Breeding a Better Stove: the Use of Genetic Algorithms and Computational Fluid Dynamics to Improve Stove Design

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Abstract

Half the world cooks using wood, often on open fires or on inefficient stoves. Collecting firewood is often left to women and children. As well as reducing the time available for education and other activities, there are many cases of women being raped while trying to collect firewood outside of refugee camps in the Darfur region. The aim of this research is to produce optimised wood stoves, reducing the amount of wood required, hence reducing carbon emissions, and improving the quality of life, particularly for women and children.

Our approach is to use computational fluid dynamics and genetic algorithms to improve the combustion conditions in wood-burning cook-stoves. In the initial experimental phase, open wood fires were characterised in terms of burn-rate, and gas temperature and velocity. Several stove designs were also assessed, including the three-stone fire (3-5% efficient), the Eritrean mogogo (5-10% efficient) and the rocket elbow (20-30% efficient).

The experimental results were replicated in a computer simulation which was validated for a range of fires. This model was embedded in

a CFD package which correctly predicted the flame height, velocity and temperature.

The validated CFD model combined with a genetic algorithm was used to optimise stove design: each stove is defined by a genome describing its dimensions; the various designs are allowed to "mate", each one vying for the attention of the "fittest" or most efficient stove; the offspring inherit a mixture of their parents' features, until an optimum design emerges. Finally the optimised design is to be built and physically tested before being modified to make it suitable for field trials and dissemination to rural communities.

Introduction

Half the world cooks using wood, often on open fires or on inefficient stoves. Collecting firewood is often left to women and children. As well as reducing the time available for education and other activities, there are many cases of women being raped while trying to collect firewood outside of refugee camps in the Darfur region[3].

There have been many attempts to produce fuel-efficient stoves or to replace wood stoves with other fuel sources or alternative means of cooking. Often research is carried out in academic institutions away from where stoves are used and although the resulting stoves can be fuel efficient, the neglect of social factors is a major barrier to successfully introducing improved stoves into the homes of those living in remote communities. In Ethiopia and neighbouring Eritrea, the staple food is injera: a spongy sour delicious flatbread, is cooked on a large griddle on a mogogo stove (see Figure 1). These inefficient, smoky stoves are made by individuals from a mixture of mud and clay, whilst the mogogo plates are supplied by the local ceramics industry. Two recently proposed "improved" stoves are not suitable for cooking injera (see Figure 1). The CleanCook alcohol stove [1], made in Sweden from aluminium, has two small burners which are insufficient to heat a mogogo plate. The change of fuel and stove also has adverse economic effects on local mogogo plate manufacturers and firewood sellers. A stove from Aprovecho with a more traditional appearance but made from concrete failed to take into account the even temperature distribution required, so although testing in the USA by boiling pots of water appeared to show improved efficiency, when it came to cooking injira, the results were inedible. Although these laudable attempts have some merit, their use requires Ethiopians to change their eating habits, threatens local economies and could thus be regarded as intrusive and colonialistic.

[3] See: www.darfurstoves.org

Figure 1: top left: classic mogogo, top right: Aprovecho improved mogogo, bottom left: ERTC design, bottom right: Cleancook stove.

There is also a design of mogogo promoted by the Eritrean government – the ETRC (Energy Research and Training Centre) mogogo, but the cost of US $40 places it out of reach of many Eritreans.

Alternative approaches involving local stakeholders have tended to be successful on a small scale, but are much more labour intensive. For example, on a recent trip with Engineers Without Borders UK in conjunction with FAMUSOD to install wood stoves in a remote village in the Imbabura region of Ecuador, Nottingham University student Rob Quail found that although initially the villagers were rather shy, by involving them in the design and material selection process, they overcame scepticism. After taking a break to go trekking for two weeks, Rob returned to the village to find that the villagers had built two stoves from his design and had begun to experiment with modifying the stoves according to their own ideas [2].

It may be impractical to involve end-users at every stage of the process in the design of improved cook stoves. An alternative approach is to tackle the problems of poor fuel economy and harmful emissions by modifying stoves which are currently in use rather than starting with a blank sheet of paper. Indigenous stoves will have undergone a natural process of evolution, with good stoves being imitated and bad ones replaced, although we must exercise caution in defining the characteristics of good stoves. A project to replace smoky stoves

in Nepal was successful in eliminating harmful indoor air pollution, but after six months, several dwellings collapsed due to termite damage; the previously used smoky stoves had been effect at killing pests whereas the new improved stoves did not fulfil this secondary (but essential) function [3].

A good example of using local knowledge in stove design is the Mirt stove distributed in Ethiopia by GTZ (see Figure 2). The stoves are made of concrete from simple moulds provided to local artisans. They are suitable for cooking injera and are fitted with traditional mogogo plates, protecting another sector of the local economy. However, these stoves are not suitable for use in Eritrea, due to the on-going tension between the neighbouring countries. Eritreans are likely to be suspicious of technology developed in Ethiopia – another factor traditionally ignored by engineers designing stoves.

Figure 2: Mirt stove

Whilst the evolutionary approach to stove design is commendable for the way in which it builds up local communities, supports the local economy and fosters a sense of ownership, the process is frustratingly slow and costly in terms of the number of new stoves that have to be built and tested, many of which will not show any improvement on the previous generation. A novel approach is to make use of genetic algorithms and computer modelling. Traditional stoves are allowed to "mate" with stoves with good fuel efficiency, such as the rocket stove depicted in Figure 3. The offspring stoves are modelled using Computational Fluid Dynamics (CFD) and assessed in terms of fitness. Fitness can be defined to include factors such as: fuel efficiency, temperature distribution, volume of material used to construct the stove (indicative of cost) and so on. In this paper we apply the methodology to the Eritrean mogogo. Details of the computational modelling and genetic algorithm (GA) are given in the next two sections, results of the simulations are then presented and discussed before conclusions and considerations for future work are proposed.

Computational Modelling

The computational fluid dynamic model of stoves was developed in Fluent 6.2, with a bespoke user-defined function to describe the rate of fuel combustion in the fuel bed. The model was simplified by assuming steady state conditions and an axi-symmetric domain, divided into three regions: the solid parts of the stove; a porous fluid region to describe the fuel bed and; a non-porous fluid region to describe the rest of the gases in the stove. The standard axi-symmetric Navier-Stokes equations were solved, coupled with the energy equation, the k-ε model with enhanced wall functions to describe turbulence, the discrete ordinates model to describe radiation heat transfer and the species transport model to describe chemistry with homogenous reactions limits by turbulent mixing as per the eddy dissipation model. No soot model was included, and it will be shown that neglecting the effect of soot on flame radiation has resulted in some significant errors.

Behaviour of solid fuel in the stove was described by a fuel sub-model, written as bespoke C-code and attached to Fluent as a user-defined function. The sub-model avoided the requirement to model each piece of fuel separately, instead applying a non-uniform flow resistance coefficient to the fuel bed, calculated from the Ergun equation. The model only accounted for the active (burning) surfaces of the fuel which were grouped together in lumps throughout the fuel bed: this was necessary in order to make combustion in the resulting flame diffusion limited as volatile matter and oxygen mix, rather than kinetically limited. Within each lump, the rate of volatile release was limited by the transfer of heat through a char layer of assumed thickness to the virgin fuel below. The rate of char combustion was limited by the supply of oxygen from free stream conditions through the species boundary layer to the char surface. The approach is novel, but the numerical model of buoyancy-driven flow was validated against experimental data from the literature [4]; the fuel model was validated against experimental data [5] and convection heat transfer as the plume of hot gases impinge on the cooking surface was also validated against experimental data [6]. Mesh independence of the model was assessed using the Richardson extrapolation.

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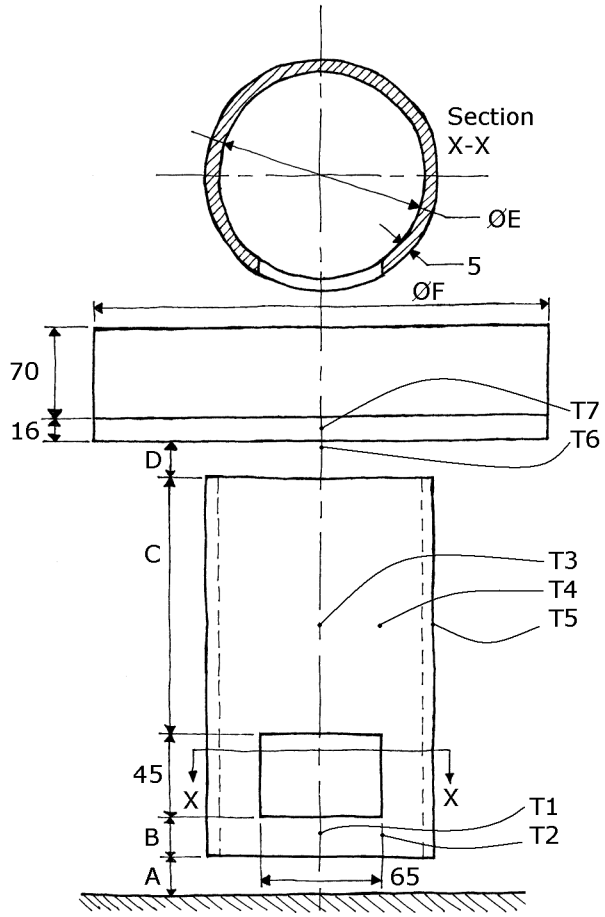

Figure 3: Principal rocket stove dimensions. Variable dimensions are denoted A to F. T1..7 indicates location of thermocouples for experimental testing.

Genetic Algorithm

The genetic algorithm (GA) mimicked Darwinian evolution following the pseudo-code in Figure 4. A generic stove was developed from the Rocket stove [7,8] which had previously been assessed experimentally. This stove was almost axi-symmetric, with an annular air inlet between the stove and the ground, a window to allow fuel to be introduced and a mogogo plate (or similar) atop as a cooking surface. For each stove a gene of single-digits scalars was stored. These were multiplied by a generic set of vectors to yield a unique stove shape for each gene or creature. The GA is an iterative process, and for each stove in each generation, the dimensions of the stove were derived as described above. The GA inserted the new dimensions into a journal file which was executed in the meshing software, Gambit 2.1, to give a coherent mesh. The mesh was then sent to Fluent 6.2 where a second journal file imposed boundary conditions, models and model parameters and set the simulation to solve for 2000

iterations. At the end of the calculation the GA exported data on the fuel burn rate and the local heat flux to the cooking surface. Finally the fitness of each stove in the generation was calculated according to the following objective function:

$$f_2 = g(q'') + \frac{h(q'')}{m_f'} \quad (1)$$

```
initialise random genome of creatures
FOR each generation
    FOR each creature
        transform gene into mesh
        call CFD to calculate fluid flow
        calculate fitness from CFD results
    ENDFOR creature
    select mates
    cross-over to create new generation
    mutation on new generation
    new generation usurps old generation
ENDFOR generation
```

Figure 4: Pseudo-code of Genetic Algorithm.

wh
ere q" is the mean heat flux passing through the cooking surface and m'_f is the total fuel burn rate. Functions g(q") and h(q") are described in Figure 5. The objective function primarily rewards stoves which achieve the target heat flux (q''_t) using the first term in Equation 1, and only when that is achieved does it heap additional fitness on stoves that minimise their fuel consumption, using the second term in Equation 1. Earlier embodiments of the objective function had an additional term to reward a uniform heat flux by monitoring local deviation from the mean flux, but this was found not to be necessary.

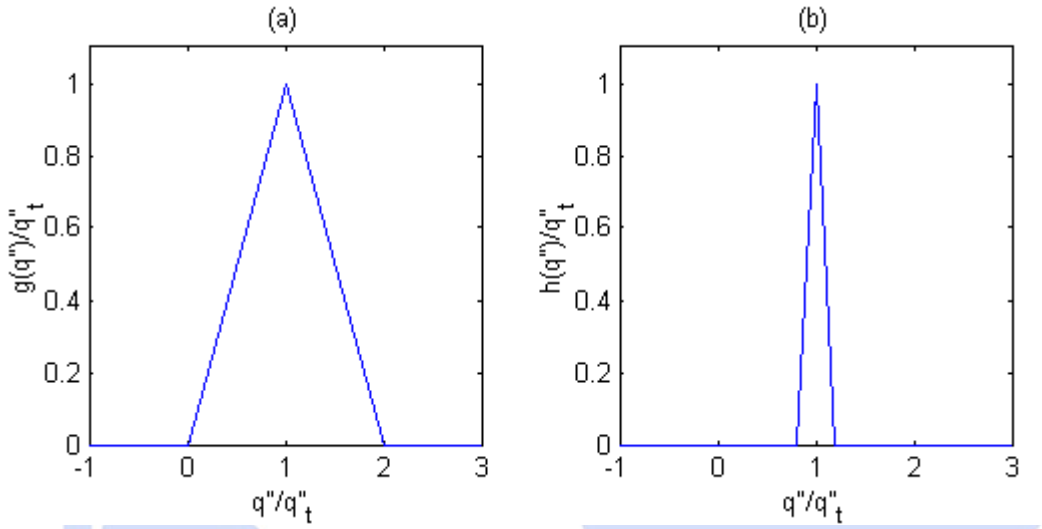

Figure 5: Functions g(q") and h(q"), which contribute to the overall objective function.

Once the fitness of all stoves had been assessed, the GA moved on to the mating phase, using the roulette wheel selection routine: a virtual roulette wheel was created with sectors sized in proportion to the fitness of each stove. Two roulette balls were set into the wheel to identify two parents. The genetic code of the two parents was mixed using a single cross-over point to produce a child. The child's genetic code was then subject to random mutations. The fittest stove from the previous generation passed automatically to the next, and the rest of the population was generated by random mating events: this encouraged rapid convergence of the results to an optimum stove design. Finally the new generation of stoves usurped the old.

The GA was run with $q"_t$ = 5000 W/m^2, giving 1 kW cooking power over a 0.5m mogogo plate. There were 10 stoves in a population and the GA was run for 50 generations. The GA was run for 10 heats, generating ten champions from random initial genomes. In a second phase, the ten champions were set against each other three separate times to give a champion of champions. The champion of champions (i.e. the best stove) was subject to a sensitivity analysis, whereby all dimensions were subject to small perturbations and the effect on stove performance was assessed to identify critical dimensions.

Results

The champion of champions is illustrated in Figure 6. It features a sharp "turbulator" (at height, z=0.32) and a recirculation region in the combustion chamber, a wide thin virgin fuel region and a tall lower section. Errors in heat

flux and fuel burn rate for the optimum stove were estimated to be 2% and 40% respectively using the Richardson extrapolation: results concerning the fuel burn rate should be treated with circumspection.

The turbulator and thin neck (z = 0.34 m) supports a large block of material. It is anticipated that these two features could easily break and render the stove useless, so a further sensitivity analysis was conducted on this region of the stove. Reducing the turbulator size reduces fitness from 6470 to 4220. Removing the turbulator completely results in a further decease to 3980. Clearly the large turbulator is important for mixing and heat transfer: a smaller version is almost as useless as no turbulator at all, and a final design would have to include an insert in this region to (a) act as the turbulator and (b) strengthen the neck. This is unfortunate as it would increase the price of the resulting stove, and move away from the initial design philosophy that the optimised stove could be manufactured on an ad hoc basis by rural women without specialist training nor recourse to purchasing components.

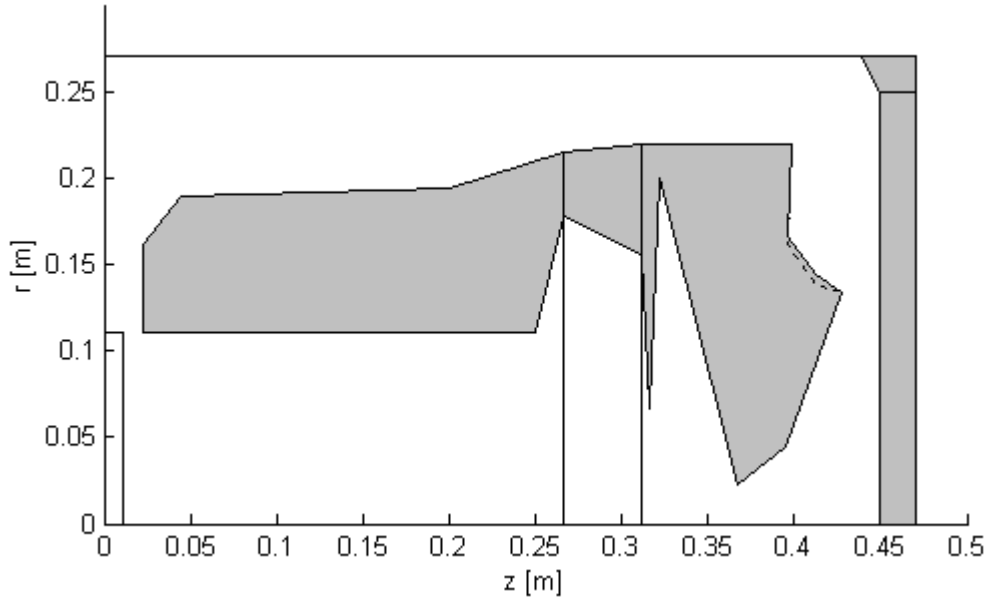

Figure 6: Schematic of the best stove proposed by the GA. The dashed line shows an improvement identified by the sensitivity analysis. The x-axis is the rotation of symmetry, the y-axis is the ground and solid material is shown shaded.

Conclusions

The proposed stove achieved a target cooking heat rate of 997W, using fuel at a rate of 0.6 g/s. This performance is equivalent to 12% efficiency or specific fuel consumption 0.4 kg fuel per kg food, compared to 0.5 for the classic mogogo. This result has not been experimentally verified, and should be viewed with circumspection given the shortcomings of the CFD model. Nonetheless, the

proposed stove requires only one bought component, the turbulator, with an estimated cost US$ 1, which compares favourably to the cost of the optimised ERTC mogogo (US$ 40) and the Aprovecho design (US$ 9) and in that respect it has realised the requirements of the project. Considerable further work is required in experimental verification, to adapt the design to manufacturing requirements and to successfully bring it to market in Eritrea.

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