Second Law Analysis and Exergy balance in biomass cookstoves

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Outline

- Natural convection driven biomass cooking stoves modelling issues
- Energy vs Exergy
- Methodology
- Entropy Generation Rate: Analytical modelling
- Validation
- Conclusion
- Reference

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Natural convection driven biomass cooking stoves modelling issues

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Natural convection driven biomass cooking stoves modelling issues

- The chimney effect taking place in biomass cooking stoves results from a conversion process between thermal and mechanical energy.

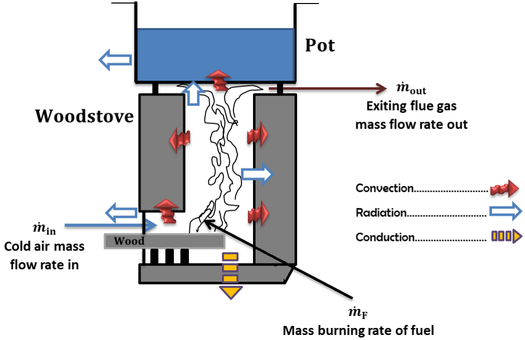


Figure: Schematic of a chimney woodstove cross-section with different heat-transfer modes.

Modelling issues

The loss coefficient - Fluid mechanics approach

The mass flow rate in the commonly form of the chimney effect equation is :

$$\dot{m}_A = CA\left(\frac{P}{RT_H}\right)\sqrt{2gh\left(\frac{T_H - T_{Amb}}{T_{Amb}}\right)} \qquad (1)$$

Where A is the flow area, h the chimney height, P the pressure, R the perfect gas constant, g the gravity constant and C the loss coefficient.
The efficiency of this conversion (thermal to mechanical) is assessed with the stove loss coefficient C.
The derivation of this C in cooking stove modelling is still uncertain.

Modelling issues

The loss coefficient - literature review

A literature review of variations in the stove flow LC

entropy-24-01019-v2.pdf

Table 1. Loss coefficient C in small-scale biomass cooking stove modelling.

Reference Authors	System Configuration	Highlights of the Study
MacCarthy [9]	Open cooking fire, Shielded cooking fire.	The study referred to various correlations in literature. Fluid flow constants and equations have been collected, deduced from a general balance of forces. However any specific value of C has been reported.
Agenbroad [21–23]	Stove without pot and Stove with pot.	Analytical stove flow modelling considered by default C remaining constant for stove operations: (a) C= 0.5 for stove without pot. (b) C = 0.35 for stove with pot. However, variable C depending on operating firepower level was experimentally observed. In theory, model accounted contributions for both losses due to viscous effects and losses due to distributed heat addition. In the assumption of a more realistic linear density profile, model suggested to replace C by the product $C = C_{viscous} \cdot C_{heat}$. Reduction of available chimney effect results in $C_{heat} = \frac{\sqrt{2}}{2} \approx 0.707$. CFD-based loss coefficient predicted stove behaviour using pressure drop with comparison to validation

Modelling issues

The loss coefficient - Thermodynamics approach

- From a purely fluid mechanics point of view, the LC being is associated with an overall pressure drop through the stove geometry
- However, from a thermodynamics point of view, in addition to fluid friction, as for any real process can present other kinds of irreversibilities associated with heat-transfer mechanisms, mixing, chemical reactions, etc., and all resulting in the loss of process efficiency related to the entropy-generation rate (2nd law of thermodynamics).
- Therefore, an energy devaluation (energy quality loss) manifests in a destruction of available work commonly known as exergy that can be assumed to be **losses of flow exergy.**

Outline

Energy vs Exergy

Quantity vs quality

The thermodynamic system equivalent to the simplified cooking stove model.

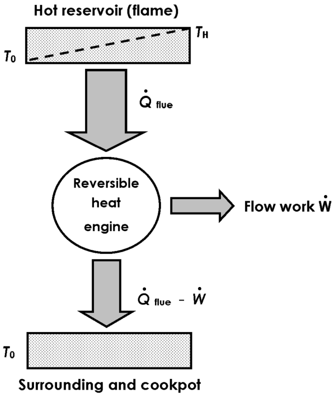


Figure: Open thermodynamic system in steady state equivalent to a reversible heat engine that operates between hot reservoir (flame) and atmospheric temperatures.

Energy vs Exergy

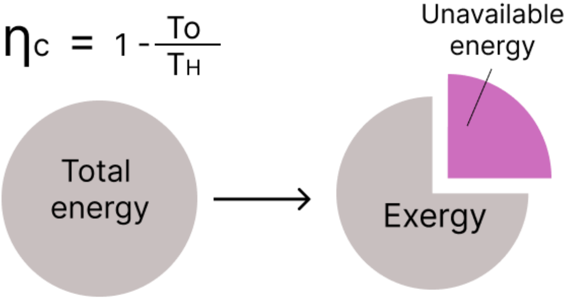
Quantity vs quality

Energy = Exergy + Anergy

Exergy = available energy

The Carnot factor

$$\eta_c = 1 - \frac{T_0}{T_H}$$



Energy vs Exergy

The mean Carnot factor by integration

The Carnot efficiency represents the fraction of the energy transferred from the heat source that can be converted to work.
According to the linear temperature profile, flame can be modeled as a heat reservoir along stove chimney height that supplies heat indefinitely at temperatures gradually raising from T_0 to T_H.

$$\eta_{c_1} = \frac{1}{T_H - T_0} \int_{T=T_0}^{T_H} \left(1 - \frac{T_0}{T}\right) dT \tag{2}$$

and

$$\eta_{c_1} = 1 - \frac{T_0}{T_H - T_0} \cdot \ln \frac{T_H}{T_0} \tag{3}$$

Exergy balance of the flowing fluid

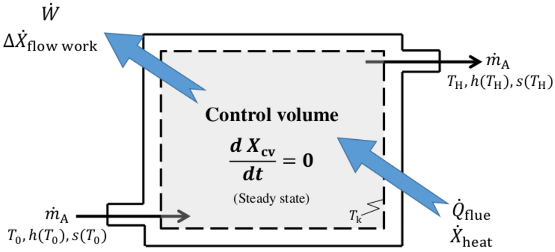


Figure: The rate of exergy change within the control volume $\dot{X}_{cv}$ is equal to the rate of net exergy transfer through the control volume boundary by heat $\dot{X}_{heat}$, work $\dot{W}$ and mass flow minus the rate of exergy destruction within the boundaries of the control volume. Note that in a steady state $\dot{X}_{cv}$ is zero.

The energy flux applied as flow work $\Delta\dot{X}_{flow}$ can be written:

$$\Delta\dot{X}_{flow} = \dot{X}_{mass,out} - \dot{X}_{mass,in} = \eta_{c_1} \cdot \dot{Q}_{flue} - \dot{X}_{destroyed,\ k} \quad (4)$$

Outline

Entropy generation rate equation

First case : Stove Operating without Cooking Pot

Starting from the Gibbs-Duhem equation, entropy generation resulting from the heat transfer and frictional pressure drop processes is:

$$\dot{S}_{gen} = \underbrace{\dot{m}_A \bar{c}_p \cdot \ln \frac{T_H}{T_0}}_{\dot{S}_{gen_{(heat)}}} + \underbrace{K \dot{m}_A g h_c \cdot \left(\frac{1}{T_0} - \frac{1}{T_H - T_0} \cdot \ln \frac{T_H}{T_0} \right)}_{\dot{S}_{gen_{(viscous\ \ and\ \ frictional\ \ pressure\ \ drop)}}} \quad (5)$$

- **frictional irreversibilities are very negligible compared to heat transfer irreversibilities !!!**

The rate of exergy loss (or exergy destruction) of useful work is given by the Gouy-Stodola theorem:

$$\dot{X}_{destroyed} = T_0 \cdot \dot{S}_{gen} \quad (6)$$

Entropy generation rate equation

Second case : Stove Operating with Cooking Pot

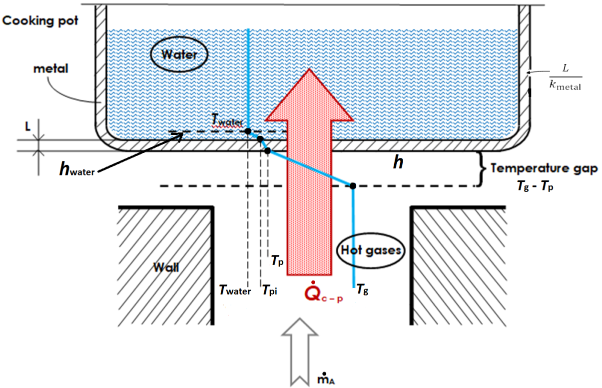


Figure: Hot gases at temperature T_g convect a certain amount of energy $\dot{Q}_{c-p}$ to the external pot surface at temperature T_p. Then the heat is conducted through the metal (pot) of small thickness and finally convected from the internal surface of the pot at temperature T_{pi} into water at temperature T_{water}.

Entropy generation rate equation

Second case : Stove Operating with Cooking Pot

The entropy-generation rate in the temperature gap between hot gases and the external pot surface can be written:

$$\dot{S}_{gen_{(c-p)}} = \frac{\dot{Q}_{c-p}}{T_p} - \frac{\dot{Q}_{c-p}}{T_g} = \dot{Q}_{c-p} \cdot \frac{(T_g - T_p)}{T_g T_p} \qquad (7)$$

The loss of exergy as a result of this irreversibility is:

$$\dot{X}_{destroyed_{(c-p)}} = T_0 \cdot \dot{S}_{gen_{(c-p)}} = \frac{T_0}{T_p}\left(1 - \frac{T_p}{T_g}\right) \cdot \dot{Q}_{c-p} = \eta_{c_2} \cdot \dot{Q}_{c-p} \qquad (8)$$

Entropy generation rate equation

Second case : Stove Operating with Cooking Pot

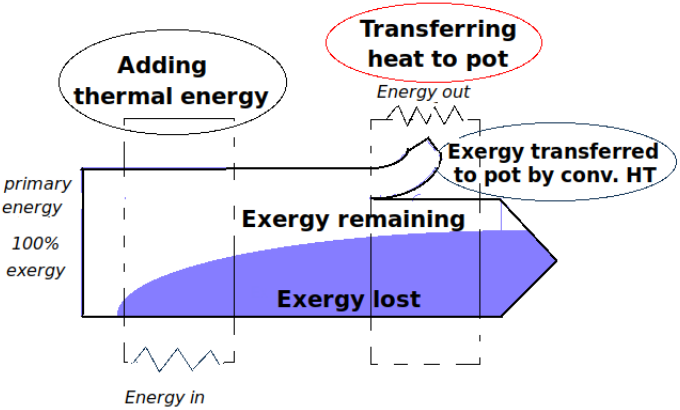


Figure: The value diagram of exergy destruction (loss) in a natural convection-driven woodburning stove operating with a pot.

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The stove

Figure: G3300 envirofit cookstove model.

Experimental (Lab-based tests)

- Measurements of air flow mass rate, flue gas temperatures at different firepowers have been done
- The relationship between firepower, T, $\dot{m}_A$ has been analyzed.
- In practice, differing firepowers is achieved by varying by hand the fuel-feed rate and fuel spacing.

Recall 1 : Extract the loss coefficient C in

$$\dot{m}_A = CA\left(\frac{P}{RT_H}\right)\sqrt{2gh\left(\frac{T_H - T_{Amb}}{T_{Amb}}\right)} \tag{9}$$

Recall 2: Calculate the Carnot factor η_{c_1} from

$$\eta_{c_1} = 1 - \frac{T_0}{T_H - T_0} \cdot \ln\frac{T_H}{T_0} \tag{10}$$

Carnot factor and Loss coefficient calculations

First case : Stove Operating without Cooking pot

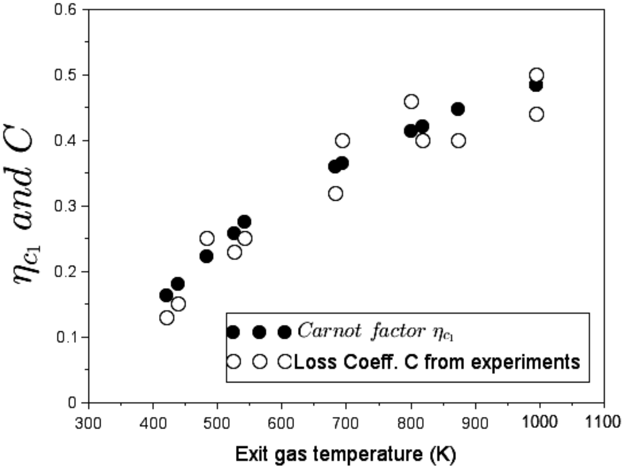

Figure: The Carnot factor η_{c_1} and the loss coefficient C in function of the flue gas temperature for the G3300 stove without pot.

Carnot factor and Loss coefficient calculations

Second case : Stove Operating with pot

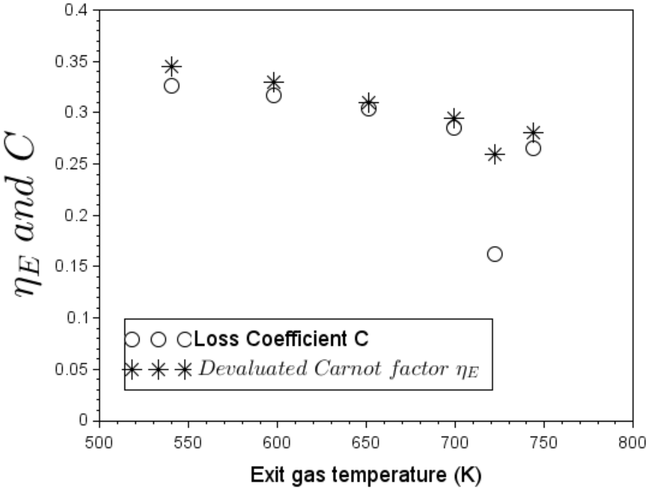

Figure: Values of devaluated exergy Carnot factor parameter compared to loss coefficient.

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Second law analysis and exergy balance bring quite a new perspective to the traditional concept of the so-called loss coefficient. From now, this flow loss coefficient can rather be regarded as the availability of internal energy to generate flow work through the stove depending upon operating conditions and consecutive energy-transfer processes undergone following the stove operating at high or low firepower levels.

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Reference

- Augustin, L.M.; Vertomene,S.T.; Bernard, N.N.; Sadiki, A.; Haddy, M.K. A New Perspective on Cooking Stove Loss Coefficient Assessment by Means of the Second Law Analysis. Entropy 2022, 24, 1019. https://doi.org/10.3390/e24081019

Thank you !