Optimization of Secondary Air Injection in a Wood-Burning Cookstove: An Experimental Study

Julien Caubel, Vi Rapp, Sharon Chen, Ashok Gadgil
ETHOS Conference
January 28, 2018
Acknowledgements

**Sponsor:** Department of Energy – Bioenergy Technologies Office (BETO)

Special thanks to **Brahim Idrissi Kaitouni, Allen Boltz, and Arjun Kaul** who devoted countless hours in the laboratory testing and optimizing the cookstoves
Many clean biomass cookstoves have been developed and tested.

[Jetter et al., 2012]
Naturally drafted stoves do not provide adequate reductions

[Jetter et al., 2012]
Forced-draft stoves reduce emissions, but are not well studied

[Jetter et al., 2012]
Forced-draft stoves reduce emissions, but are not well studied

[Jetter et al., 2012]
Achieve 90% emission reductions using air-injection stove

- Experimental study to identify/understand critical parameters that drive emission reductions

Stove must:
- Use unprocessed wood
- Be continuously fed
- Operate at high firepower (5 kW)

[Jetter et al., 2012]
Modular stove (MOD) design

Rapid, parametric adjustment of key design parameters:
1. Grate height
2. Pot height
3. Primary air entrainment
4. Secondary air flow rate
5. Secondary air injection pattern (position/# of holes)
Secondary air injection components

1. Temperature
2. Time
3. Turbulence

Secondary air parameters:
1. Flow Rate (CFM)
2. Velocity (m/s)

\[ v = \frac{Q}{A} = \frac{Q}{N\left(\pi d^2/4\right)} \]

- \( v \) = velocity
- \( Q \) = flow
- \( N \) = # of holes
- \( d \) = hole diameter
Performance metrics are measured with replicate laboratory stove tests

**Cold Start Water Boiling Test:**
- Boil 5 L of water
- Constant firepower (**5 kW**)
- Conducted >130 trials
- Compare with Three Stone Fire (TSF)
Size-Resolved PM Measurement

Isokinetic, diluted (20:1) sample from duct to 2 instruments:

- **TSI 3091 Fast Mobility Particle Sizer (FMPS)**
  - Range: 6 – 295 nm
  - Last four bins omitted

- **TSI 3321 Aerodynamic Particle Sizer (APS)**
  - Range: 350 – 2500 nm
  - Aerodynamic diameter converted to electrical mobility diameter (PM density = 2.4 ± 0.2 g/cm³)
PM size distribution: Flow rate

1 air injection pattern tested at 3 flow rates
PM size distribution: Flow rate

Ultrafine particles (UFP) 10 – 50 nm increase with flow rate

- Secondary air cools combustion zone
- PM-forming volatile gases oxidize less readily
- PM nucleation and growth increases
PM size distribution: Flow rate

Lowest PM volume emissions at 1 CFM (50 – 295 nm):
- 0.75 CFM = not enough turbulent mixing (too little velocity)
- 1.25 CFM = too cold (too much flow rate)
- 1 CFM = optimal balance of the temperature/mixing
PM size distribution: Flow rate

![Graphs showing PM size distribution for different flow rates.](image)
PM size distribution: Flow rate

0.75 and 1 CFM distributions very similar, but increases sharply at 1.25 CFM

- Combustion at 1.25 CFM below oxidation temperature
- Promotes particle growth: (1) Volatile gases condense
  (2) High velocity promotes agglomeration
PM size distribution: Velocity

Test optimal flow rate (1 CFM) using 2 air injection patterns:

- Pattern 1 = 6 holes = 20 m/s
- Pattern 2 = 9 holes = 16 m/s

All holes have 0.0625” (1.59 mm) diameter
PM size distribution: Velocity

Increasing velocity reduces PM from 25 – 295 nm:

- More velocity = more mixing = more oxidation
- Less volatile gases = Less PM formation
PM size distribution: Velocity

- Left graph: 
  - Y-axis: $dN/d\log D_p$ per Cooking Power [#/kWd]
  - X-axis: Particle Diameter [nm]
  - Showing various lines indicating particle size distribution.

- Right graph: 
  - Y-axis: $dV/d\log D_p$ per Cooking Power [cm$^3$/kWd]
  - X-axis: Particle Diameter [nm]
  - Comparing velocity effects at 16 m/s and 20 m/s with shaded regions indicating range.

The graphs illustrate the distribution of particles by size and the effect of velocity on cooking power in a particular context.
PM size distribution: Velocity

Particle distribution 350 – 2500 nm nearly identical:

- At 1 CFM, combustion temperature above oxidation of volatile gases and PM generation low
- Not much PM to agglomerate or gas to condense: Velocity does not affect particle growth
PM size distribution: TSF vs. MOD

Optimal MOD stove configuration:
- Flow rate = 1 CFM
- Velocity = 20 m/s
PM size distribution: TSF vs. MOD

MOD significantly reduces all particles > 10 nm:

- ~ 90% PM reduction from 50 to 295 nm
- Remaining particles < 10 nm: Decrease accumulation mode (growth) but does not suppress nucleation (formation)
PM size distribution: TSF vs. MOD

MOD stove reduces particle number and volume emissions by ~100x throughout measurement range (350 – 2500 nm)
Secondary air injection reduces emissions in wood combustion

- Secondary air injection is highly dependent on flow rate and velocity
  - Experimental optimization/validation required
- Apply design principles to cookstove for market (1 billion households), alleviating health and climate impacts from biomass cooking

[Jetter et al., 2012]
Supplementary Slides
Performance and Emissions

- CO/PM$_{2.5}$ nearly **double** as flow increases and velocity constant
  - Combustion temperature drop below oxidation temperature of CO and PM-forming volatile gases (~750 – 800 C)
- More velocity = more mixing = more cooling= more emissions
Performance and Emissions

- BC increases with flow, decreases with velocity throughout
  - More secondary flow = colder combustion = less BC oxidation
  - More injection velocity = more mixing = more BC oxidation
  - BC reduction w/velocity at 1.25 CFM = oxidation temp (~300 C)

- BC/PM2.5
Parametric Study: CO and PM$_{2.5}$ Emissions

Tested 2 air injection patterns (6 and 9 holes) at 3 flow rates

- 6 Parametric configurations at 5 injection velocities
Emissions double when flow increases from 1 to 1.25 CFM at 20 m/s

- Secondary air injected at room temperature (~ 25 C) and cools the combustion zone
- At 1.25 CFM, below ~750 – 800 C oxidation temperature of CO and many PM-forming volatile gases
Parametric Study: 
CO and PM$_{2.5}$ Emissions

Emissions increase with velocity at 1.25 CFM

- Below oxidation temperature of CO and PM-forming volatile gases
- More velocity = more mixing = more cooling = more emissions
BC emissions increase with flow rate

- BC oxidation rate proportional to temperature
- More secondary air = lower temperature = less BC oxidation
Parametric Study: BC Emissions and BC/PM$_{2.5}$ Ratio

BC emissions decrease with velocity at every flow rate

- BC forms in fuel-rich zones of flame
- More velocity = more mixing with oxygen = less BC formation/more BC oxidation
- Combustion above BC oxidation temperature (~340 °C) throughout
Parametric Study: BC Emissions and BC/PM$_{2.5}$ Ratio

- BC to PM$_{2.5}$ ratio decreases at 1.25 CFM
  - PM increases while BC continues to decrease at 1.25 CFM
  - Oxidation temperature below that of PM-forming volatile gases (~750-800 C) but above that of BC (~340 C)
Optimal Configuration:
1 CFM flow rate at 20 m/s velocity