Computational Modelling of Biomass Stoves: A Literature Review

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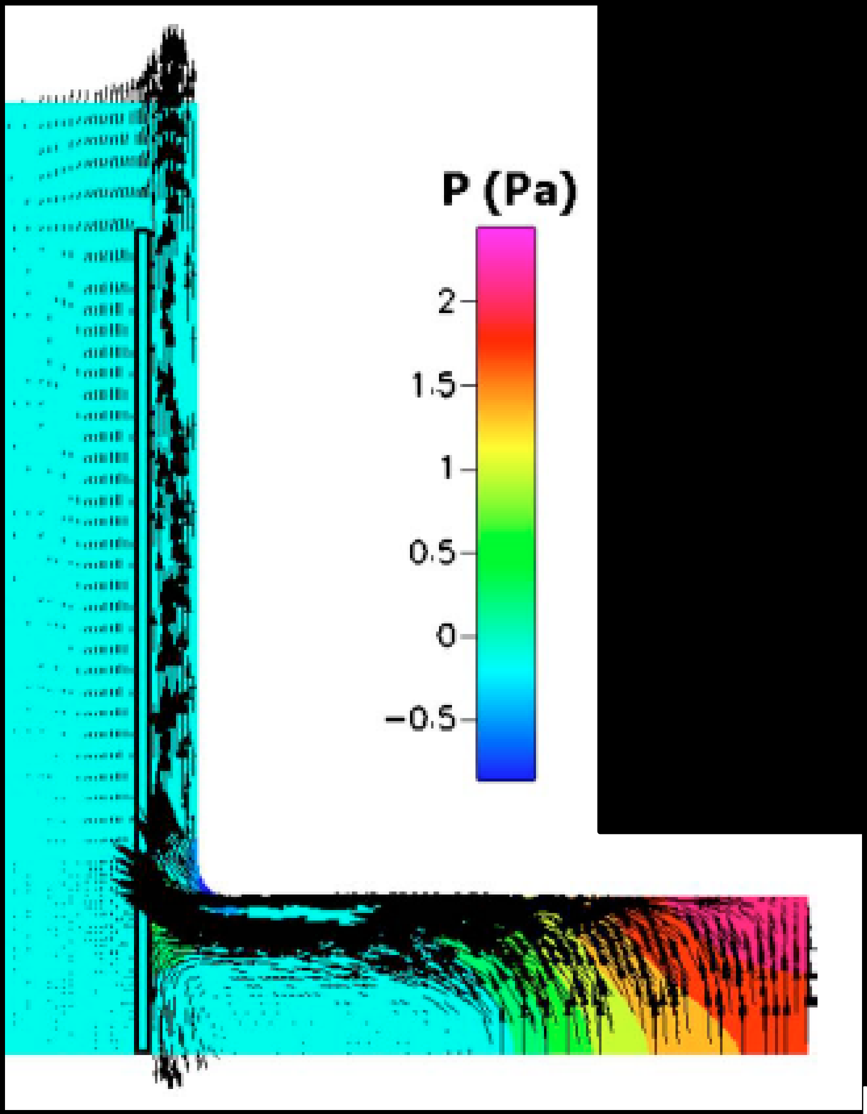
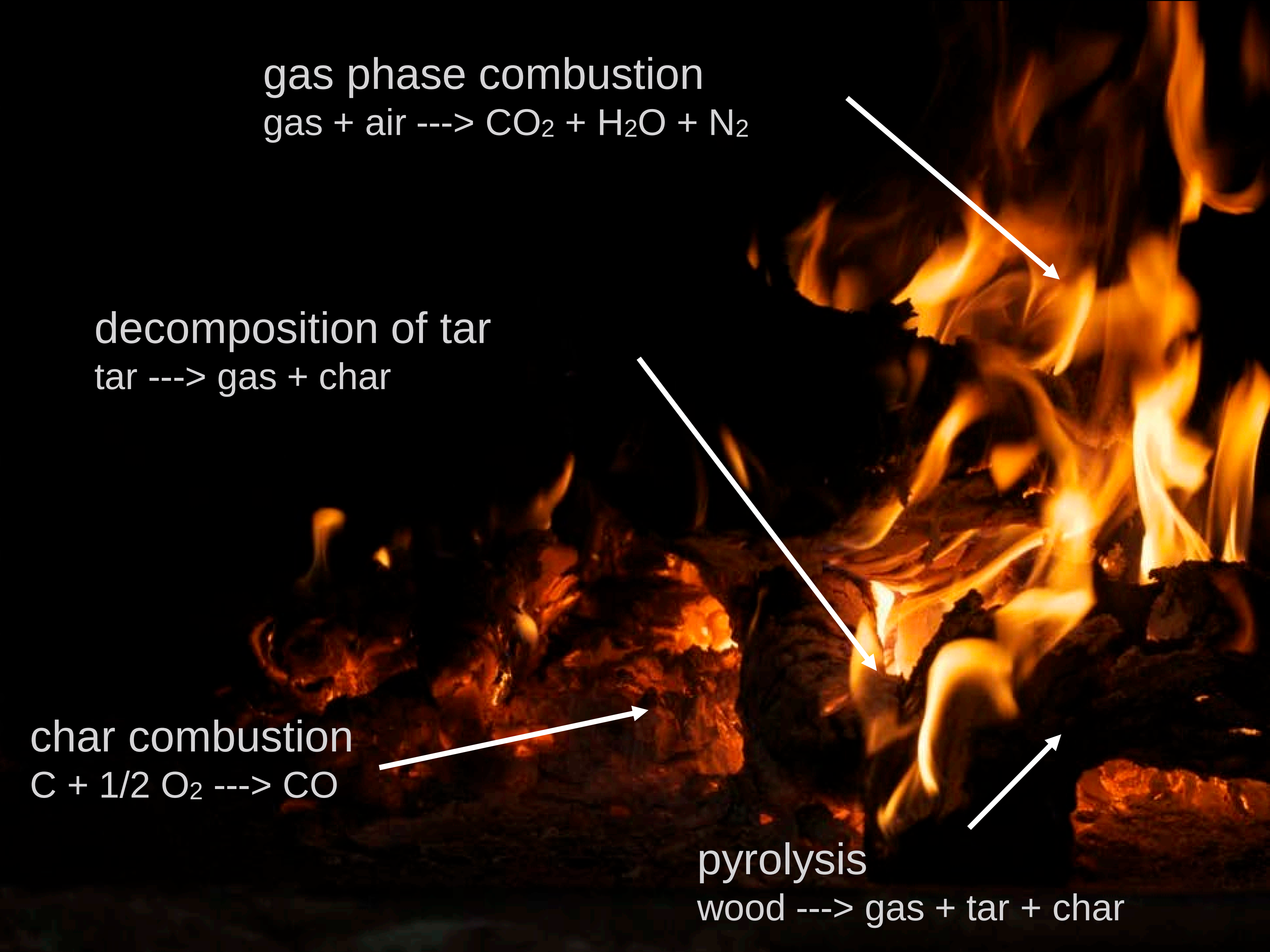
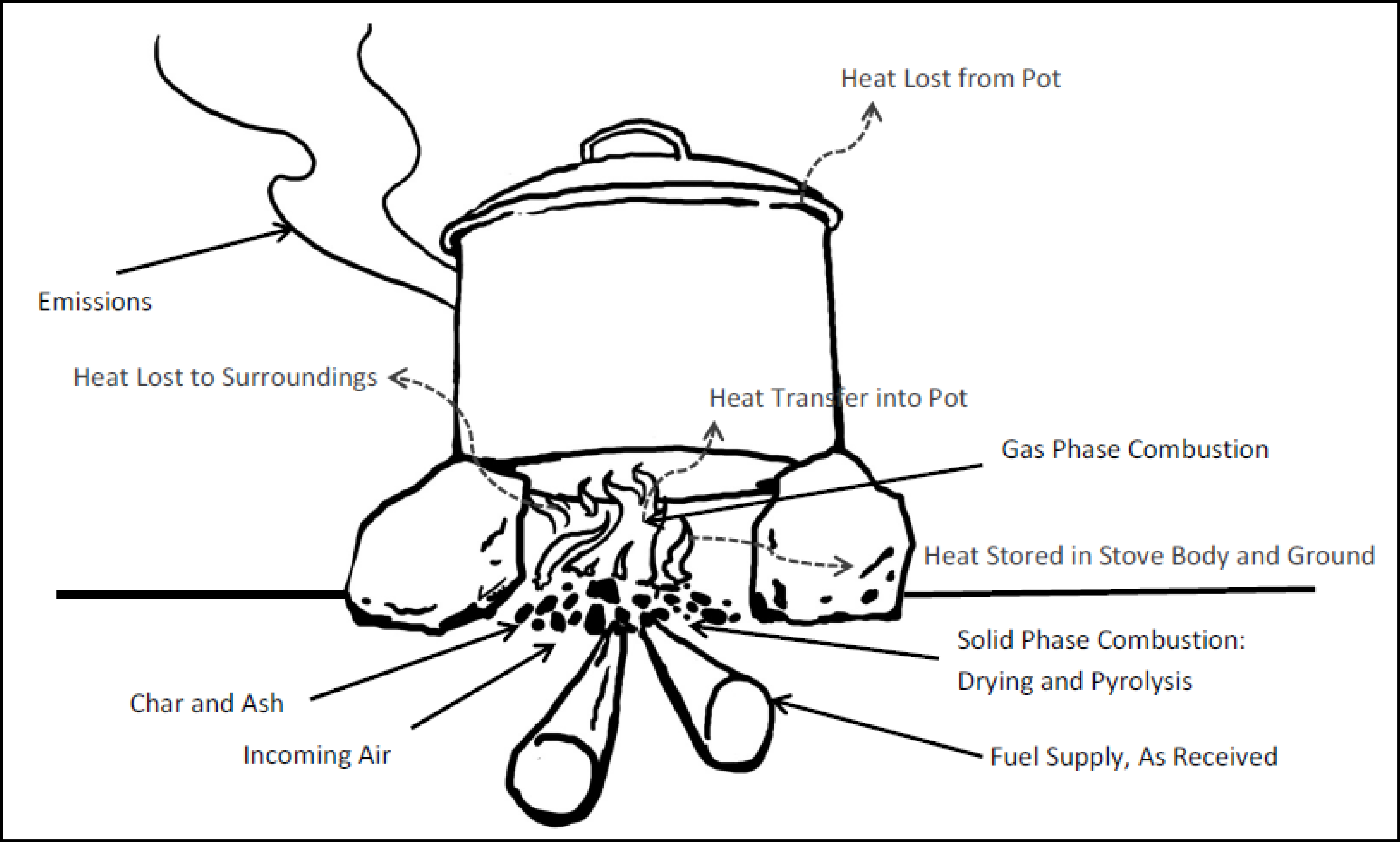
Why Model?



- Understand processes within a stove
- Predict effects of design/input changes without extensive experimentation
- Use algorithms to optimize design geometry

Image: Wohlgemuth, 2009


gas phase combustion
gas + air ---> CO_2 + H_2O + N_2
decomposition of tar
tar ---> gas + char
char combustion
C + 1/2 O_2 ---> CO
pyrolysis
wood ---> gas + tar + char


Heat Lost from Pot
Emissions
Heat Lost to Surroundings
Heat Transfer into Pot
Gas Phase Combustion
Heat Stored in Stove Body and Ground
Solid Phase Combustion:
Drying and Pyrolysis
Char and Ash
Incoming Air
Fuel Supply, As Received

Every process can be explained mathematically…

- Solid phase combustion
  - Drying, pyrolysis, char combustion rates
- Gas phase combustion
  - Species evolution, heat release in flame, and pollutant production
- Fluid flow and heat transfer
  - Draught and excess air
  - Heat transfer to stove, pot, and surroundings

History of Stove Modelling

- 1980's
  - Eindhoven University (Prasad) – First mathematical descriptions
  - Princeton University (Baldwin) – Stove Design, Development, Dissemination
  - Asian Institute of Technology (Bhattacharya) - Charcoal
- 2000+
  - Indian Institute of Technology
    - (Ravi et al) – Sawdust Stove
    - (Date) – CTARA Stove
  - Indian Institute of Science
    - (Mukunda) – Reed-type Gasifier Stove, Sawdust Stove
  - UICT India (Kausley)– Harsha Stove
  - Iowa State University (Bryden) – Plancha Optimization
  - Colorado State University (DeFoort) – Rocket Elbow
  - Ohio State University (Andreatta) – Pot Skirt Model

Eindhoven Models: Flow and Heat Transfer

- Suction/draft in the stove is generated due to convection per Bernoulli's equation:

$$\Delta P_{1-2} = gh(\rho_{Amb} - \rho_H) = \frac{1}{2} f \rho_H v^2$$

- Convective heat transfer to pot:

Bottom

$$\frac{T_g - T_a}{T \; - T_a} = 0.9(r/D)^{-1.06}$$

$$Nu = \frac{h(r)D}{k} = 0.32 \Pr^{0.33} \mathrm{Re}_D^{0.7} \left(r_1 / D \right)^{-1.23}$$

Sides

$$\frac{T}{T_s} = 7.7 \frac{\rho_s}{\rho_a} \left(\frac{L+12}{b_s} \right)^{-0.6}$$

$$Nu_s = \frac{h(L)s}{k} = 0.25 \Pr \mathrm{Re}^{0.}$$

- Volumetric flow analysis:

From Flow Analysis

$$V_F = \frac{g \rho_0}{12 \mu} \left(1 - \frac{T_0}{T_2} \right) \left(\frac{d^3 DH}{L} \right) \left(\frac{T_0}{T_m} \right)$$

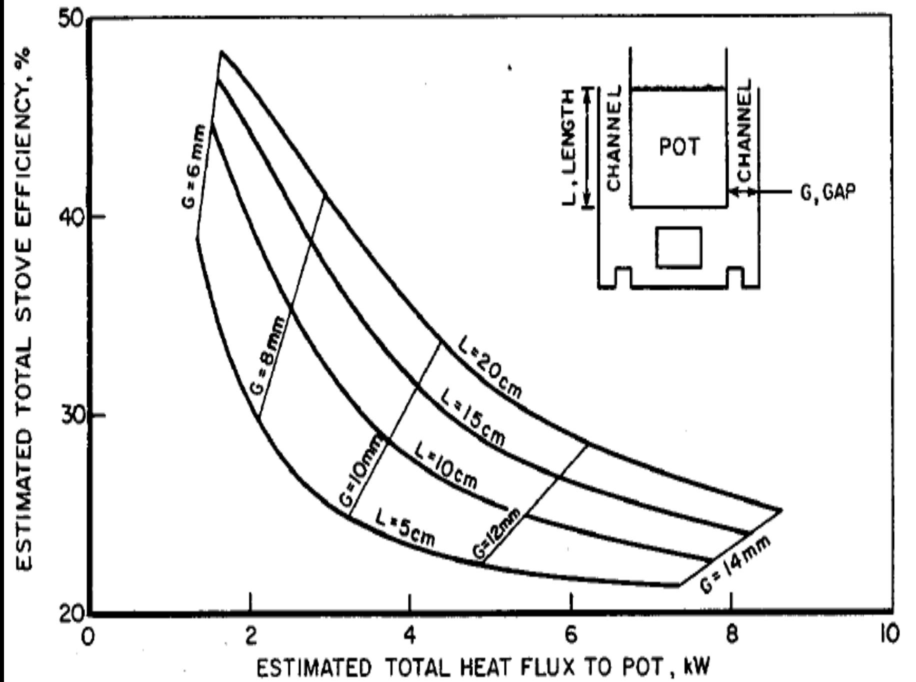
From Heat Transfer Analysis

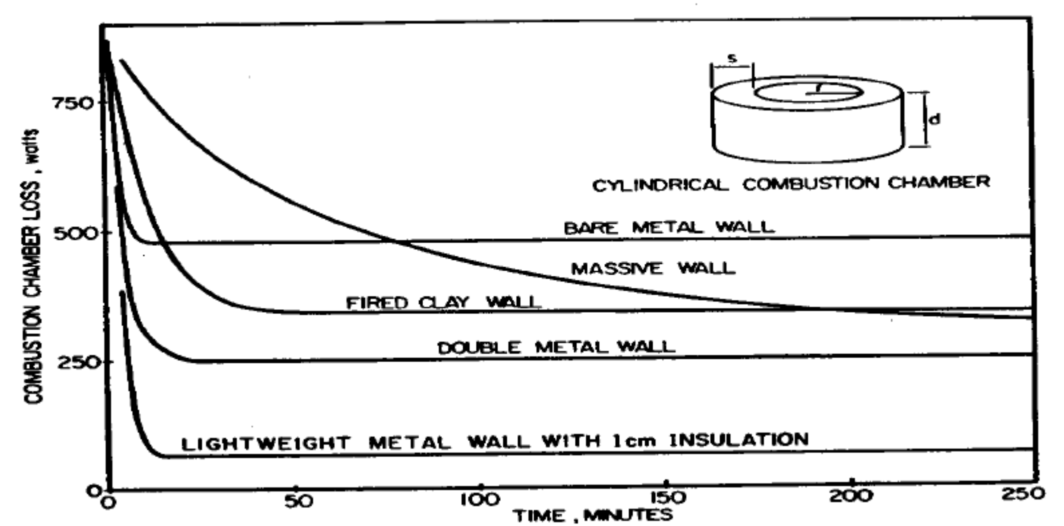
$$V_H = \frac{1.86^{3/2}}{2^{1/2}} \alpha_m \frac{T_0}{T_m} \frac{1}{\left(\ln \frac{T_1 - T_B}{T_2 - T_B} \right)^{3/2}} \frac{DL}{d}$$

Baldwin Model: Solid Combustion & Heat Transfer

- Uses 1st order finite difference method to solve:
  - Differential equations for 3 modes heat transfer, with experimentally known boundary conditions
  - Includes effects of thermal storage, insulation
  - Solid phase combustion including transient heat conduction, Arrheinus rate equation for pyrolysis, continuity, and char combustion

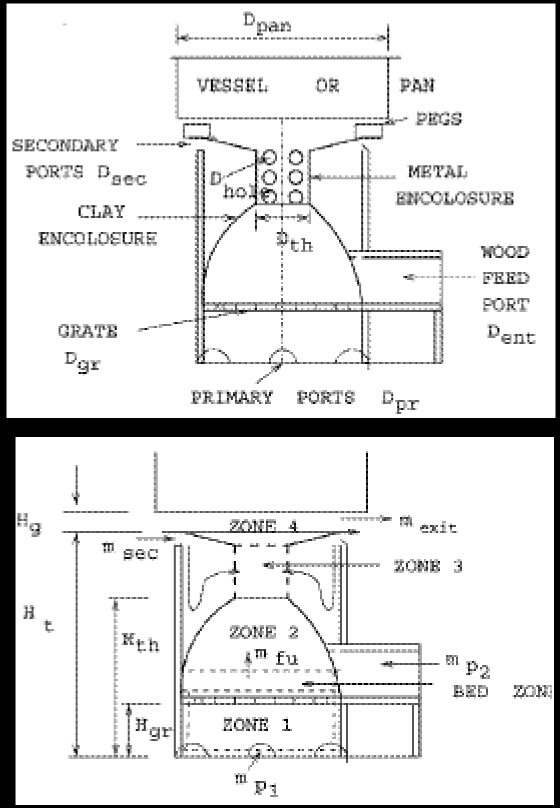
FIGURE 11A: Total stove efficiency versus heat flux to the pot as a function of channel gap and length for family sized stoves.





Date Model: Zonal model including gas species

- Assumed wood is fed to stove at exact burning rate, with constant burning surface area
  - Includes volatile calculation to predict CO_2, CO, H_2, H_2O, C_nH_{2n+2}
  - Charcoal (CO neglected)
  - Tar neglected
- Hautmann quasi-global 4-step reaction mechanism used to predict consumption/generation rates of each gas phase species (volatiles plus O_2, N_2)
- Effects of stove height, diameter, fuel parameters, cooking tasks studied



CTARA Stove

Bryden Model: Plancha Optimization

- CFD software to predict heat transfer through plancha
- Experimental input & validation
- Paired with evolutionary algorithms to optimized baffle placement

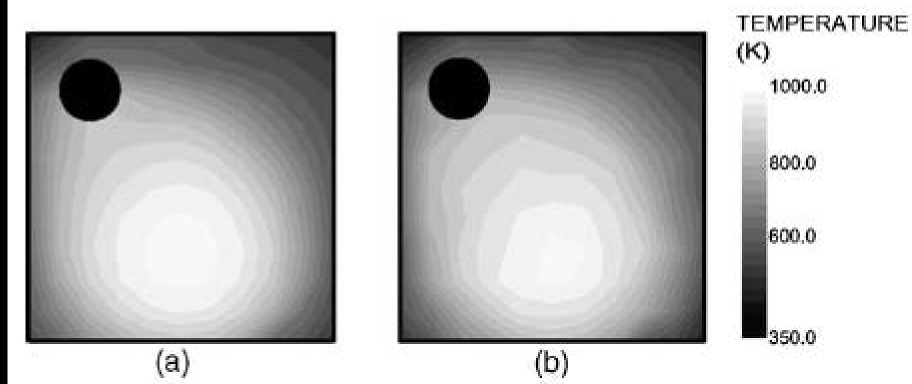
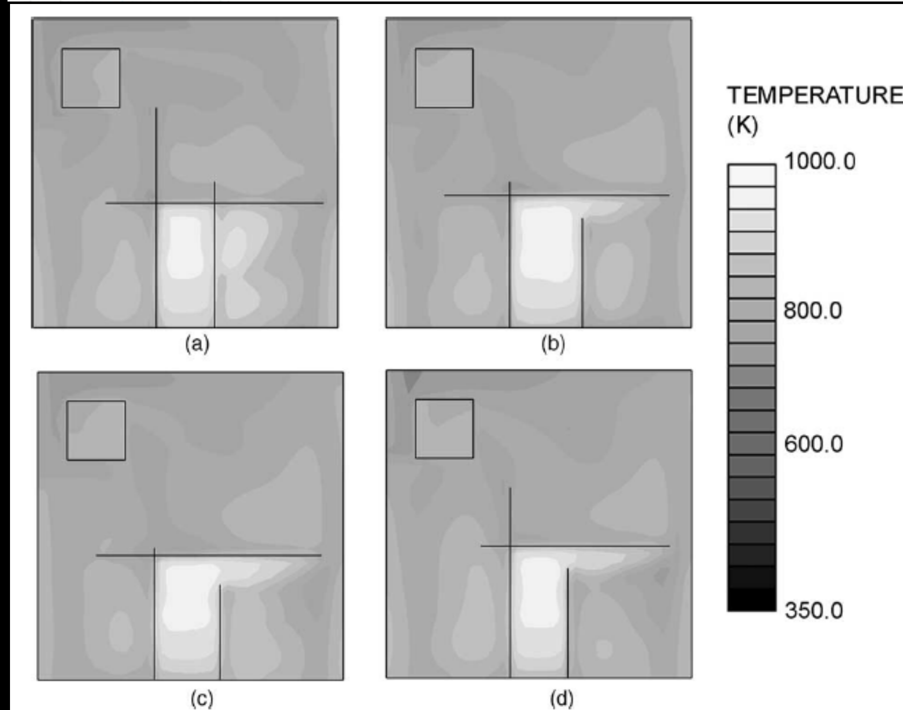


Fig. 3. Predicted (a) and measured (b) temperature distribution for an unbaffled stove.



What questions remain?

- Prediction of emissions
  - Emissions data is currently experimental
- Radiation heat transfer
  - Depends on particles
- Adaptive geometry
  - Current models allow only minor dimensional changes
- Pairing with optimization algorithms
  - Effects of geometry are tabulated individually rather than optimized as a whole

Conclusions

- Designs today based on models from the 1980's
- Powerful software makes detailed models possible now
- Little work is currently being published
- Models may indicate next best steps and/or find a "silver bullet"

Future Work

- Develop a complete zonal model
  - Pyrolysis
  - Gas Phase
  - Pollutant formation
  - Heat transfer
- Allow variable input parameters of geometry, fuel, cooking vessel and process, feeding method
- Validate experimentally
- Use genetic algorithms to find optimum design