A HEAT TRANSFER MODEL FOR CONCEPTUAL DESIGN OF BIOMASS COOKSTOVES

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MECHANICAL ENGINEERING

THE DESIGN PROCESS

1. Determining user needs and preferences
2. Design specification
3. Conceptual design ←
4. Preliminary design
5. Detailed design
6. Manufacture
7. Delivery/implementation

(Pugh, 1990)

CONCEPTUAL MODEL

- Tool to drive design
- Practical equations to use for design today
- Compare stoves without building

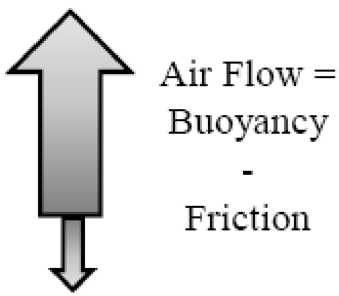
COOKSTOVE MODELING

Eindhoven

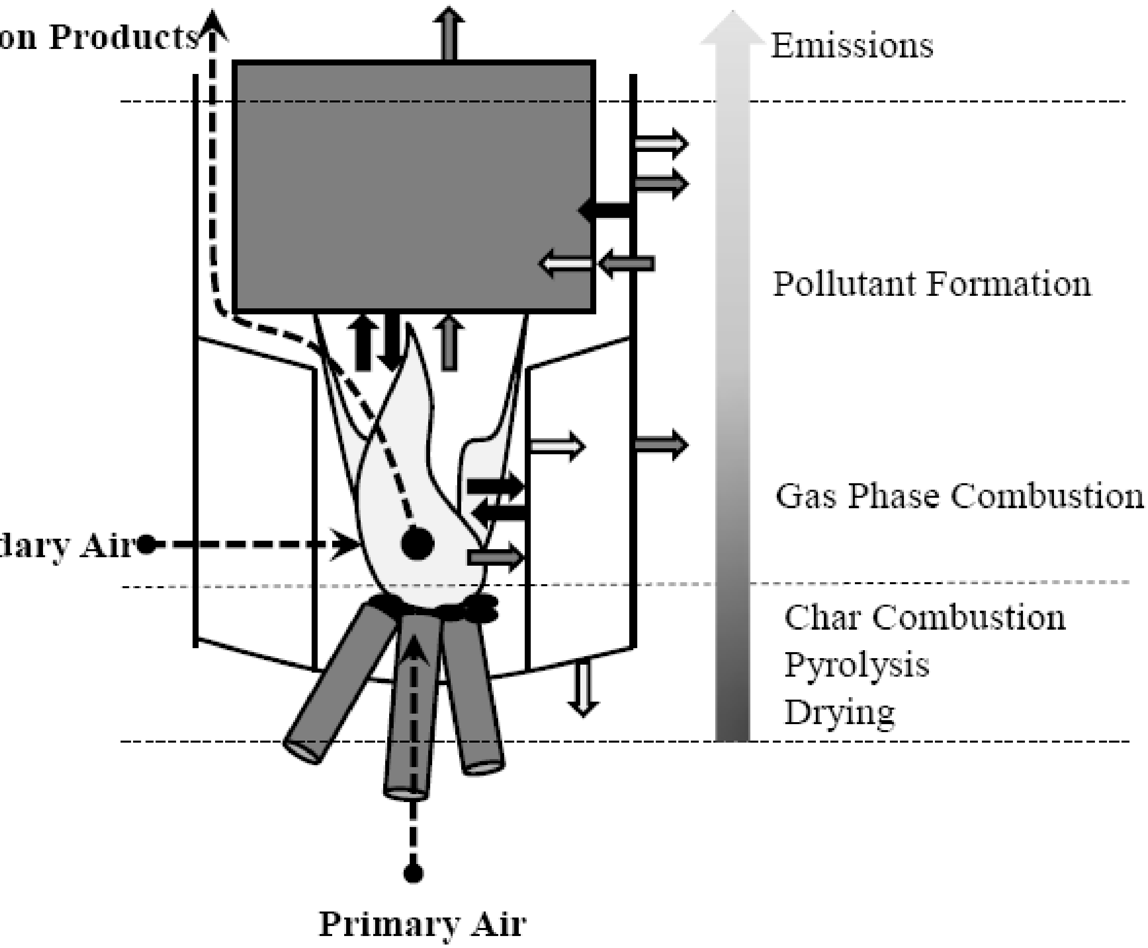
Baldwin

Date

CFD



NO EXISTING GENERALIZED EQUATION SET



DESIGN VARIABLES

Operating Variables

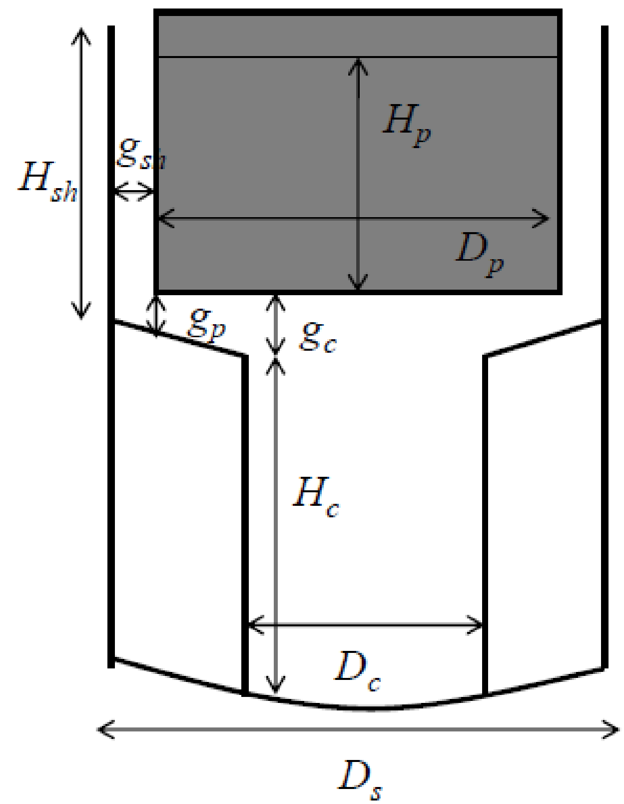
- Firepower
- Fuel Moisture
- Pot Diameter
- Water Volume

Material Variables

- Body conductivity
- Shield thickness & conductivity

14 total variables

Geometrical Variables



MODEL CONSTRUCTION

Assumptions

- Steady State
- Axisymmetric
- Complete & instantaneous combustion
- Uniform mixing & temperature distribution
- Air as ideal gas

Constraints

- $D_c < D_p$
- $H_c > 0.1$ m
- Cylindrical
- Flat-bottomed pot
- Only validated within variable ranges from experiment

MODEL VALIDATION BY EXPERIMENT

Validated & Optimized to published data

- Wood
- Sufficient detail provided
- Single pot flat-bottomed pot

63 points of varying design

- Bussmann, 1986
- MacCarty, 2010
- Jetter, 2012

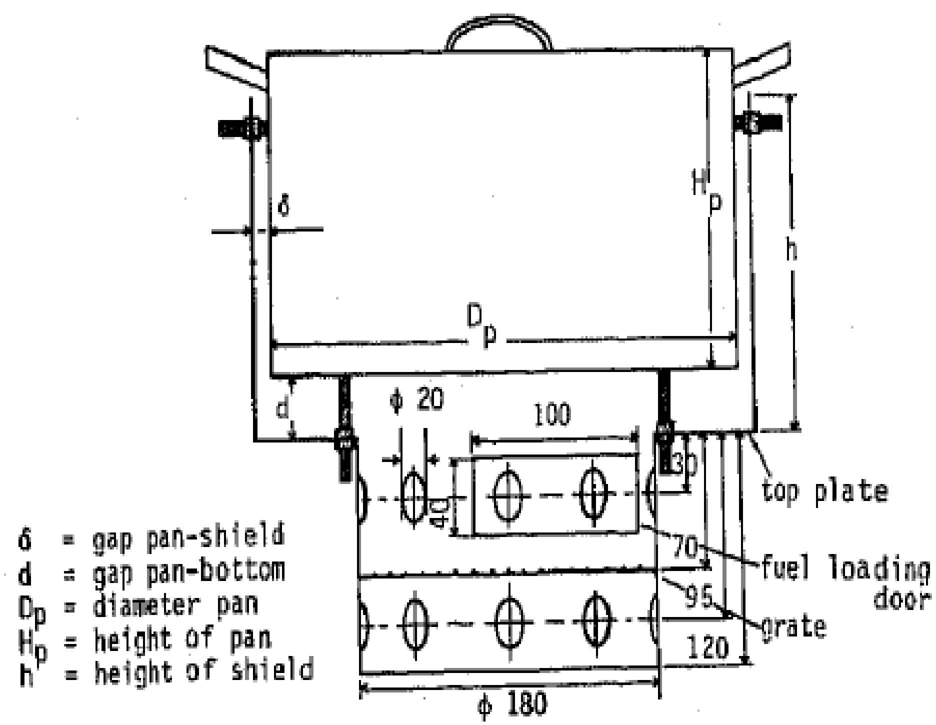


Fig. 1. Standard configuration of the stove.

FLUID FLOW

Flow = Buoyancy - Losses

$$\frac{1}{2}\rho_{exit}V_{exit}^{2} = g(H_c + g_c + H_p)(\rho_{amb} - \rho_{exit}) - \sum_i \rho_i \frac{V_i^2}{2}\left(\frac{f_{D,i}x_i}{D_{h,i}} + K_{f,i}\right)$$

F -- friction factor, determined from Moody diagram

K -- loss coefficient for bends, expansions, & contractions, determined from literature correlations

HEAT TRANSFER

Blackbody Radiation w/ adjustment factor φ=0.2

Wall losses 1-D thermal resistance analog

Pot Bottom

$$\overline{\mathrm{Nu}}_{p,bottom} = 0.248\,\mathrm{Re}_{D_c}^{0.809}\left(D_p / D_c\right)^{-0.484}$$

Pot Sides

- Shielded
- Unshielded

$$\overline{\mathrm{Nu}}_{p,side} = 0.001\,\mathrm{Re}_{D_c}^{1.385}\left(g_{sh} / r_p\right)^{-0.053}$$

$$\mathrm{Nu}_x = 0.0296\,\mathrm{Re}_x^{4/5}\,\mathrm{Pr}^{1/3}$$

ENERGY BALANCE

Conservation of energy in the char zone

$$\dot{m}_{ch} HHV_{ch} = \dot{m}_{g,ch}\left(h_b - h_{amb}\right) + \phi_{fl}\varepsilon_{ch}\sigma A_b F_{b-p}\left(T_f^4 - T_p^4\right) + \phi_g \varepsilon_{ch}\sigma A_b\left(1 - F_{b-p}\right)\left(T_b^4 - T_{wall}^4\right)$$

Conservation of energy in the flame zone

$$\dot{m}_v HHV_v + \dot{m}_{g,ch}\left(h_b - h_{amb}\right) = \left(\dot{m}_g - \dot{m}_{g,ch} - \dot{m}_w\right)\left(h_{fl} - h_{amb}\right) + \dot{m}_{g,ch}\left(h_{fl} - h_{amb}\right) + \dot{m}_w\left[\bar{c}_{p,\mathrm{H_2O}}\left(T_{fl} - T_{amb}\right) + h_{fg,\mathrm{H_2O}}\right]$$

Conservation of energy in the combustion chamber

$$\left(\dot{m}_g - \dot{m}_w\right)\left(h_{in} - h_{out}\right) = \frac{\phi_g \sigma A_{wall}\left(\frac{A_{p,rad}}{A_{wall}} F_{b-wall}\right)\left(T_{wall\,\mathrm{int},i}^4 - T_p^4\right)}{H_c / x} + \frac{\phi_{fl}\varepsilon_{ch}\sigma A_b\left(F_{b-wall}\right)\left(T_{wall\,\mathrm{int},i}^4 - T_b^4\right)}{H_c / x} + \dot{m}_w \bar{c}_{p,\mathrm{w}}\left(T_{out} - T_{in}\right) + q_{wall}$$

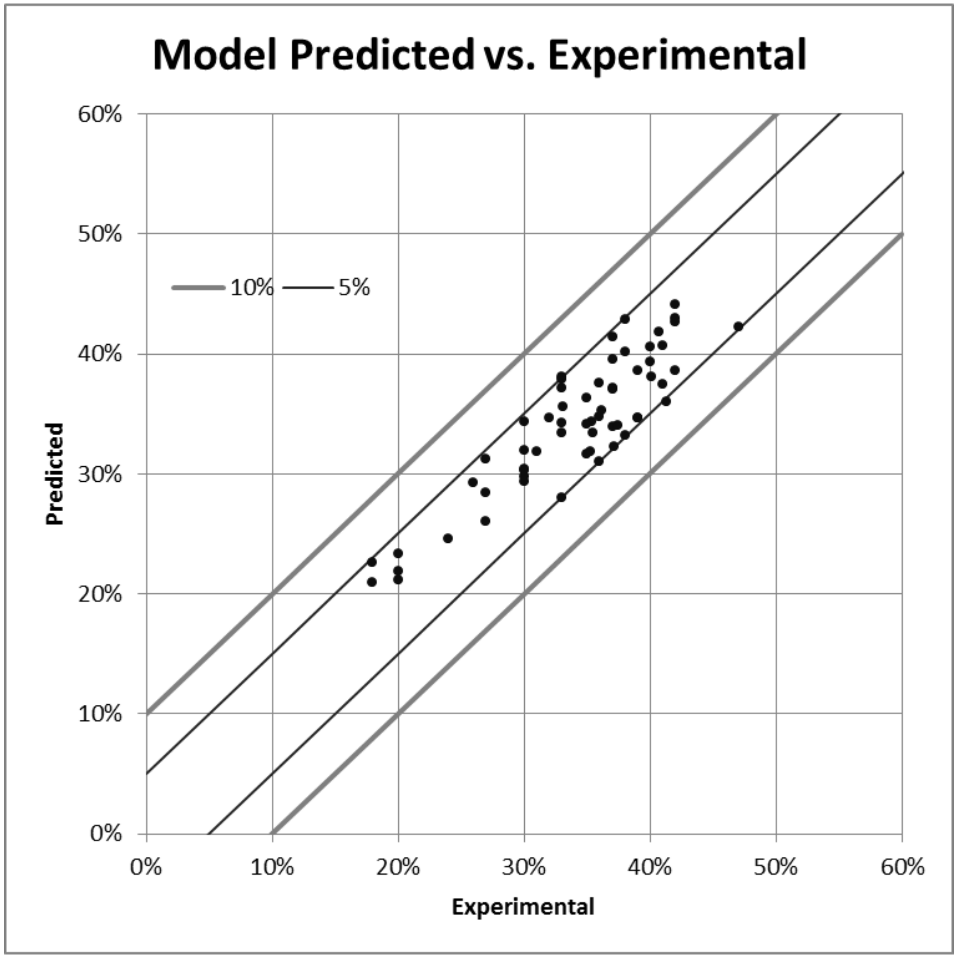
where

$$q_{wall} = \frac{T_{in} - T_{amb}}{R_{conv,\mathrm{int}} + R_{cond} + R_{conv,ext}} = \frac{T_{in} - T_{wall\,\mathrm{int},i}}{R_{conv,\mathrm{int}}} = \frac{T_{wallext,i} - T_{amb}}{R_{conv,ext}}$$

$$R_{conv,ext} = \frac{1}{2\pi r_c x\left(1.42\left(\frac{T_{wallext,i} - T_{amb}}{H_s}\right)^{0.25} + \sigma\varepsilon_{wall} A_{wall}\left[\frac{T_{wallext,i}^4 - T_{amb}^4}{T_{wallext,i} - T_{amb}}\right]\right)}$$

$$R_{conv,ext} = \frac{1}{2\pi r_c x\left(1.42\left(\frac{T_{wallext,i} - T_{amb}}{H_s}\right)^{0.25} + \sigma\varepsilon_{wall} A_{wall}\left[\frac{T_{wallext,i}^4 - T_{amb}^4}{T_{wallext,i} - T_{amb}}\right]\right)}$$

MODEL PREDICTION OF THERMAL EFFICIENCY



60/63 points:
predicted within 5.3%

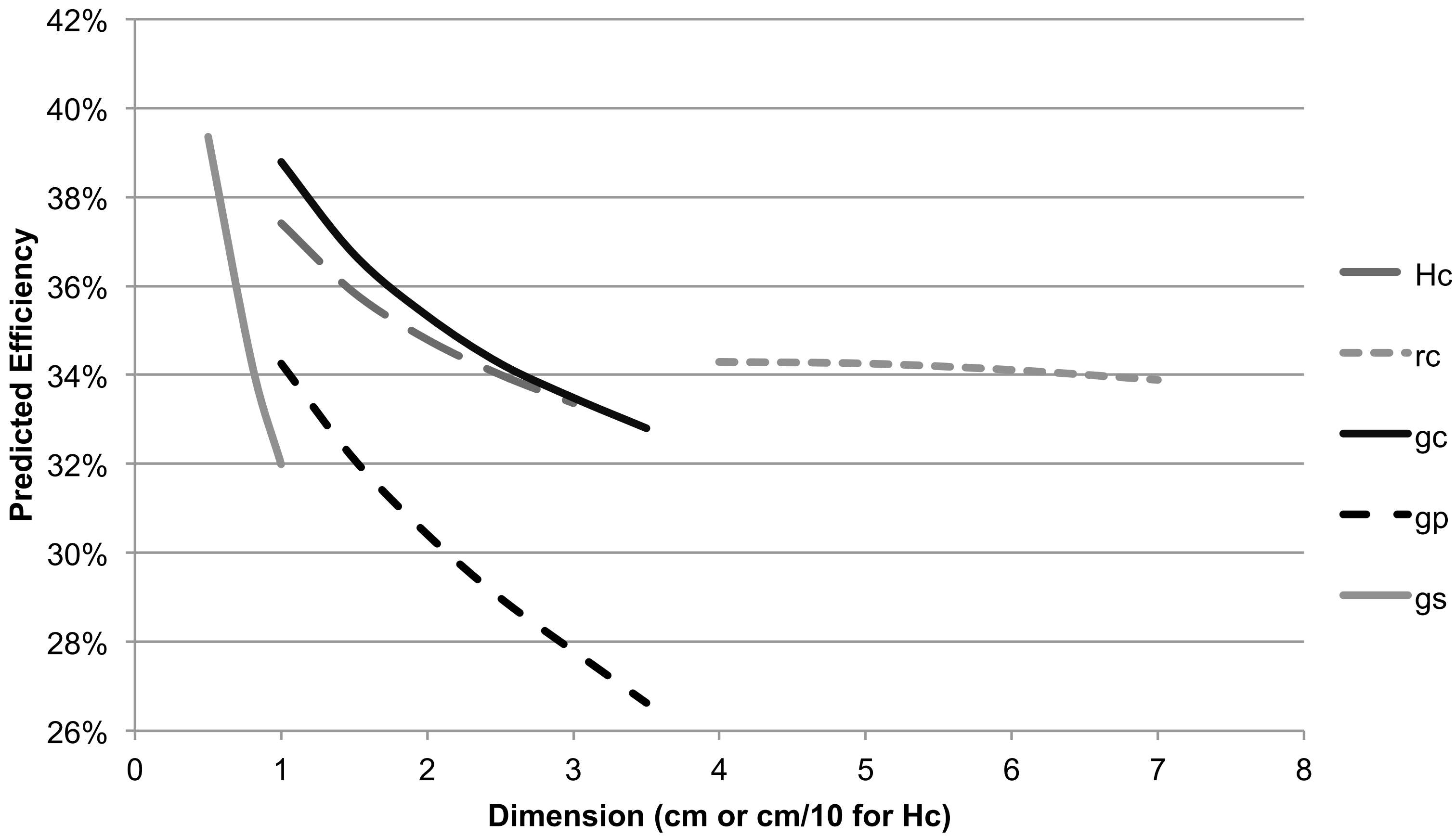
3/63 points:
pressure loss>buoyancy

Experimental efficiency via WBT expected to have up to 10% error (Taylor, 2009)

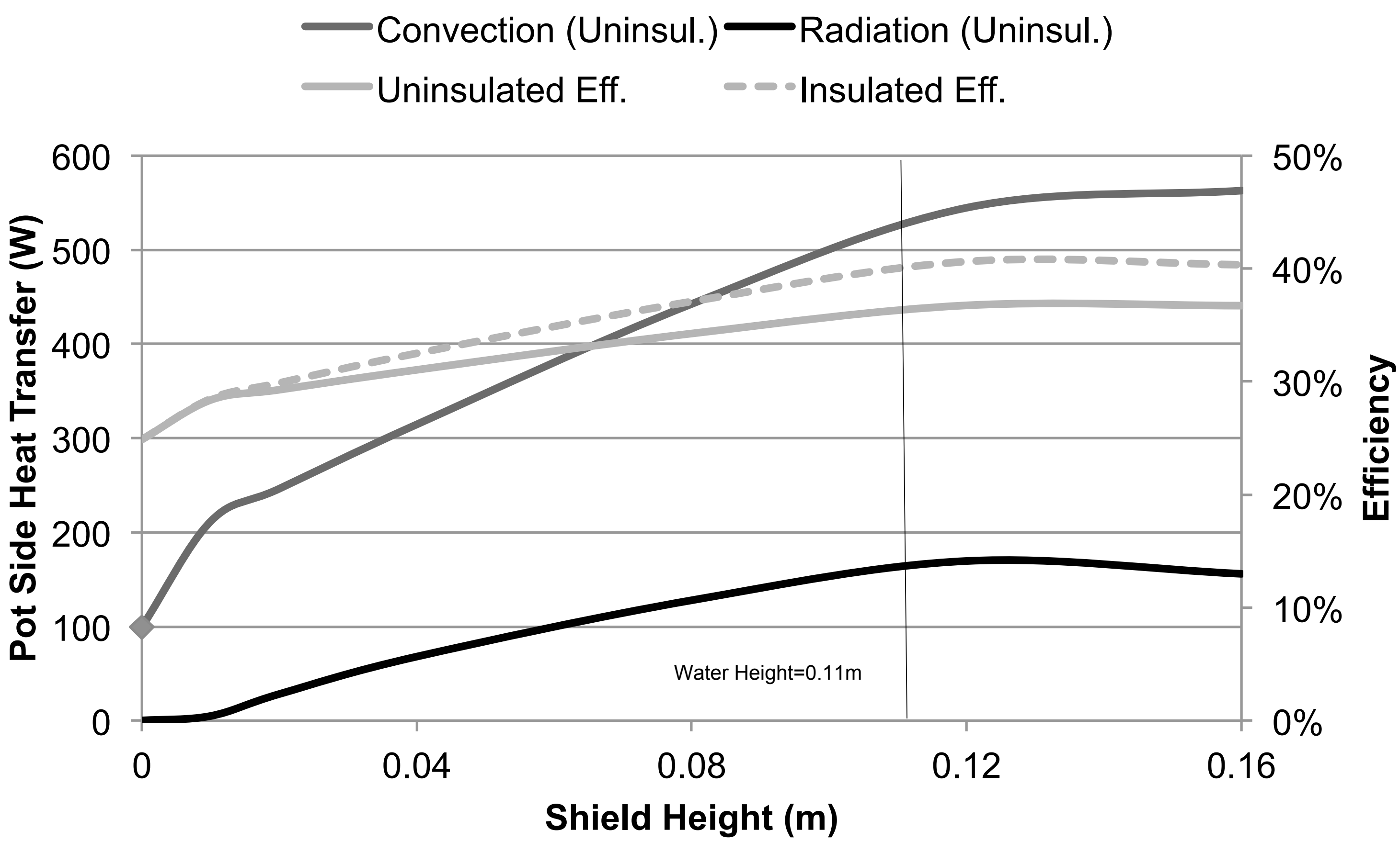
OPERATING VARIABLES

Firepower (W)	MC	η
2000	15%	29.3%
	20%	29.2%
	25%	29.1%
	30%	29.0%
5000	15%	35.3%
	20%	35.0%
	25%	34.7%
	30%	34.4%

GEOMETRICAL SENSITIVITY



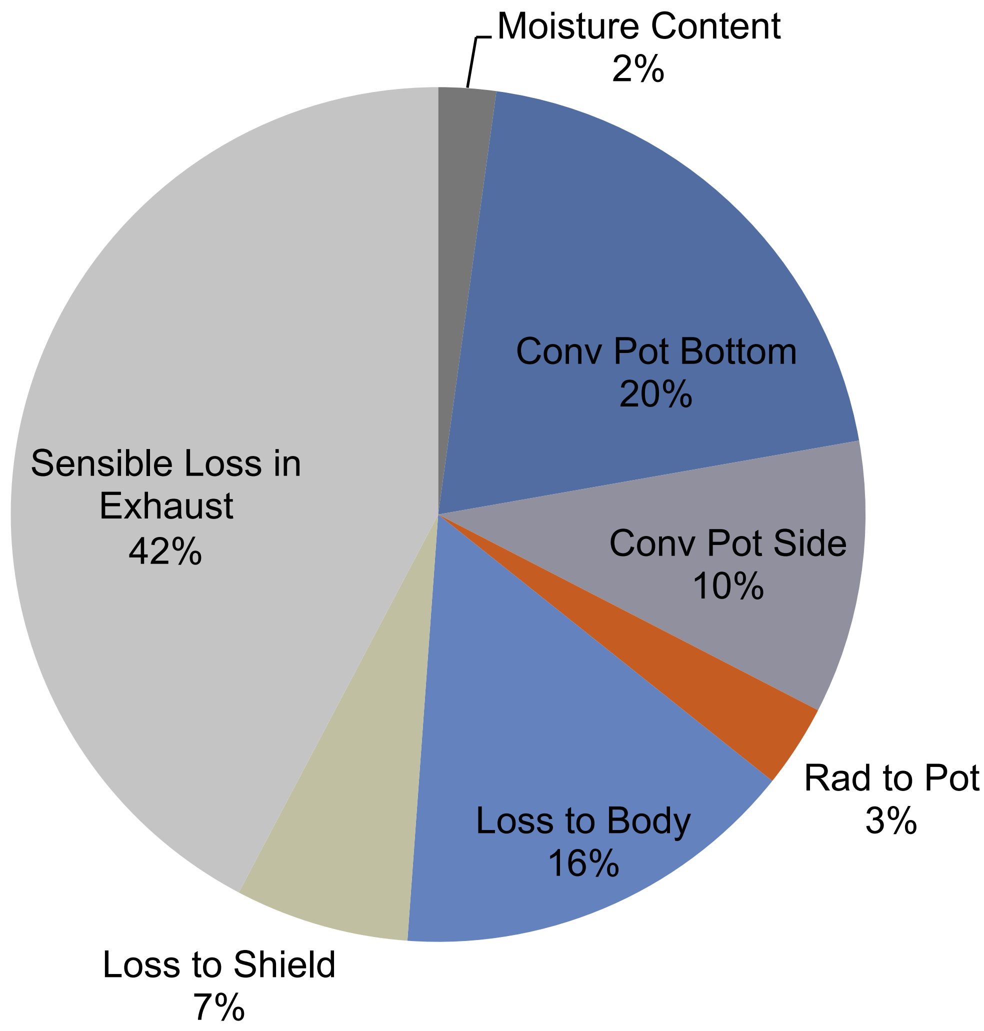
EFFECTS OF SHIELD



MATERIAL STUDY

Body Material	Conductivity (W/m^2K)	Predicted Efficiency
Fiberglass/perlite	0.04	42.3%
Pumice	0.43	36.2%
Fireclay brick	1.0	34.3%
Cement mortar	1.73	33.4%
Sheet metal	35	34.4%

ENERGY FLOWS



CONCLUSIONS

- **Thumb rules confirmed**
- **Study variables without experiment**
- **Preliminary/conceptual design before detailed design:**
  - CFD
  - Prototypes
  - Lab & field experiment
- **Engineering judgment**
- **Stoves need more experimental data with sufficient detail for creating models**

FUTURE WORK

- **Submit for publication:**
  1. Literature review
  2. Model
  3. Conceptual design article
     - Present at DETC conference
- **Add emissions predictions**

THANK YOU

Questions?