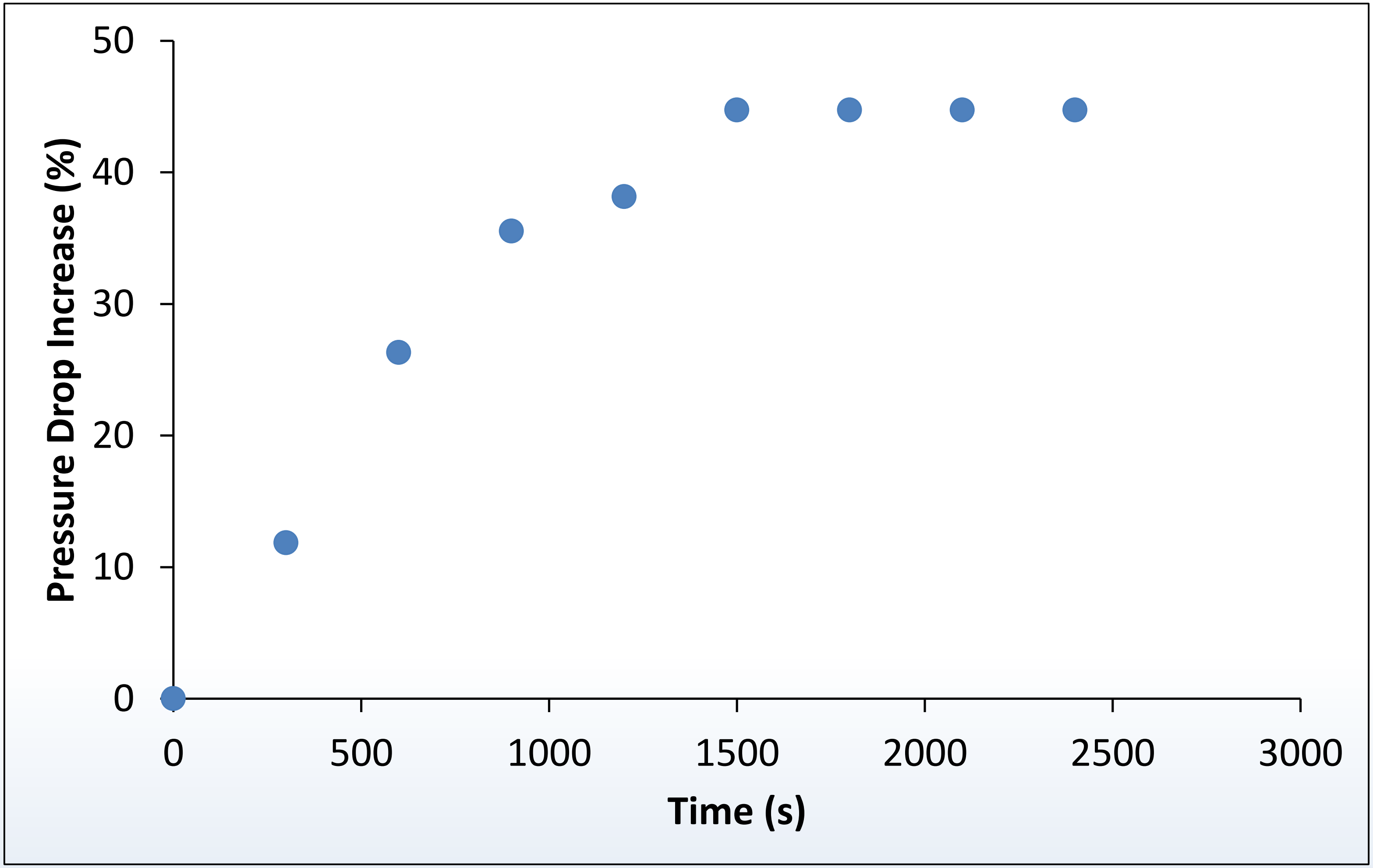
40 mins



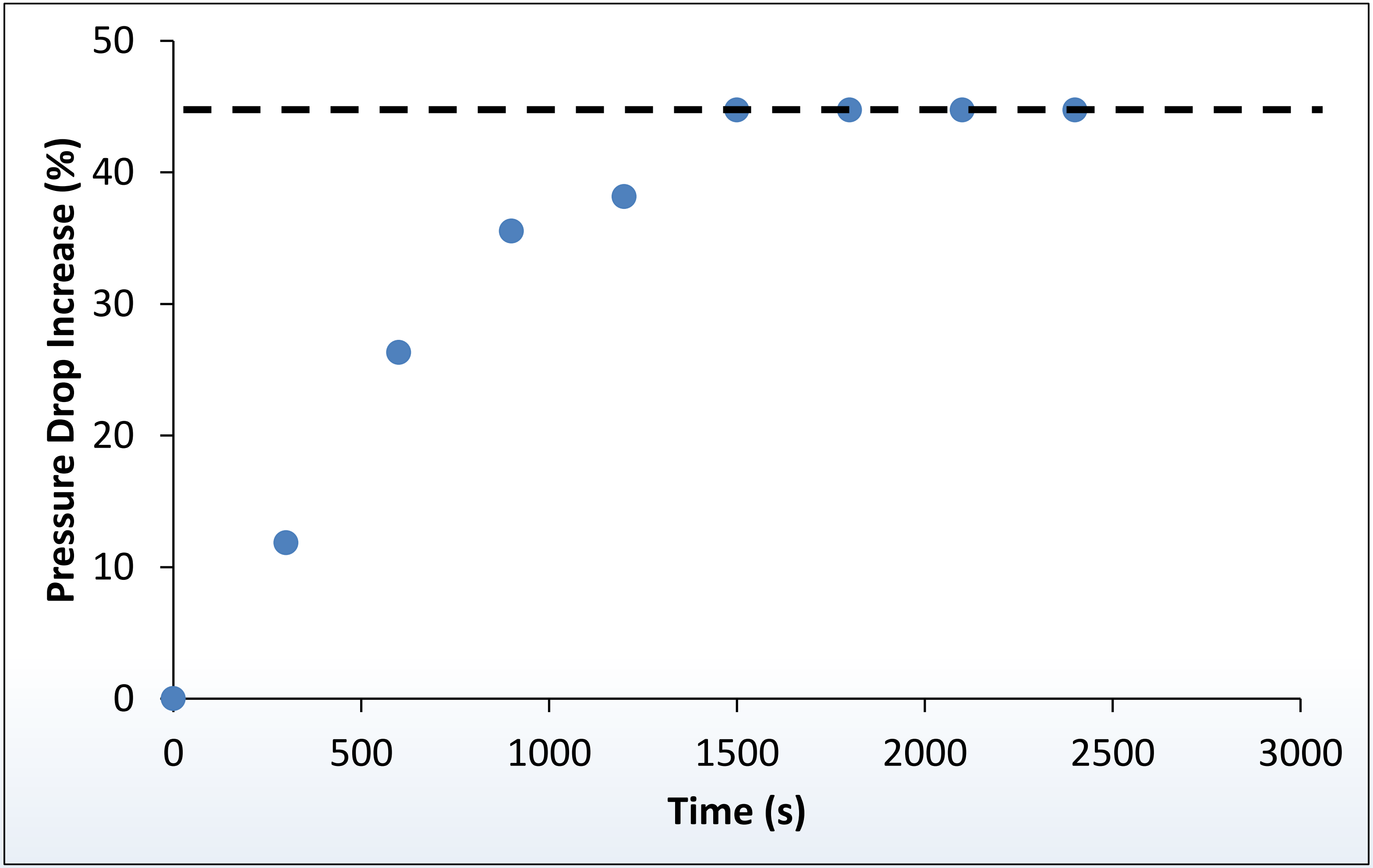
Pressure Drop Increase with Fouling



Pressure Drop Increase with Fouling



Pressure Drop Increase with Fouling



Summary

- Heat recovery from gas streams is important for high energy efficiency and it will be economic, one day
- Numerical results suggest elliptical tube can improve HX performance
- Preliminary experimental work adds to the understanding of how fouling affects the pressure drop
- Further considerations are needed in judging a best HX design, e.g. cost, availability