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Distributed Sensing Technologies

Biomass Heater Testing:
Overview of Performance and Emissions Evaluation

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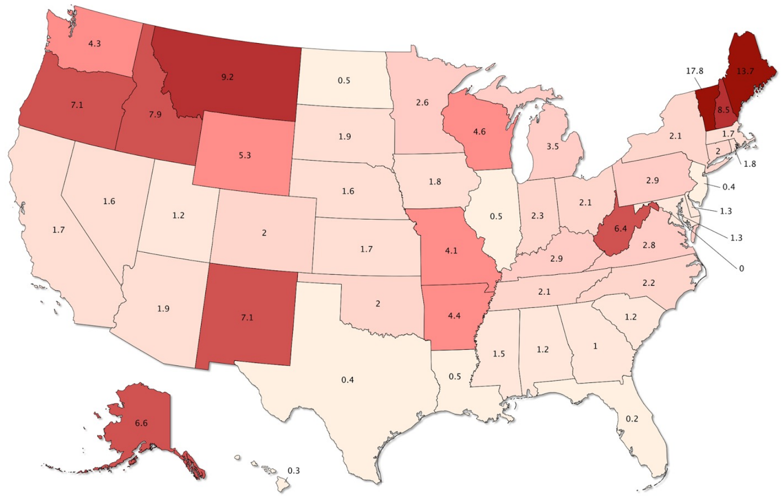
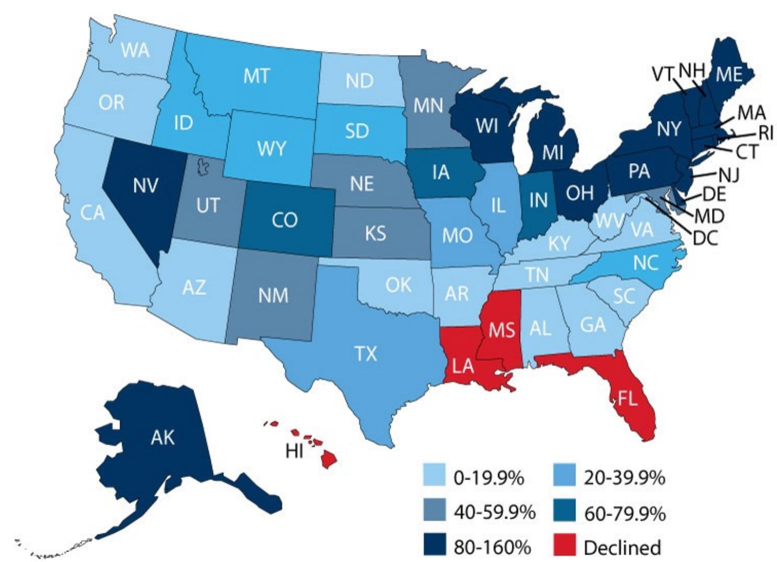
Biomass Heaters

- **13 million US homes have biomass heaters**
- **A fuel of necessity:** 2% of US homes use biomass as primary heat source
- **Major source of air pollution:** < 2% of CA homes have biomass heaters, but emit >20% of winter-time PM
- **More wood heaters are coming online over time**

Percentage of homes heated by wood



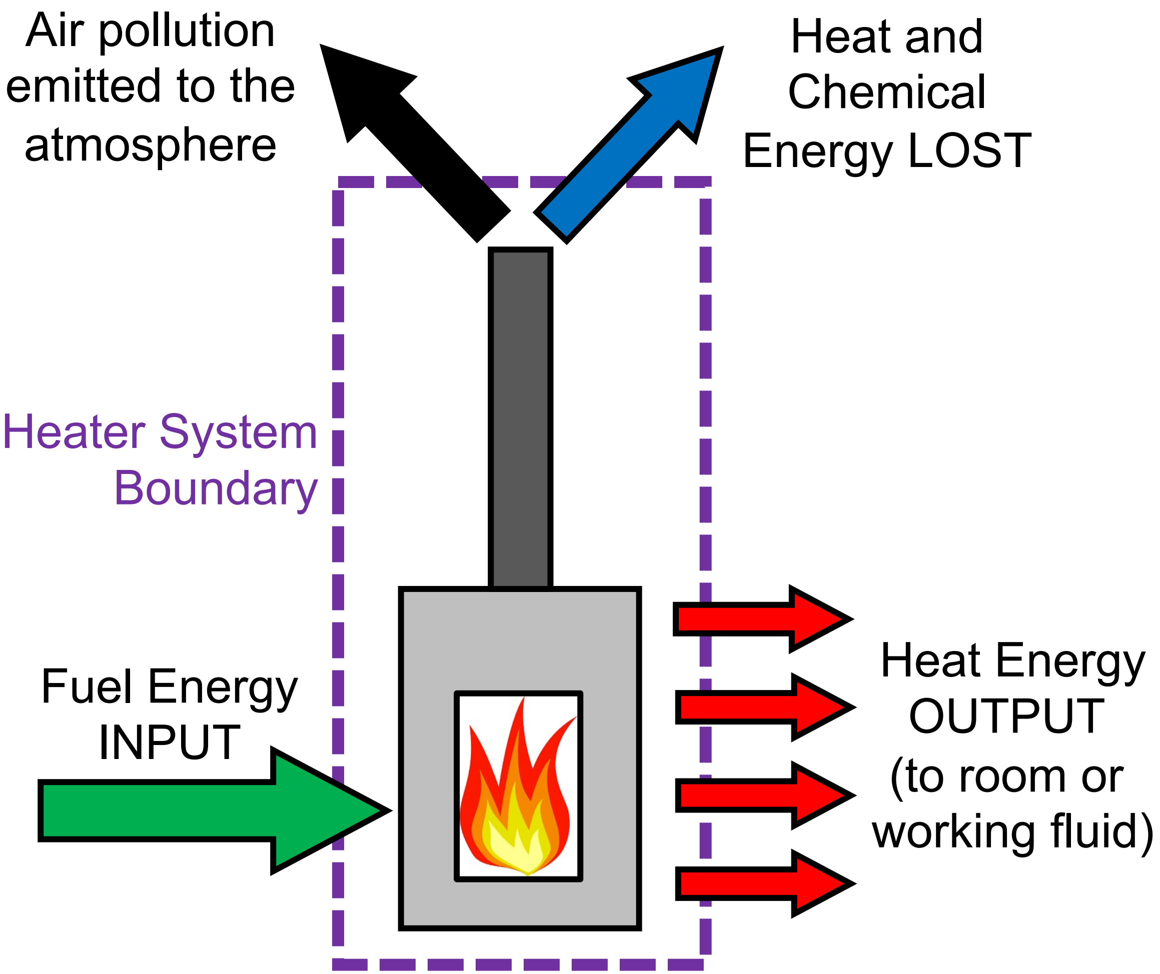
Rise in wood heat: 2000 to 2012



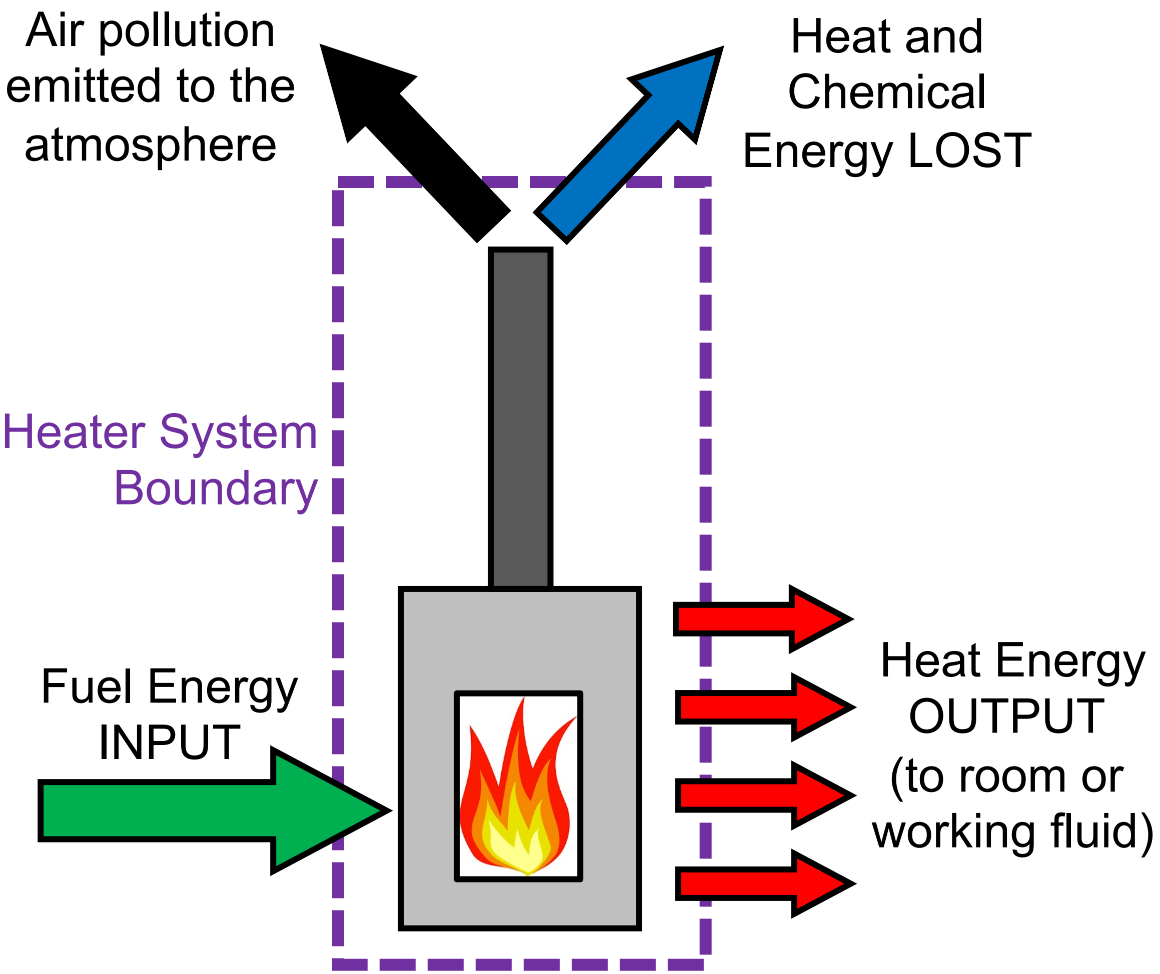
Why characterize biomass heaters?

- Inform implementation
  - Depending on context, some heaters may be more appropriate than others (e.g. firewood v. pellets)
  - Promote successful and responsible adoption
- Impact evaluation
  - Public health and the environment
  - Carbon emissions/Renewability
  - Air pollution, deforestation, land use management
- Regulatory compliance
  - Air pollution emissions and user safety
- Research and development
  - You can't improve what you can't measure

Biomass Heater System



Biomass Heater System



Quantify **OUTPUTS** (heat + pollution) per unit of fuel energy **INPUT**

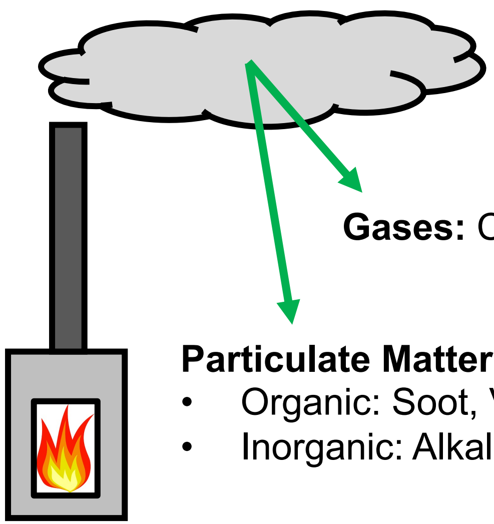
Biomass Heater Characterization

Air Pollution Emissions

- Quantify the **MASS** of pollutants emitted
- Normalize by run time, mass of fuel input, and/or thermal energy (or power) output

There are 2 main types of air pollution:

1. **Gases:** Only CO_2 and H_2O *ideally*
2. **Particulate Matter** (PM): Liquid or solid particles suspended in the air



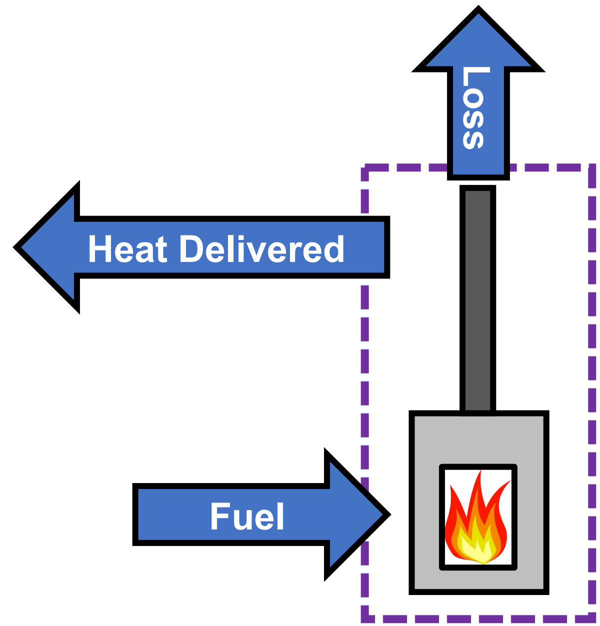
Gases: CO_2,CO,NO_x,OGC

Particulate Matter:

- Organic: Soot, VOCs, PAH, etc.
- Inorganic: Alkali salts and ash

Thermal Performance

- Quantify the useful energy (heat) delivered to user per unit of energy input (from fuel)
- This is known as **thermal efficiency**



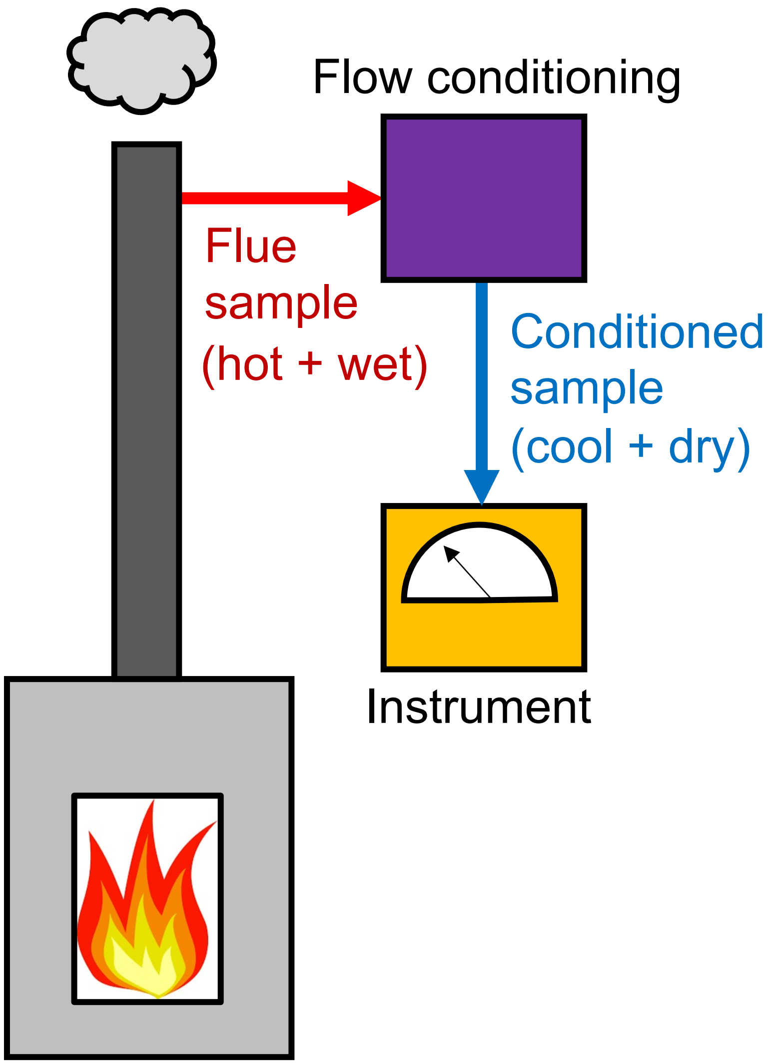
Fuel Energy (E_{fuel}) = Heat Delivered + Losses

Thermal Efficiency = Heat Delivered/E_{fuel}

Aspects of heater characterization

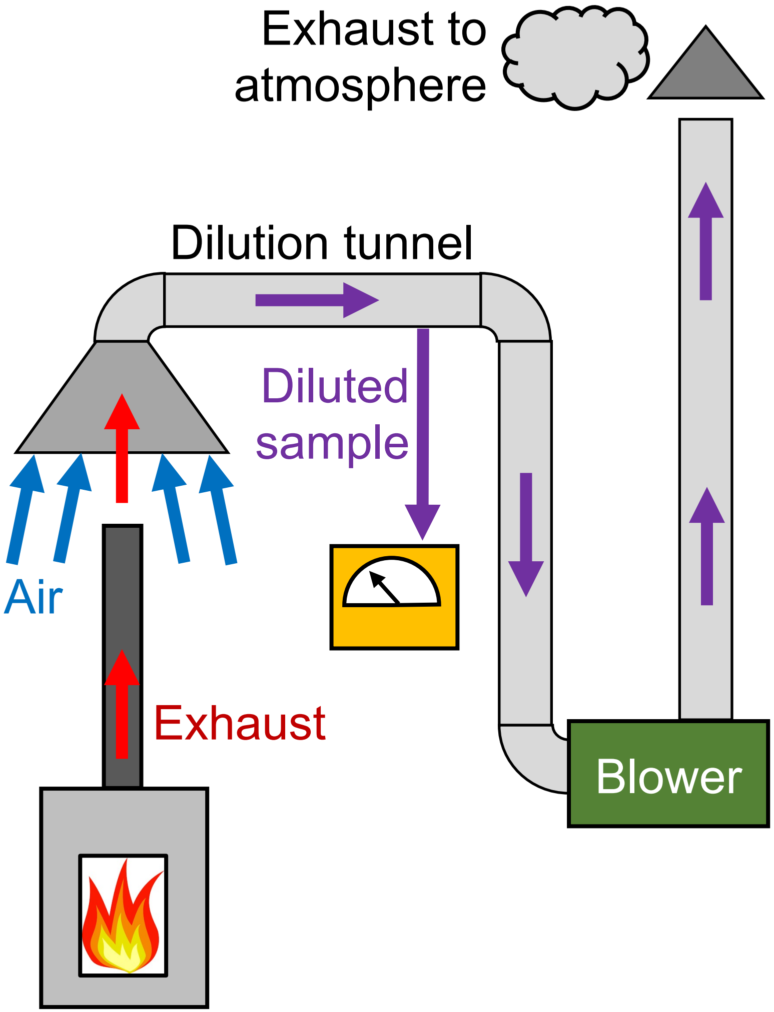
1. **Emissions sample: Flue v Dilution Tunnel**
2. Emissions measurement: PM and Gases
3. Efficiency determination: Direct v Indirect
4. Test Cycles

Flue sampling is simplest but hard on instruments



- Aspirate exhaust gases directly from the flue to the pollution instruments
- Exhaust gases are hot and wet, so must condition the sample flow to prevent damaging the instruments
- Simple and generally easier to implement in both lab and field
- Tough on the instrumentation (generally designed for ambient monitoring)
- Measurement artifacts may occur since hot emissions from flue are different from those emitted to the atmosphere

Dilution tunnel is “gold standard” but complex



- Capture all the exhaust into a steel duct system and mix with ambient air
- A blower actively draws the diluted mixture through ducts at high velocity
- Typical dilution ratios of 10 to 30 (1 part exhaust per 10 to 30 parts of air)
- Mimics emission to atmosphere, so data are more representative of “real world”
- Diluted exhaust is closer to ambient conditions, so easier on instruments
- Highly controllable and repeatable
- Very complex and cumbersome
- Only suitable for lab testing

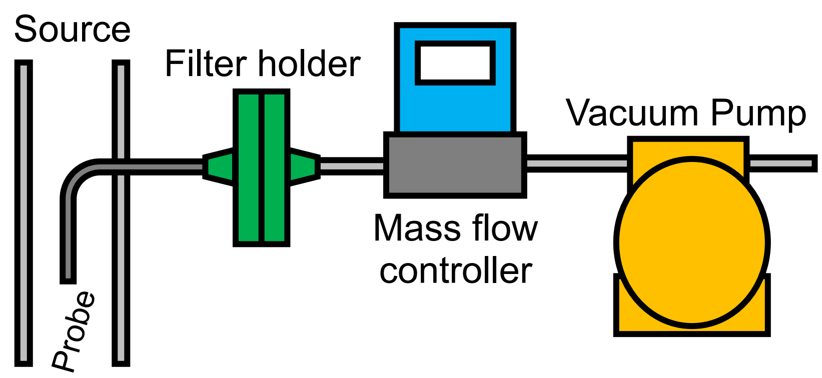
Aspects of heater testing

1. Emissions sample: Flue v Dilution Tunnel
2. **Emissions measurement: PM and Gases**
3. Efficiency determination: Direct v Indirect
4. Test Cycles

Gravimetric PM measurement

- Load a fibrous filter with PM pollution from heater at a known sample flow rate

$$m_{PM} = (m_{dirty} - m_{filt})\frac{Q_{source}}{Q_{sample}}$$



- Reliable, accurate, and time-tested method
- Compatible with flue and dilution tunnel sampling
- Provides only **one** integrated measurement of total PM mass emitted during sampling

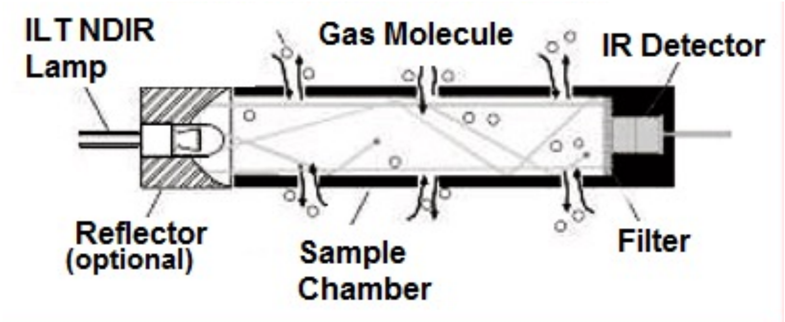
Gas measurement

Key species (indication)

- **CO_2:** Primary combustion product. Thermal performance and climate impact.
- **CO:** Toxic byproduct. Combustion quality and human health.
- **O_2:** Consumed from air. Thermal performance.

All measured in real-time from the heater flue directly.

Nondispersive Infrared (NDIR): Expensive, but accurate, robust, and long-lasting (CO_2 and CO)



Electrochemical cells: Cheap, but fragile, short-lived, and less accurate (CO and O_2)

Aspects of heater testing

1. Emissions sample: Flue v Dilution Tunnel
2. Emissions measurement: PM and Gases
3. **Efficiency determination: Direct v Indirect**
4. Test Cycles

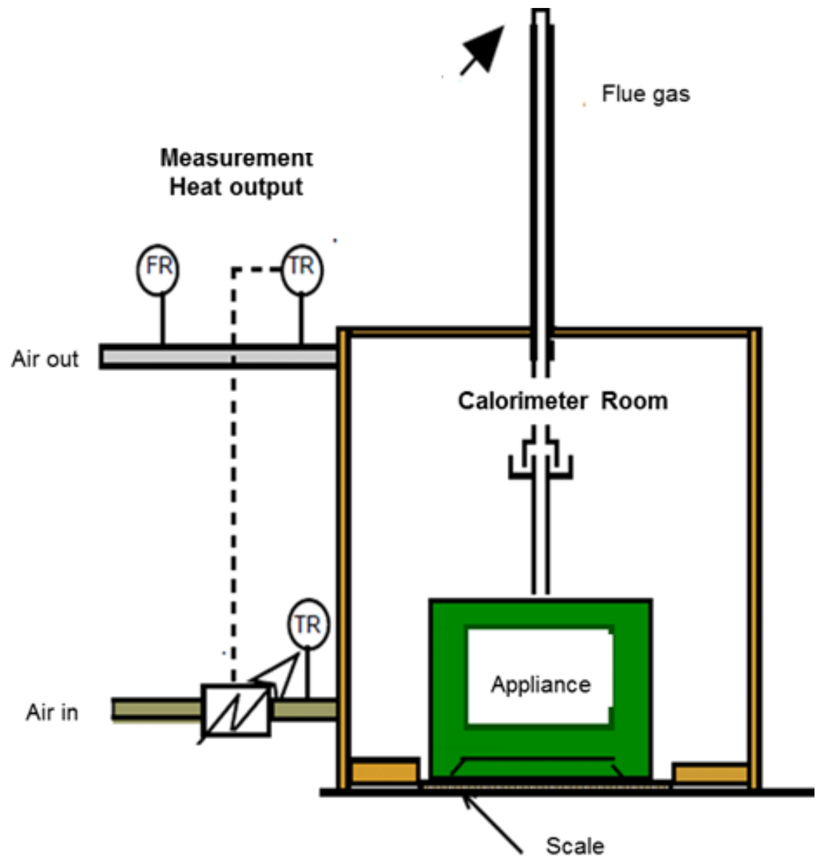
Thermal Efficiency: Direct Method

- Insulated calorimeter room built around the appliance
- Air is circulated at a controlled flow rate. Log temperature in/out.
- Yields direct measurement of stove's useful heat output (***E**_**out**_*)
- Cumbersome experimental set-up

$$\text{Efficiency} = 100 \times \frac{E_{out}}{E_{in}}$$

Determine energy input (***E**_**in**_*) from fuel mass and heat content (LHV)

$$E_{in} = m_{fuel} LHV$$



(ISO/DIS 13336)

Thermal Efficiency: Indirect Method

Measure energy loss from flue:

- Chemical: Incomplete combustion
- Latent: Vaporization of water in fuel
- Sensible loss: Exhaust of hot gas

Need measurements of:

- Fuel mass and composition
- CO_2, CO, and O_2 in the **flue**
- Temperature of flue gases and air

- Requires little or no additional experimental set up
- Relies on many assumptions, rather than direct heat flux measurement

Energy Loss Mechanisms:

$$E_{loss} = E_{chemical} + E_{sensible} + E_{latent}$$

Energy Conservation:

$$E_{in} = E_{out} + E_{loss}$$
$$E_{out} = E_{in} - E_{loss}$$

Thermal Efficiency:

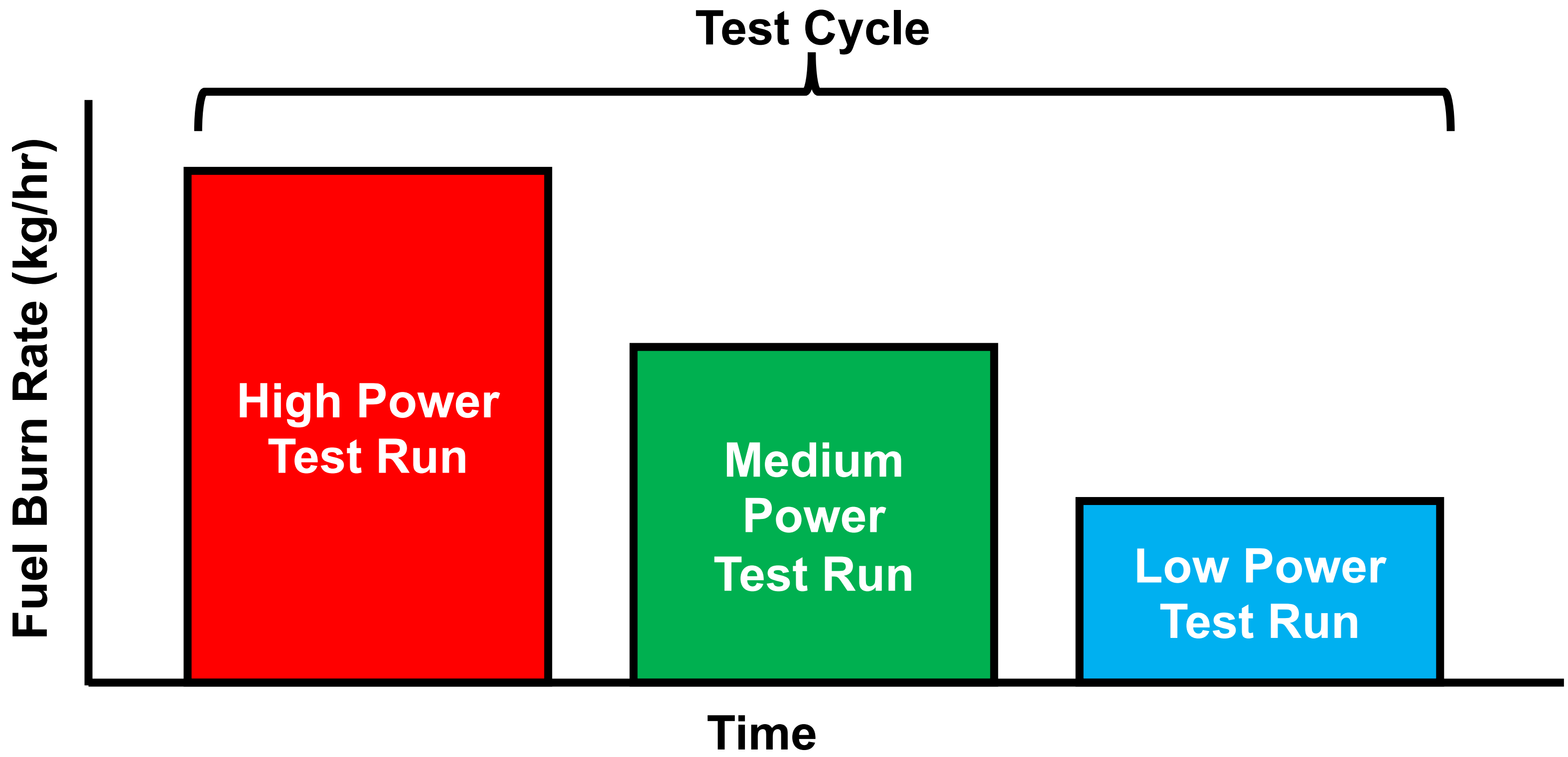
$$\text{Efficiency} = 100 \times \frac{(E_{in} - E_{loss})}{E_{in}}$$

Aspects of heater testing

1. Emissions sample: Flue v Dilution Tunnel
2. Emissions measurement: PM and Gases
3. Efficiency determination: Direct v Indirect
4. **Test Cycles**

Test Cycles

- Typically, individual test runs at prescribed power output levels
- Repeatable operating conditions across tests and heater models
- Not representative of "real-world" operating conditions

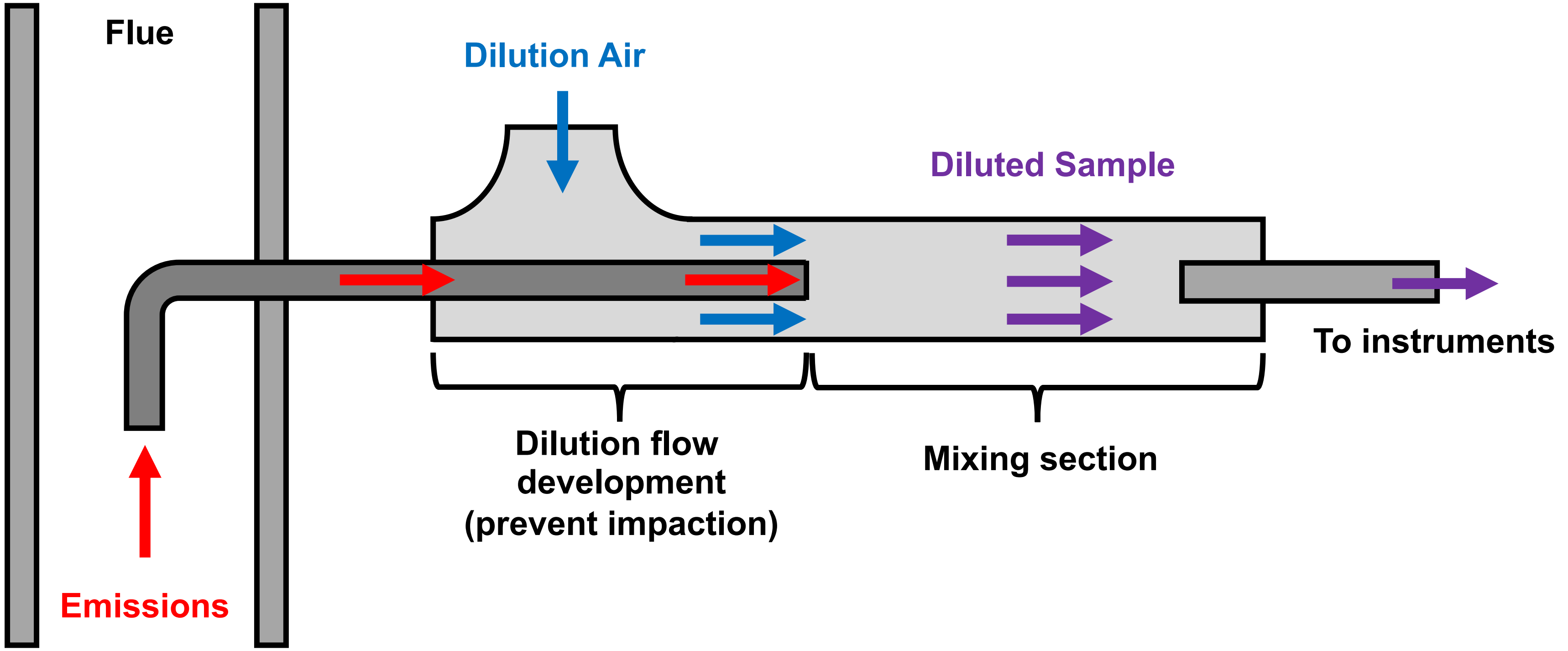


Future of Biomass Heater Evaluation

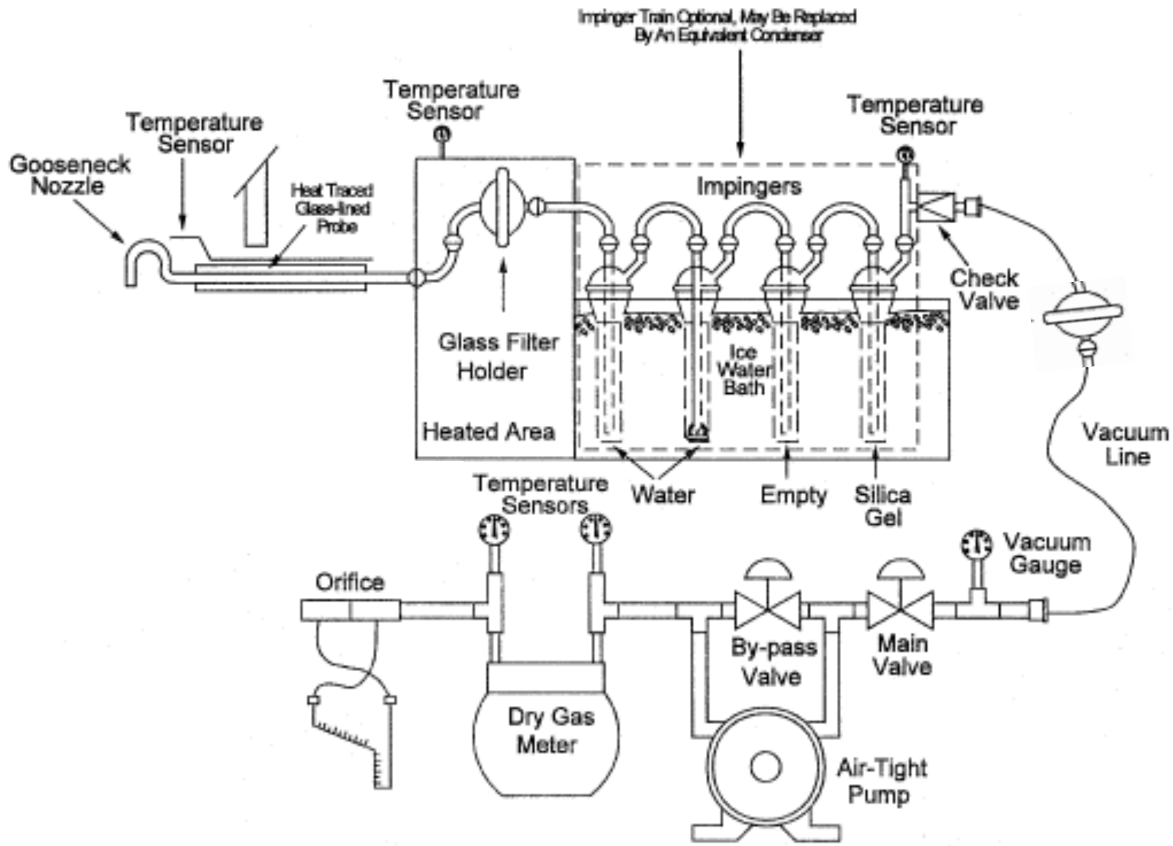
1. Direct dilution from flue
2. Modernize emissions sampling methods
3. Real-time PM mass concentration data
4. Direct flue velocity measurement
5. “Real-world” test cycles

1. Direct Dilution from the flue

- Dilute emissions from the flue for measurement with clean air
- Advantages of dilution tunnel in small and convenient package
- Facilitate lab testing and enable field testing

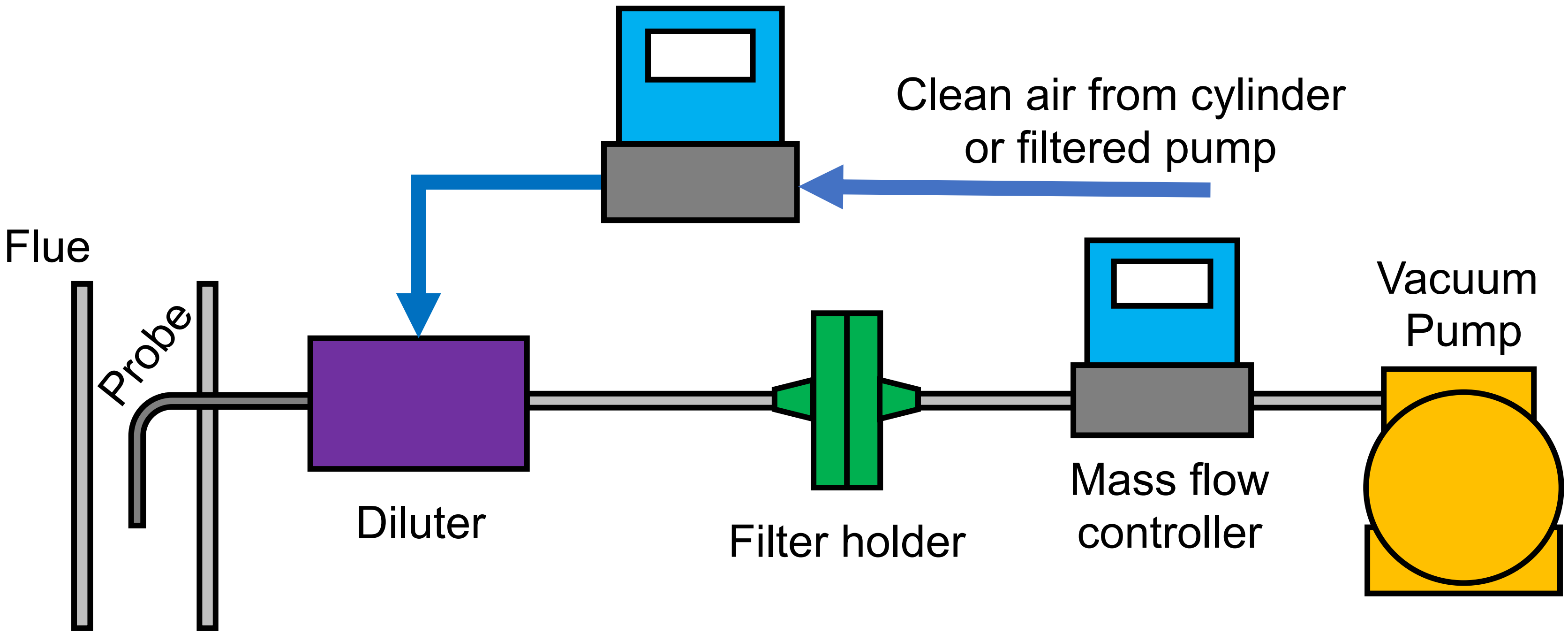


2. Modernize emissions sampling methods



- Heated box, dual filters, impingers, dry gas meter, pressure gauges, valves, orifice, etc. all manually controlled and logged
- All this to draw known air volume though filters and address shortcomings of direct flue sample (condensable PM)

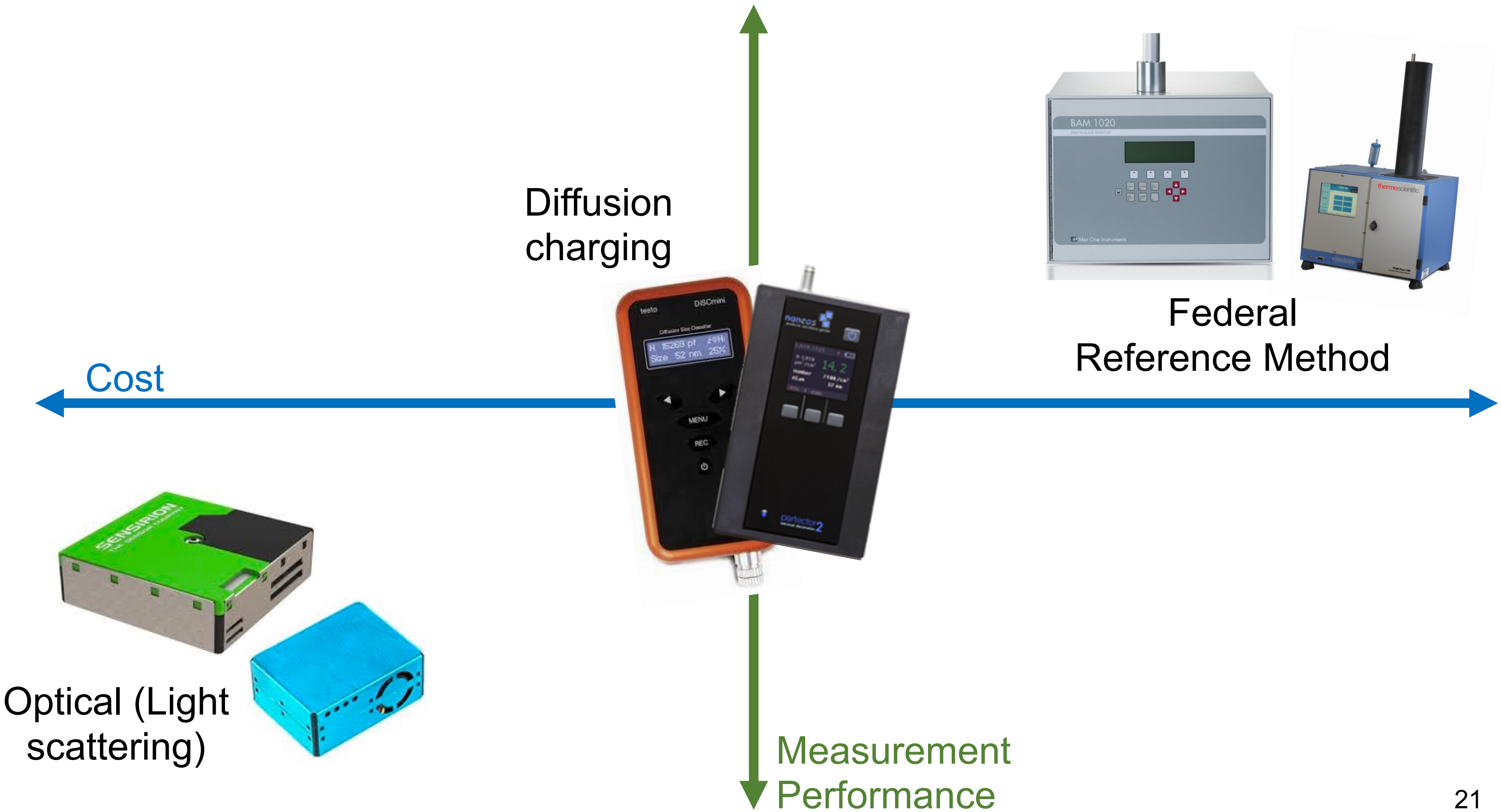
2. Modernize emissions sampling methods



- Dilute the flue sample directly with clean air
- MFCs maintain flow and log temperature + pressure digitally
- Providing automatic logging and control of diluted PM sample

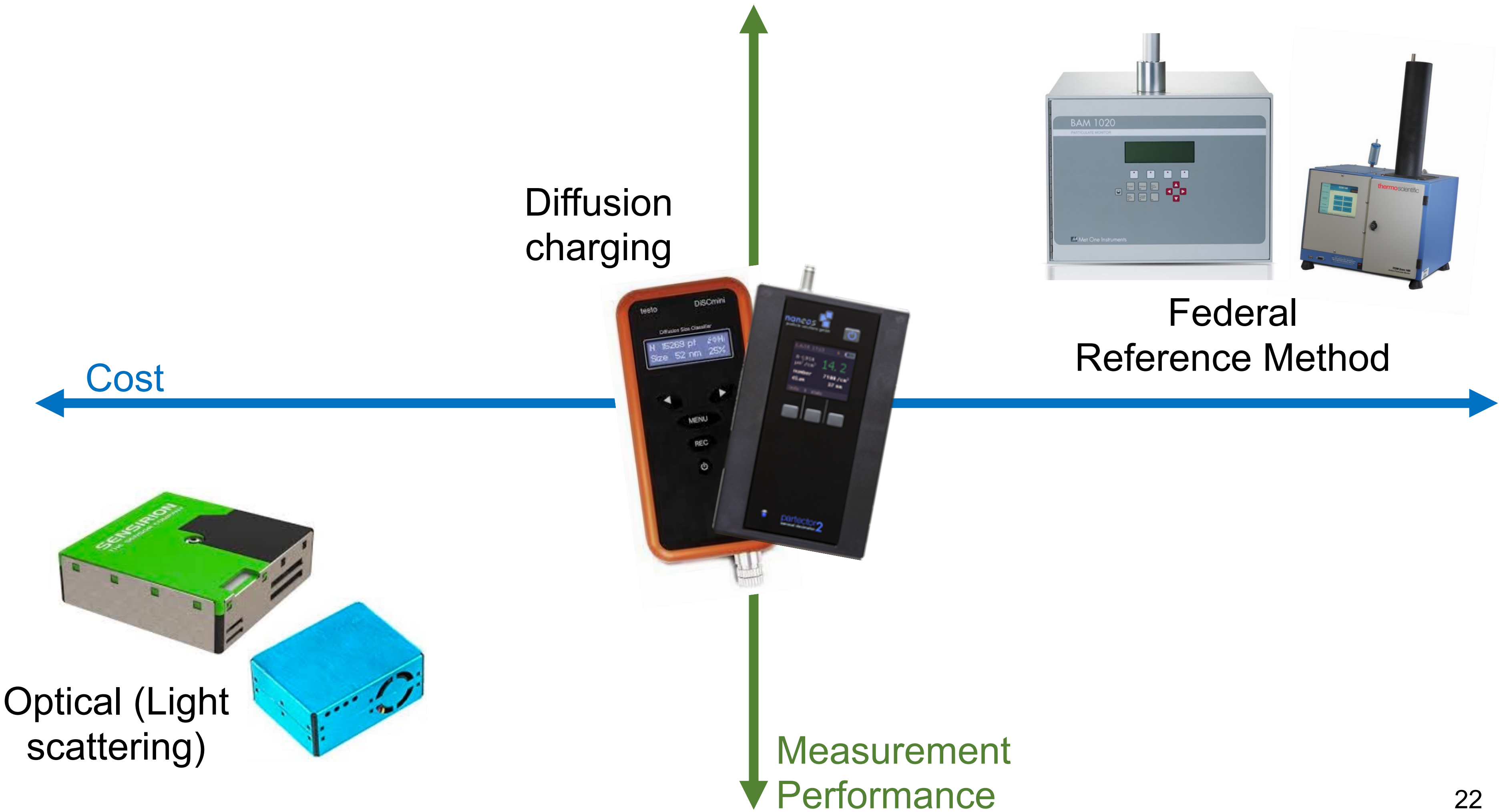
3. Real-time PM concentration data

- Identify operational periods to target for emissions reductions and characterize formation mechanisms



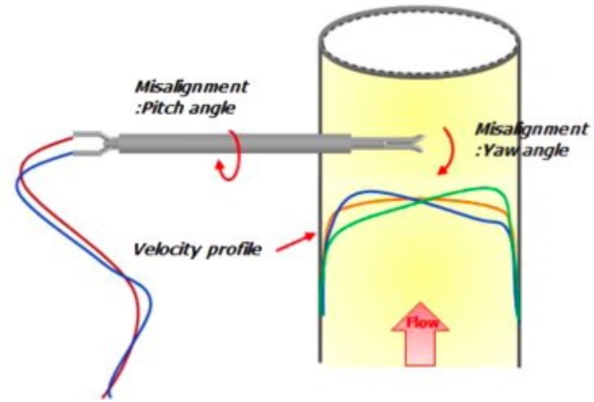
3. Real-time PM concentration data

- Lots of real-time PM monitors on the market to fit a variety of needs: **Leverage PM technologies for heater characterization**



4. Direct flue velocity measurement

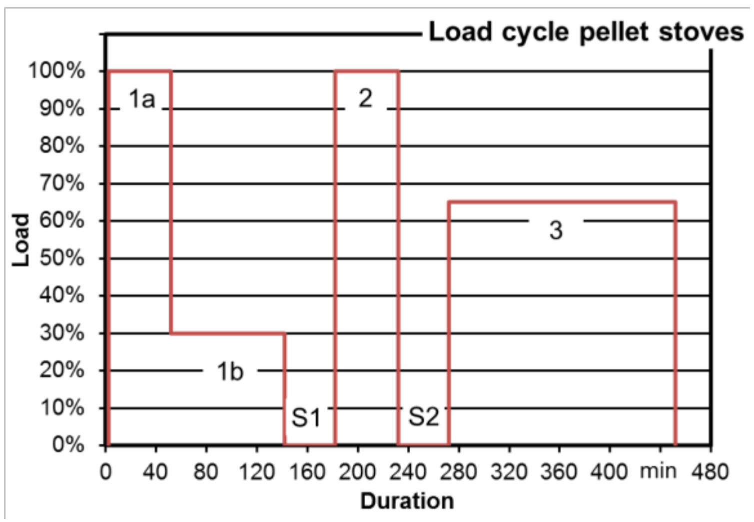
- Greatest source of uncertainty for both emissions and performance characterization
- Rely on fuel mass balance subject to inaccuracies
- Measure directly for better characterization
- Difficult to measure at residential scale: Develop new hardware and methods
- Pitot tube, integrating grid, or hot-wire anemometer



5. "Real world" test cycles

- Standard test cycles useful for characterization and comparison, but not for evaluating impacts on human health and environment
- Develop test cycles that more closely resemble field operation
- Lab and field results can be compared more meaningfully

BeReal Pellet Test Cycle



Phase	Operational mode	Load level	Duration
1a	Cold start	Nominal load: 100 %	50 min
1b	Load change	Partial load: 30 %	90 min
S1	Standby	0 %	40 min
2	Warm start	Nominal load: 100 %	50 min
S2	Standby	0 %	40 min
3	Warm start	Partial load: 65 %	180 min
			Σ: 7.5 h

Conclusion

1. Biomass heaters are an important energy source, but their air quality impact can and should be reduced
2. Characterize heater performance to inform design and implementation improvements
3. Focus on emissions and thermal performance: Current methods presented
4. Research efforts focus on making heater testing more accessible, accurate, and representative of field operation

Thank you!

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