Improving Efficiency and Reducing Cost in Steam Power Plant Air Preheaters

Mei Chung, Mark Lewis, Vijay Ramanujan, Chris Stanczak

Overview: schematic of a pulverized coal-fired boiler

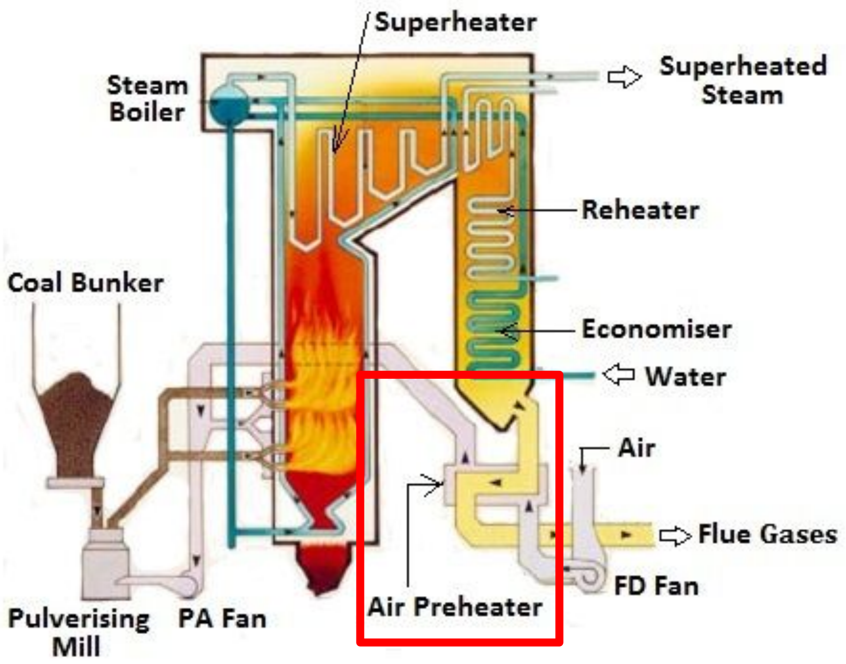

Figure 1. Schematic of a pulverized coal-fired boiler [2]

Boiler:

- Transfers heat produced by the combustion process of a fuel to the working fluid [1]

Air-preheater:

- Use heat from the hot flue gas to raise the temperature of the air before entering the boiler [3]
- This is important because:
  - T_{air} increases → efficiency of the boiler also increases
- Credited with saving 25% fuel, provides up to 20% of the heat transfer in the boiler [4]

Overview: schematic of a rotary air-preheater

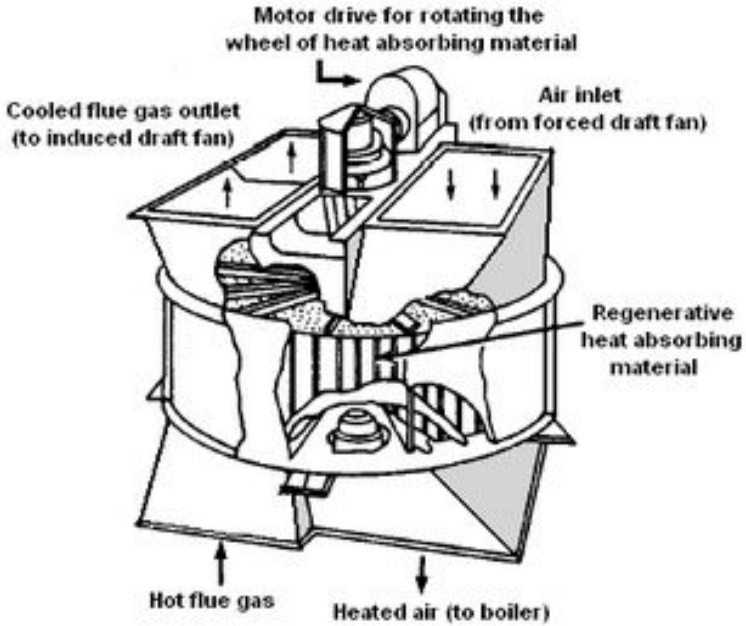

Figure 2. Schematic of rotary air preheater [4]

Ljungström Air Preheater Components [3]

- Rotating basket divided into multiple segments
- Heat conductive materials
  - Absorb heat from the hot flue gas, and transfer to the cold air
  - Ceramic sheets
- Seals (single or multiple)

Figure 3. Heating elements of an air preheater [5]

Previous work done to improve the air preheater

On the effects of rotational speed on preheater performance:

- Increasing the rotational speed → increased hot area of the outlet section → better heat transfer → $T_{air,out}$ increased and $T_{gas,out}$ decreased → increased efficiency [6]
  - Efficiency is only increased up to a certain limit
  - Trade off between better heat transfer and max/min temperatures achieved
- Velocity of the hot and cold air have more significant effect on efficiency than the rotational speed [7]

On the effects of materials [6]:

- Effect of plate material change on the efficiency limited

On the use of multiple heat sources:

- Integration of combustion air preheating system with a bypass flue (BPF) configuration [8]
  - Waste energy of the flue gas after the APH and BPF exploited to warm the primary and secondary air → preliminarily heated (by wasted flue gas) primary air and secondary air enters the APH and absorb energy from the flue gas

Previous work done to improve the air preheater

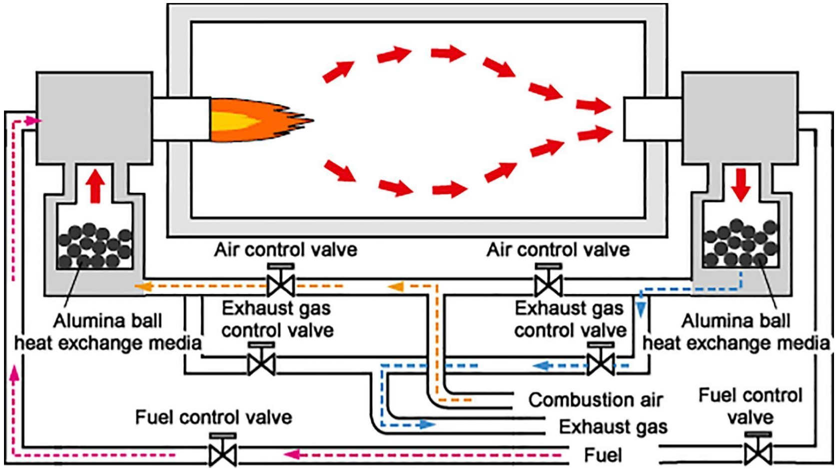

Figure 4. Regenerative burner system schematic [9]

On **Heat Recovery Burner Systems** [9]:

- New design for the air preheater
- Two alternating burners
- One burner is igniting the coal, opposite burner ejects exhaust gases through a medium that collects and stores heat

Current air-preheaters can still improve effectiveness

- **Air Leakage** – pressure differences between hot gas and cool air cause air leakages [10]
    - Leak rates with well designed seals should be below 10%
    - Typical leak rates are about 15-20%, with rates of larger than 30% not being uncommon [11]

- **Low heat transfer and corrosion** – current air preheaters have low heat transfer, which is proportional to the surface area of the heating elements [3]
    - Heat transfer area is reduced due to erosion and corrosion of the heating elements, mainly due to sulfuric acid dew-point corrosion [12]

- **Reduced efficiency due to fresh air purging [13]**

Our Proposed Modification

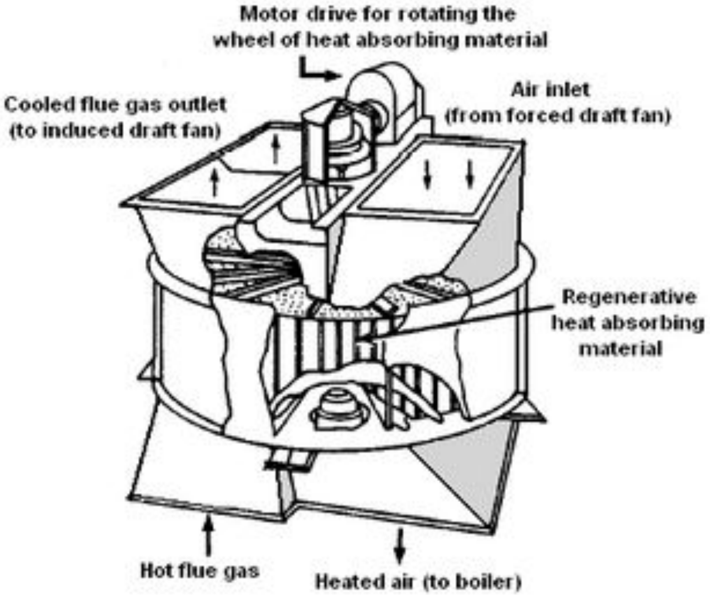

Figure 2. Schematic of rotary air preheater [4]

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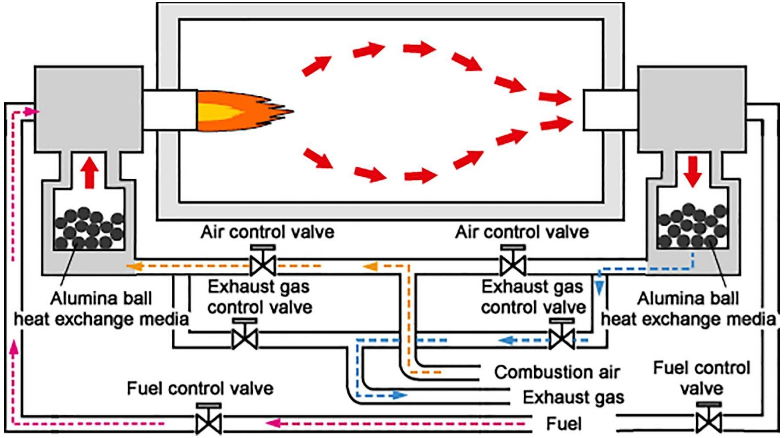
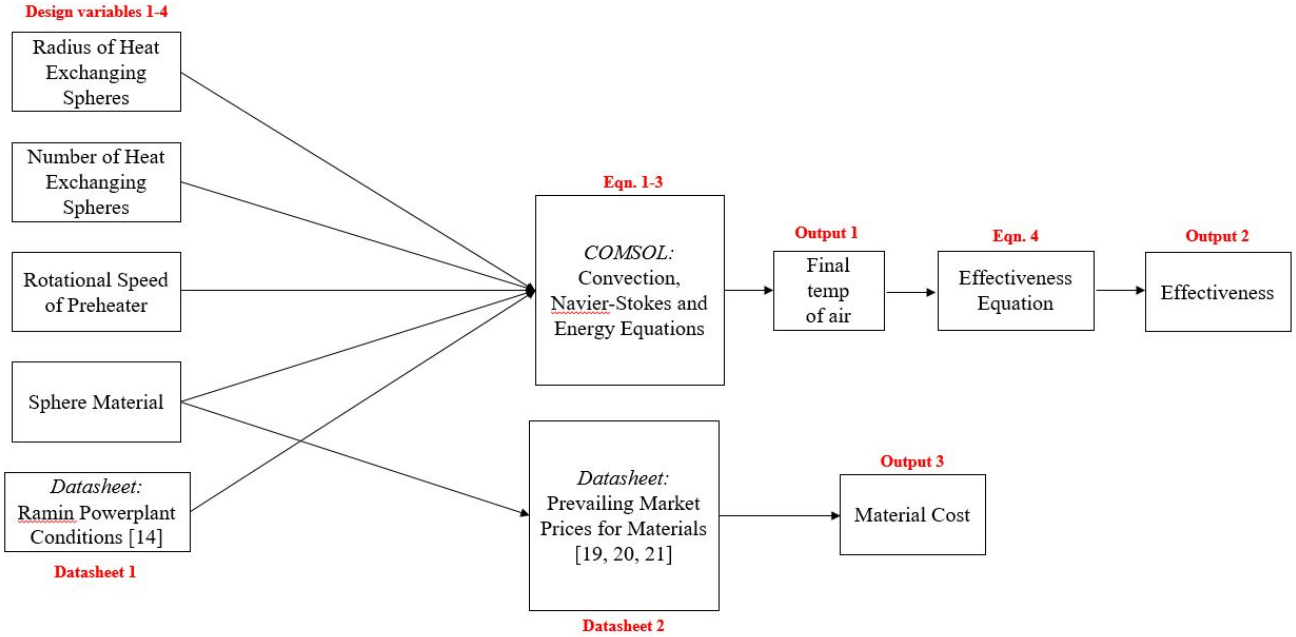


Figure 4. Regenerative burner system schematic [9]

Our Goals: Increase effectiveness while decreasing material costs

	Goal 1	Goal 2
Problem	Low effectiveness of Ljungström air preheater due to low heat transfer	Material cost of air preheater can be lowered
Goal	Increase preheater effectiveness to 70%	Reduce material costs to $0.650/kg
State of the Art Value from Previous Work	~61% [14, 15, 16]	$.900 / kg [17]
Design Variable(s) to be Manipulated in this Project to Attain Target	Radius of heat exchange heating element spheres [9], number of spheres, RPM	Material of spheres

Design Calculations Flow Diagram



Main equations: Navier Stokes and Energy Equations [18]

$$\nabla \cdot \vec{V} = 0 \qquad (1)$$

Divergence of Velocity

Mass Continuity

$$\rho \frac{\partial \vec{V}}{\partial t} + \rho \left(\vec{V} \cdot \nabla \right) \vec{V} = -\nabla p + \mu \nabla^2 \vec{V} + \rho \vec{g} \qquad (2)$$

Internal Forces

Pressure Forces

Viscous Forces

Gravity Force

Momentum Balance

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \overrightarrow{V} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \qquad (3)$$

Rate of change of energy per unit volume

Convection of energy into a point by flow

Net heat flux

Internal heat source

Total Energy

Main equations: Effectiveness Equation [14]

$$\epsilon = \frac{\dot{m}_{air,in} C_{P,air} (T_{air,out} - T_{air,in})}{\dot{m}_{flue,in} C_{P,flue} (T_{flue,in} - T_{air,in})} \quad (4)$$

- Effectiveness = ratio of heat transfer to ideal possible heat transfer
- Numerator = change in enthalpy of air
- Denominator = Change in enthalpy of incoming flue gas

$\dot{m}_{air,in}$ = *mass flow rate of air*
$C_{P,air}$ = *heat capacity of air*
$T_{air,\ out}$ = *outlet temperature of air*
$T_{air,\ in}$ = *inlet temperature of air*

$\dot{m}_{flue,in}$ = *mass flow rate of flue gas*
$C_{P,flue}$ = *heat capacity of flue gas*
$T_{flue,\ in}$ = *inlet temperature of flue gas*

Ramin Power Plant Datasheet [14]

Benchmark for variable range design

9864 mm	Matrix diameter	2 rpm	Rotational speed
650 mm	Cold layer height	1250 mm	Hot layer height
634.2 K	Inlet gas temperature	348.9 K	Inlet air temperature
–1.89 kPa	Inlet gas pressure	2.97 kPa	Inlet air pressure
–3.11 kPa	Outlet gas pressure	1.65 kPa	Outlet air pressure

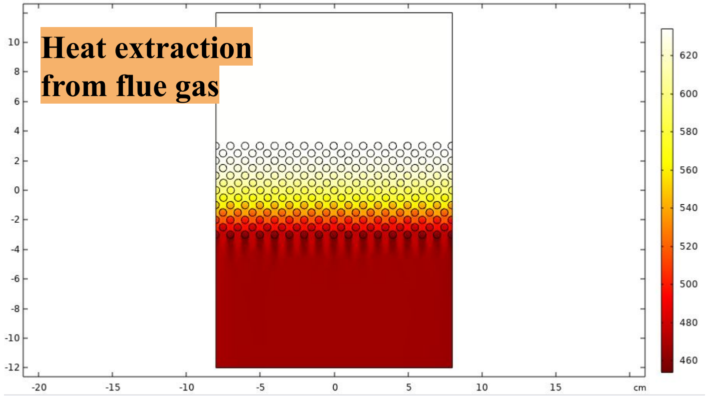
Boundary conditions

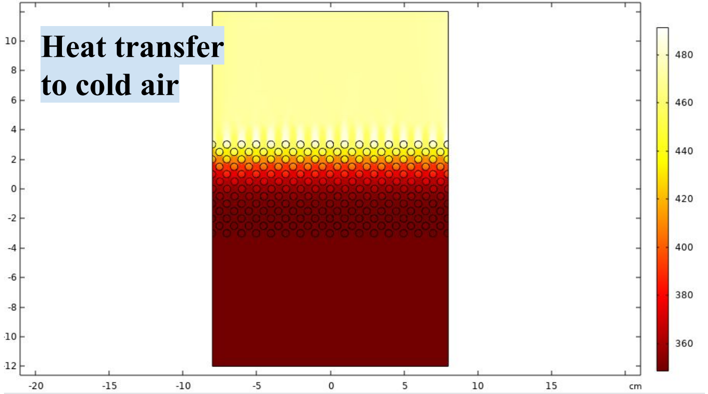
Material Cost Data Sheets

Material	**Cost [$ / ton]**
Alumina	1,500 [19]
Steel	1,020 [20]
Aluminum	1,900 [21]

COMSOL Set Up

- Iterations to simulate rotation
- Spheres of different sizes with area taken up by spheres held constant
- 2D heat transfer simulation





GOAL 1

Simulation Sweep 1: Variables and Boundary Conditions

Variables and Ranges:

- **Ball Material:** Steel, Alumina, Aluminum
- **Ball diameter:** 0.5 cm, 1 cm, 2 cm
  - *Ran simulations with larger diameters, but they were not able to transfer enough heat*
- **RPM:** 1, 2, 4

Boundary Conditions [18]:

- $T_{air,\ in} = 348.9$ K
- $T_{gas,\ in} = 634.2$ K
- $P_{gas,\ in} = -1.89$ kPa
- $P_{air,\ in} = 2.97$ kPa

Simulation 1: Results

Trial	1	2	3	4	5	6	7	8
Ball material	alumina	alumina	alumina	alumina	alumina	alumina	alumina	alumina
Ball diameter (cm)	0.5	0.5	0.5	1	1	1	2	2
Duration of half spin (s)	8.5	15	30	8.5	15	30	15	30
Cools down before end of rotation	N	N	Y	Y	N	N	N	N
Average	542.44	545.20	467.49	430.58	541.71	500.65	537.83	516.84
End T	511.70	402.47	347.86	347.58	454.61	370.55	488.48	432.11

Trial	9	10	11	12	13	14
Ball material	aluminum	aluminum	aluminum	aluminum	aluminum	aluminum
Ball diameter (cm)	0.5	0.5	1	1	2	2
Duration of half spin (s)	15	30	15	30	15	30
Cools down before end of rotation	Y	Y	N	Y	N	N
Average	466.47	407.95	474.37	416.43	477.64	432.31
End T	348.62	348.14	356.49	348.75	384.72	350.50

Trial	15	16	17	18	19	20	21
Ball material	steel	steel	Steel	steel	steel	steel	steel
Ball diameter (cm)	0.5	0.5	1	1	1	2	2
Duration of half spin (s)	15	30	8.5	15	30	15	30
Cools down before end of rotation	N	N	N	N	N	N	N
Average	536.23	459.36	462.11	530.60	485.76	526.42	502.53
End T	389.97	347.85	365.40	434.39	359.36	470.38	410.72

Validation of Calculations: Correlation Case Study

- COMSOL heating times for the 0.5 cm diameter sphere were compared to correlations from Heat and Mass Transfer for Spheres subject to Forced Convection [22]
- Values from correlations for 0.5 cm diameter cylinders were also compared for reference
- Derivation in **Appendix IV**

Geometry	**Time to for cold air to heat to T = 630 K (s)**
2D Sphere (Calculated in COMSOL)	14
Sphere (Correlation)	17.5
Cylinder (Correlation)	23.2

Simulation Sweep 2: Parameters and Boundary Conditions

Parameters:

- **Material:** Alumina
- **Ball diameter:** 0.5 cm
- **RPM:** 2

Variable:

- **# Rows of Spheres**

Boundary Conditions [18]:

- $T_{air,\ in}$ = 348.9 K
- $T_{gas,\ in}$ = 634.2 K
- $P_{gas,\ in}$ = -1.89 kPa
- $P_{air,\ in}$ = 2.97 kPa

Simulation 2: Results

# Rows	1	2	3	4	5	7	9
Average T_air,out	383.23	398.62	421.61	447.68	470.92	514.18	545.20
End T_air, out	348.90	348.88	349.00	349.99	353.50	370.71	402.47
Average effectiveness	12.03%	17.43%	25.49%	34.62%	42.77%	57.93%	68.80%
Cost	$1,706.69	$3,413.37	$5,120.06	$6,826.75	$8,533.43	$11,946.80	$15,360.18

# Rows	10	11	13	15	17	19
Average T_air,out	555.30	564.72	577.17	585.77	588.24	596.33
End T_air, out	421.85	441.57	473.61	497.68	511.13	532.96
Average effectiveness	72.35%	75.65%	80.01%	83.03%	83.89%	86.73%
Cost	$17,066.86	$18,773.55	$22,186.92	$25,600.29	$29,013.67	$32,427.04

- Effectiveness increases with the number of spheres (at a trade off of costs)
- More than **7 rows** of spheres achieve current state of the art effectiveness
- More than **10 rows** exceed goal effectiveness

GOAL 2

Costs Comparison

- Current air preheater heating elements made of Corten Steel [23]

- Cost of Corten Steel = $900 / ton [17]
- Cost of Alumina = $1,500 / ton [19]
- Cost of Steel = $1,020 / ton [20]
- Cost of Aluminum = $1,900 / ton [21]

- **Total cost of air preheater:** ~$4.3 M [24]
    - $30K negligible, cost impact small

Our Goals: Increase effectiveness while decreasing material costs

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-Thank You-

APPENDIX

I. List of contributions of each group member to project

- *Mei Chung*
  - Editor, overview of system design, COMSOL simulations, plot of how goal parameters vary with values of design variables
- *Christopher Stanczak*
  - COMSOL simulations, schematic of system and explanation of parts, main equations used in calculations and flow diagram
- *Mark Lewis*
  - COMSOL simulations, quantifiable goals for the project, discussion of how we know our calculations are correct
- *Vijay Ramanujan*
  - Background on system including previous work, remaining unsolved problems, and how project is addressing these challenges

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III. Main equations: Navier Stokes and Energy Equations [18]

$$\nabla \cdot \vec{V} = 0 \qquad (1)$$

Divergence of Velocity

Mass Continuity

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Internal Forces

Pressure Forces

Viscous Forces

Gravity Force

Momentum Balance

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \overrightarrow{V} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \qquad (3)$$

Rate of change of energy per unit volume

Convection of energy into a point by flow

Net heat flux

Internal heat source

Total Energy

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III. Ramin Power Plant Datasheet [14]

Benchmark for variable range design

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Boundary conditions

III. Material Cost Data Sheets

Material	Cost [$ / ton]
Alumina	1,500 [19]
Steel	1,020 [20]
Aluminum	1,900 [21]

IV. Correlation Calculations for 0.5 cm diameter Circular Geometries [22]

Thermal and Mechanical Properties of Alumina (from COMSOL)

Density (kg/m^3)	3900
Heat Capacity (J/K)	900
Thermal Conductivity (W/m-K)	27

Thermal and Mechanical Properties of Air (from COMSOL)

Thermal Conductivity (mW/m-K)	48
Dynamic Viscosity (T = 634.2 K) (Pa-s)	4.6×10^{-5}
Dynamic Viscosity (T = 348.9 K) (Pa-s)	3.93×10^{-5}
Prandtl Number (T = 634.2 K) (Pa-s)	0.735

IV. Correlation Calculations for 0.5 cm diameter Circular Geometries [22]

$$Re_D = \frac{\rho v d}{\mu} = 3519$$

Sphere Correlation

Average Nusselt Number	Restrictions
$\overline{Nu_D} = 2 + \left(0.4\,\mathrm{Re}_D^{1/2} + 0.06\,\mathrm{Re}_D^{2/3}\right)\mathrm{Pr}^{0.4}\left(\frac{\mu}{\mu_s}\right)^{1/4}$	$0.71 \le \mathrm{Pr} \le 380$ $3.5 \le \mathrm{Re}_D \le 7.6\times10^4$ $1.0 \le (\mu/\mu_s) \le 3.2$

$$\Rightarrow Nu = \frac{hL}{k_{air}} = 36.64$$

$$\Rightarrow h = 703.5\ \frac{W}{m^2 \cdot K}$$

Cylinder Correlation

$\overline{Nu_D} = 0.683\,\mathrm{Re}_D^{0.466}\,\mathrm{Pr}^{1/3}$	$\mathrm{Pr} \ge 0.7$

$$\Rightarrow Nu = 27.7 \quad \Rightarrow h = 531\frac{W}{m^2 \cdot K}$$

IV. Correlation Calculations for 0.5 cm diameter Circular Geometries [22]

Sphere

$$Bi = \frac{hL}{k_{sphere}} = 0.0651 < 0.1$$

Since Biot number is less than 0.1, lumped capacitance method can be used

Cylinder

$$Bi = \frac{hL}{k_{cylinder}} = 0.0492 < 0.1$$

Since Biot number is less than 0.1, lumped capacitance method can be used

$$T_\infty + (T_i - T_\infty)exp(-\frac{hAt}{\rho V c_p}) = T - T_\infty \longrightarrow$$

$T_i = 348.9K$

$T_\infty = T_{fluegas} = 634.2K$

Geometry	Time to for cold air to heat to T = 630 K (s)
Sphere	17.5
Cylinder	23.2

V. Nomenclature

$\dot{m}_{air,in}$	Mass flow rate of air (kg/s)
$C_{P,air}$	Heat capacity of air (J/K)
$T_{air, out}$	Outlet temperature of air (K)
$T_{air, in}$	Inlet temperature of air (K)
$\dot{\mathrm{m}}_{\mathrm{flue,in}}$	Mass flow rate of flue gas (kg/s)
$\mathrm{C}_{\mathrm{P,flue}}$	Heat capacity of flue gas (J/K)
$\mathrm{T}_{\mathrm{flue,\ in}}$	Inlet temperature of flue gas (K)
ε	Air preheater effectiveness
V	Velocity (m/s)

ρ	Density of fluid (2D) (kg / m^2)
t	Time (s)
p	Pressure of fluid (Pa)
μ	Dynamic viscosity (Pa-s)
g	Gravitational acceleration (m / s^2)
T	Temperature (K)
k	Thermal conductivity (W / m-K)
Q	Heat generated (J/s-m^2)

VI. Nomenclature

Re_D	Reynolds Number
d	Diameter (m)
Nu	Nusselt Number
h	Convection coefficient (W/m^2-K)
Pr	Prandtl Number
Bi	Biot Number
T_i	Initial temperature (K)
T_∞	Surrounding fluid temperature (K)
V	Volume (m^3)

VII. COMSOL Datasheets

- See attached Excel file