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# "Weiterentwicklung des Multi-Fuel Injera Mitads zur Anpassung an unterschiedliche Kocher"

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# 1 INTRODUCTION

Improved cook stoves are designed to reduce or even substitute the use of solid fuels in kitchens of developing countries. This is urgently required, because the increasing shortage of solid organic fuels and the severe health risks resulting from incomplete combustion of these fuels in poorly ventilated kitchens give reason for immediate action. Ongoing deforestation forces especially women and children to travel long distances to collect the daily required amount of cooking fuel. In some areas of Tigray, northern Ethiopia, deforestation has already resulted in complete absence of forests. There firewood has to be "imported" from adjacent areas. It is transported over long distances on horse cards and donkeys to local markets, where it is sold at ever rising prices per kilo (in March 2011 1,20 Ethiopian Birr per kilo (0,05€/kg)). With decreasing availability of wood at increasing prices households are obliged to draw on a variety of different fuel sources. This, when ascending the WHO energy ladder towards sources like gas and electricity, will lead to the necessity to adopt appropriate stoves, like a gas or electric stove respectively. However, the dissemination of improved stoves, also biomass stoves, is rather difficult. Fuel choice and the reasons for the hesitant stove acceptance have been closely investigated. Under resource scarcity the following four factors were found to be the most relevant for a household's choice of fuel: (a) economics of fuel and stove type and access conditions to fuels, (b) technical characteristics of cook stoves and cooking practices; (c) cultural preferences; and (d) health impacts (Masera et al., 2000). In Ethiopia, Eritrea, Somalia and Sudan the staple food consists of different traditional flatbreads. The decision for an improved cook stove is thus hampered by an additional factor: the flatbreads Injera, Anjero or Kisra cannot be baked on the promoted improved stoves for pots. Traditionally these flatbreads are baked on up to 60 cm round or square griddles on open fire, where the required even heat distribution throughout the griddle is reached due to a large surface of the heat source. Three stone fires are highly inefficient, thus about 60% of the total energy required by one household is used for Injera baking in Ethiopia (EESRC, 1995), 46% when using firewood and 70% when using dung (Mekonnen 2009a, Mekonnen 2009b). Adopting improved cook stoves for cooking purposes other than injera baking cannot have the intended effect, when the preparation of the flatbreads is not manageable with these stoves. As firmly positioned in the tradition, injera baking has always been considered as an individual task distinct from other cooking activities. Consequently special improved stoves for the preparation of injera were designed. In urban Tigray Gebreegziabher et al. (Gebreegziabher et al., ) found that injera is baked on one of four commonly used wood burning stoves or the electric mitad. About 93% of the sample households (n=350) used the traditional clay enclosed Tigrai-type stove, while open hearth stoves with three stones as well as Tehesh and Mirte Stoves were very rarely used. The Tigray stoves are usually built by the household members themselves rather than being bought. The Mirte stove was designed by the Ethiopian Energy Studies Research Centre in the early 1990s and is sold as assembly of parts from cement and pumice. When properly utilized, it serves for approximately 8 years (Damte & Koch, 2011) at a price of 90-130 ETB (ca. 4-6 €). In total about 17 million wood fired stoves are currently in use in Ethiopia, compared to an estimated 500,000 electric mitads. They are designed as electrically heated clay *mitad* with carved in copper wires. About 20% of urban households use these mitads (Gebreegziabher et al., ).

In this study an economically operating and appropriate technical solution for injera baking with biogas and other improved cook stoves is presented. The demand for such a technology becomes obvious when considering the concept of the National Biogas Program Ethiopia (NBPE), which was launched to promote domestic biogas in a 5 year period from 2008-2012. 14,000 biogas digesters of the sizes of 4 to 10m³ were planned to be installed in 4 selected regions. The dimension of a household's biogas plant was measured against the individual energy demand for cooking and lighting, while totally excluding the energy demand for injera baking. This was necessary, because the Program could not yet provide a functioning technical solution for injera baking with biogas. Consequently biogas was not easily accepted since maximally 40-55% of the total energy requirement could be substituted and injera baking remained subject to hazardous wood stoves or open fire. To help biogas as a promising solution for rural energy problems to gain more acceptance a solution for injera baking with biogas was developed. The presented technology consists of an extension to a common biogas stove and to any other stove with a central heat source. The so called multi fuel injera mitad was analysed and compared to the currently used techniques and technologies. Different heat distribution systems were designed and tested in combination with numerous different materials for the actual mitad. These materials range from the traditionally used clay mitad to different metals with intermediate steps including the combination of clay and metal.

## 2 MATERIAL AND METHODS

### 2.1 Chemical analysis of the original Ethiopian clay mitad

In Ethiopia the source of energy to heat the mitad may vary, but there is only one kind of material used for mitads – clay. In order to assess the status quo of Ethiopian injera mitads concerning heat conductivity and temperature shock resistance, and to define the potential for improvement of the traditional mitad, a 600 mm diameter, 25 mm thick mitad from Ethiopia was analysed. Because the exact material composition of the used clay as well as the firing temperature of the traditional mitad was unknown, relevant factors for the appropriateness of this material for its purpose were analysed: chemical and mineral composition (DIN 51 070), temperature shock resistance (DIN 51 068) and porosity (DIN 52 103) of the fired mitad. In the chemical analysis the major mineral components and the loss on ignition were identified with X-ray fluorescence analysis (XRF) in 1g of fired clay from the original mitad. Via X-ray diffraction (XRD) the crystalline structures of the mitad was analysed to get an idea about contained minerals, but results showed, that only the analysis of basic raw material from clay and volcanic ash could deliver the required information. With XRF the chemical composition of volcanic ash, clay and a 2:1 mixture of both, as the mixture used in mitad production, were determined. XRD could now deliver results on the minerals involved and difference thermo analysis (DTA) with thermogravimetry analysis (TG).

The raw material from Ethiopia was analysed afterwards. Thermal shock resistance was determined as measure for resistance to temperature changes as they occur in practice. 10 times the mitad was heated up to 600°C in an electric oven and then immediately quenched in cold water. As indicator for the porosity of the material the absorption of water was measured. Heat conductivity was determined as described below.

### 2.2 Analysis of heat conductivity

All relevant material variations were tested on heat conductivity using the thermo-scanning method defined by Popov et al. ({{112 Popov,Yuri A. 1999}}. Measurements were conducted at laboratory conditions. All samples were coloured with a thin layer of black spray paint to reduce the effect of different colours. Two different standards were used:

- standard 1: fused quartz (TC = 1.35 W $m^{-1}$ $K^{-1}$, TD = 0.85.*10*-6 $m^2$ $s^{-1}$) and titanium alloy (TD=0.05 W $m^{-1}$ $K^{-1}$, TD=2.587 *$10^{-6}$ $m^2$ $s^{-1}$)

- standard 2: glass (TC=0.717 W $m^{-1}$ $K^{-1}$, TD=0.389*$10^{-6}$ $m^2$ $s^{-1}$) and fused quartz (see above)

### 2.3 Simulations of flue gas evacuation systems with CFD

As intermediate step between systematic design and practical realisation of prototypes and as control mechanism during modifying prototypes fluid dynamics within the flue gas evacuation system were simulated in Ansys Fluent. The detected influences on heat distribution, for example wind or draft, tillage of the mitad and inhomogeneous flame could only be partly projected by simulations.

## 2.4 Realisation of Material and Design Variations

The traditional clay-ash mitad was substituted by a variety of alternative materials. A in industrial ovens commonly used backing griddle made of a cement-fibreglass-composite was used in tests as well as different kinds of metal griddles. 3 and 5 mm steel and 3 mm stainless steel plates were tested, 20 mm aluminium and 40 mm aluminium foam griddle were considered, but not further pursued due to their high costs. Also trials of directly combining metal and clay were conducted in order to combine the positive characteristics of both. Although the different heat expansion coefficients of clay and metal theoretically does not allow successful firing of a composite material, but by choosing a small enough size of the metal component, the absolute expansion could be kept very low. A variety of sample mitads of 330 mm diameter and 12-15 mm thickness was produced. As clay KMR-05-45 (red clay, chamotte size <0.5, 45%) and FW-02-25 (white clay, chamotte size < 0.2, 25%) were used in combination with fine cast steel granulate (∅ 0.4-0.8 mm), coarse hard casting granulate (∅ 1.4-1.7), corundum granulate (1.0-2.0 mm) and iron powder (150 µm) at different contents. After firing the most promising composition in terms of heat conductivity and producibility (no cracking or bending during firing) was determined. Accordingly, a 60 cm diameter mitad of this composition was produced and used for further analysis. Further trials in order to improve the baking characteristics of steel mitads were coating of steel samples with glass at up to 1150°C and coating with enamel at up to 600°C. Alternatively also the incorporation of mineral components into the heat distribution system was tested. Differently sized kinds of rocks were combined with the funnels in the first tests and were then replaced by differently shaped clay pieces (KMR-05-45). These were only air dried and directly used without firing.

The even distribution of heat from a central heat spot onto a 60 cm diameter mitad required the development of a heat distribution system. A variety of different flue gas evacuation systems was designed, simulated, built and tested.

## 2.5 Analysis of Heat Distribution

Thermal imaging was used as method to determine heat distribution and temperature (Fluke IR-camera), while time and gas consumption (TG 3, Ritter) were recorded in parallel. Each flue gas evacuation design in combination with the different mitads was tested for heat distribution. Besides the heat images numerous baking tests were conducted in Ethiopia. Energy consumption, time and injera quality were measured.

## 2.6 Method Development for Efficiency Measurement of Injera Mitads

The controlled cooking test (CCT) is the commonly used method to measure the efficiency of injera mitads. It requires the baking of a defined number of injeras, the traditional Ethiopian flatbread made of sourdough from teff (*Eragrostis Teff*) while time and fuel consumption are measured. The baking process, e.g. the spiral-shaped application of the liquid dough, the baking and steaming process and removing the large flatbread off the mitad without tearing it, requires special skills. Also the preparation of the dough is based on traditional knowledge, certain climate conditions and ingredients, which are only available in Ethiopia. There are regional differences in dough composition, injera thickness, preferences concerning the eyes or holes on the injera surface etc. Thus, conducting the CCT with injera baking is not easily standardised. This makes it difficult to compare tests from different parts of Ethiopia, but especially from outside of Ethiopia are certainly not representative. Concerning the development of a method independent of injera baking there are further difficulties to consider. Whenever clay mitads are used their temperature is determined by sprinkling water on the surface. The distinct sound of boiling water sprinkles on clay is recognised by the injera bakers and if the mitad has become too warm it is cooled down with water that is spread with a cloth. This loss of energy is difficult to determine and to consider, but it is also not possible to avoid. Open fire as well as electric mitads do not heat the clay griddle evenly, thus the whole mitad is heated to a much higher temperature than required in order to reach at least 180°C throughout the whole plate. Hotter areas are then cooled down again. This is also done after every baked injera and when necessary the mitad is cooled down.

The method should substitute the real procedure of injera baking with all the different phases: preheating, baking,

An alternative method, easy to apply and suited for all kinds of mitads had to be developed. In the development of this method the different baking properties of different materials had to be considered, which are highly determined by heat conductivity and heat capacity. Therefore also the different phases of energy use before, during and after the baking process had to be considered. The method should allow comparing different kinds of energy efficiencies, because not only heat transfer from mitad to injera needs to be considered, but also heating time, baking time and baking temperature depending on the material and exploitability of stored heat.

The method was developed referring to DIN-EN 30-1-2, (1999), a standard method to determine the efficiency of gas stoves. This test is a standardised water boiling test, in which a solid aluminium pot of defined size and weight with a certain amount of water, each depending on the power of the analysed stove, is used. To measure the efficiency of a solid mitad a flexible container was designed that fits with the large and sometimes uneven 0,36m$^2$ surface. The flexible pot consists of a flat round bag made of composite material from sheeted polyethylene (PE), aluminium and polyamide (PA) (the material is usually used for packaging coffee) with a threaded flange welded into the centre of one round side of the bag. The PA-layer faces outward, the PE-layers are welded together along the diameter. The flange allows attaching a temperature sensor.

3 phases were distinguished for the efficiency tests:

1. heating phase: time and energy consumption until required baking temperature is reached (metal: 100°C, clay: 180°C)
2. baking phase: after the baking temperature is reached the flexible container filled with 8L of water is positioned concentrically on the mitad and left for three minutes covered with a lid. After this imitation of the baking process the stove is turned off, the bag is immediately removed from the mitad, thoroughly shaken and the water temperature is measured through the flange opening.
3. cooling phase: when the flexible bag is removed after 3 minutes another bag also filled with 8 litres of water of previously measured room temperature is positioned concentrically on the mitad. After 10 minutes (the time period, which can be used for baking 2 injeras on a traditional clay mitad after the energy supply is cut down) the temperature of the water is measured. This represents the energy that is stored within the mitad.

The efficiency of the multi fuel injera mitad depends on the efficiency of the stove it is combined with. In the tests conducted here, a Cambodian type biogas stove and a wood fuelled rocket stove were used.

## 3 RESULTS

### 3.1 Characteristics of the traditional clay mitad

The traditional mitad consists of the mineral components shown in Tab.. The high iron content of about 6% is typical for African clays, but the sodium content of nearly 1.5% is unexpectedly high. Loss on ignition of 1.9% indicates the content of carbonates and organic impurities like residues of charcoal. Although the XRF analysis did not deliver detailed information on the originally used clay material, because the database did not contain information on the respective clays, it showed that potash-sodium bicarbonate-silicates, pure potash silicates and mullite had probably formed during firing. The analysis of the raw materials clay and ash revealed, that mullite was already contained in the clay before firing. Mullite is used in technical ceramics to improve stability and thermal shock resistance, but it only forms through metamorphosis of kaolinite at temperatures above 1200°C. The thermal shock resistance of the analysed mitad was very high - after 10 tests neither cracking nor chipping had occurred. The measured porosity amounts to 41.8%, whereas no further characterisation of the pores and their distribution was applied.

| | | raw material | | | fired material |
|---|---|---|---|---|---|
| | | vulcanic ash | clay | ash-clay mixture | clay mitad |
| $SiO_2$ | [%] | 74,89 | 65,51 | 68,29 | 70,97 |
| $Al_2O_3$ | [%] | 13,49 | 16,20 | 15,45 | 14,58 |
| $TiO_2$ | [%] | 0,27 | 2,11 | 1,5 | 0,91 |
| $Fe_2O_3$ | [%] | 3,48 | 10,72 | 8,44 | 6,08 |
| MgO | [%] | 0,08 | 1,84 | 1,15 | 0,72 |
| CaO | [%] | 0,52 | 1,87 | 1,4 | 0,96 |
| $Na_2O$ | [%] | 1,90 | 0,33 | 0,91 | 1,47 |
| $K_2O$ | [%] | 5,15 | 1,18 | 2,61 | 3,82 |
| $SO_3$ | [%] | 0,00 | 0,00 | 0,00 | 0 |
| Rest | [%] | 0,22 | 0,24 | 0,25 | 0,49 |
| GV | [%] | 6,07 | 14,35 | 12,41 | 1,9 |

The volcanic ash consists of 60% quartz of which a high amount occurs in a glassy phase and the remaining 40% are potassium silicates and sodium silicates. The high amount of iron minerals indicate volcanic origin. The clay consists of 20% calcium-magnesium-silicate (orthoclase), 16% mica, 14% iron hydroxide (goethite), 13% quartz, 2.6% of titan dioxide (anatase) and ca. 9% of a highly hydrated kaolinitic material (probably montmorillonite). Due to the montmorollonite the clay forms a very sticky and swellable plastic substance, which must be mixed with volcanic ash and a lot of water for further processing. The specific mixture of 2:1 ash to clay allows very low firing temperatures of around 600°C and leads to the significantly high thermal shock resistance. The high amount of iron is responsible for the dark red-brown colour and the high porosity, which makes the mitad fairly light and well insulating.

The heat capacity of the traditional mitad used for the analysis described above ranges from 0.31 to 0.43 $W\ m^{-1}\ K^{-1}$ (mean 0.34 $W\ m^{-1}\ K^{-1}$). A second traditional mitad of obviously higher porosity was tested and there a higher inhomoginity within the material was determined: 0.26 and 0.44 $W\ m^{-1}\ K^{-1}$ (mean: 0.33 $W\ m^{-1}\ K^{-1}$)

### 3.2 Characteristics of Material Variations

Table 1 shows the composition of the different clay-metal sample mitads and their respective behaviour during firing at 900°C. The samples containing iron powder (sample 3-5) cracked and bend stronger during firing than the samples containing different kinds of granulate. Except the sample with corundum granulate (not listed in Table 1), it crumbled to small pieces during firing, but all samples containing cast iron granulate were stable with only minor bending and without any cracks. The content of 50% cast iron granulate had shown the best behaviour during firing, thus a 600 mm ∅ sample mitad (sample 8) was produced for further tests.

Table 1: composition of clay-metal mitads

| sample | clay composition | | | | | behaviour during firing |
|---|---|---|---|---|---|---|
| | clay type | % fine granulate | % coars granulate | % iron powder | metal content | |
| 1 | FW-02-25 | 15 | 15 | 0 | 30 | |
| 2 | FW-02-25 | 37 | 13 | 0 | 50 | |
| 3 | FW-02-25 | 0 | 0 | 50 | 50 | bend, cracked |
| 4 | FW-02-25 | 0 | 0 | 30 | 30 | cracked |
| 5 | KMR-05-45 | 0 | 0 | 50 | 50 | bend, cracked |
| 6 (reference) | FW-02-25 | 0 | 0 | 0 | 0 | |
| 7 | KMR-05-45 | 30 | 0 | 0 | 30 | |
| 8 | FW-02-25 | 50 | 0 | 0 | 50 | |

The heat conductivity measurements as shown in Table 2 revealed that the incorporation of highly conductive material like metal into clay can increase the conductivity of a clay griddle. The comparably high value of 2.8 W $m^{-1}$ $K^{-1}$ in sample 3, which contains 50% iron powder, shows the effect very clearly. The standard deviation of about 8 to 10% indicates an inhomogeneous distribution of metal pieces within the fired clay in all samples.

Table 2: heat conductivity of selected clay-metal mitads

| number | heat conductivity [W $m^{-1}$ $K^{-1}$] | | | standard deviation [%] |
|---|---|---|---|---|
| | mean | min | max | |
| 1 | 0.8 | 0.7 | 1.0 | 9.9 |
| 3 | 2.8 | 1.9 | 3.2 | 8.2 |
| 5 | 1.7 | 1.4 | 2.2 | 9.7 |
| 8 (∅600) | 1.3 | 1.1 | 1.6 | 7.8 |

Figure 1 shows as example the measurement of sample 5. The standard deviation of 9.7% results from the changing heat conductivity along the measuring distance of 300 mm. The bottom blue line shows the temperature of the sample in front of the heat source (sensor T cold). The dark red line indicates the temperature of the sample surface behind the heat source (sensor T hot), while another sensor is placed also behind the heat source, but with an offset to the measuring axis (sensor T hot y). The temperature is shown in light red.

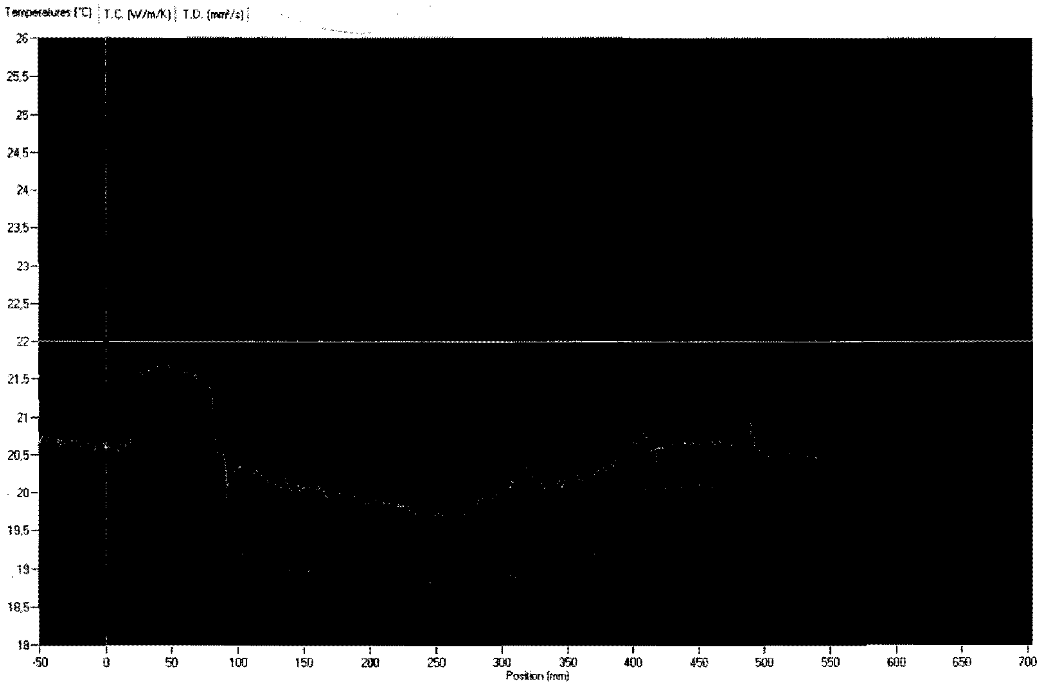


Figure 1: Heat conductvity measurement diagram

### 3.3 CFD Simulations

CFD Simulations were done for 0° and 10° inclination. The effect of inclination as found in practical tests could be simulated, thus proven to be one of the major problems of the mitad design. Several modifications of the design were simulated and tested in practice.

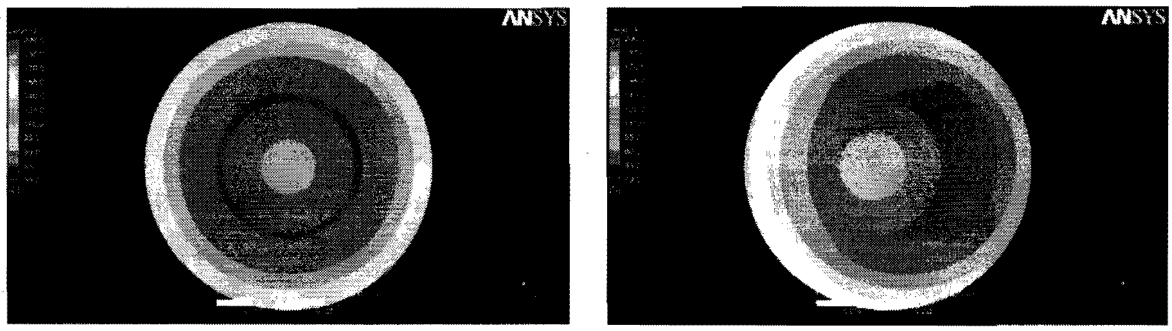


Figure 2: final mitad heating at 0° and 10° nclination on biogas stove

### 3.4 Prototypes

Heat distribution from a central heat spot was realised as different funnel systems. The sensitivity to inclination and draft were reduced by differently shaped blockage systems as shown in Figure 3.

The comparably low heat capacity of the metal baking surface had to be increased be increased as a result of baking tests conducted in Ethiopia. This could be achieved by adding different clay components to the whole system. The differently shaped clay parts are shown in Figure 4.

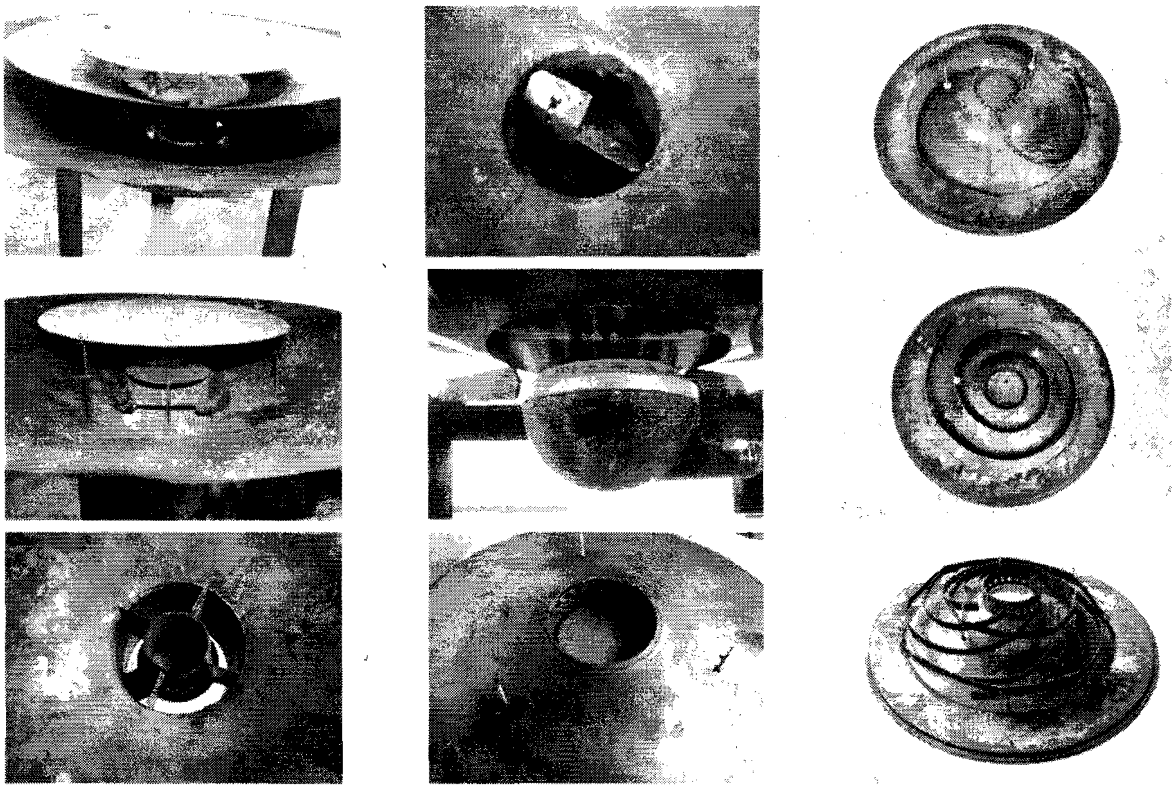

Figure 3: flue gas blockage systems to reduce sensitivity against incination

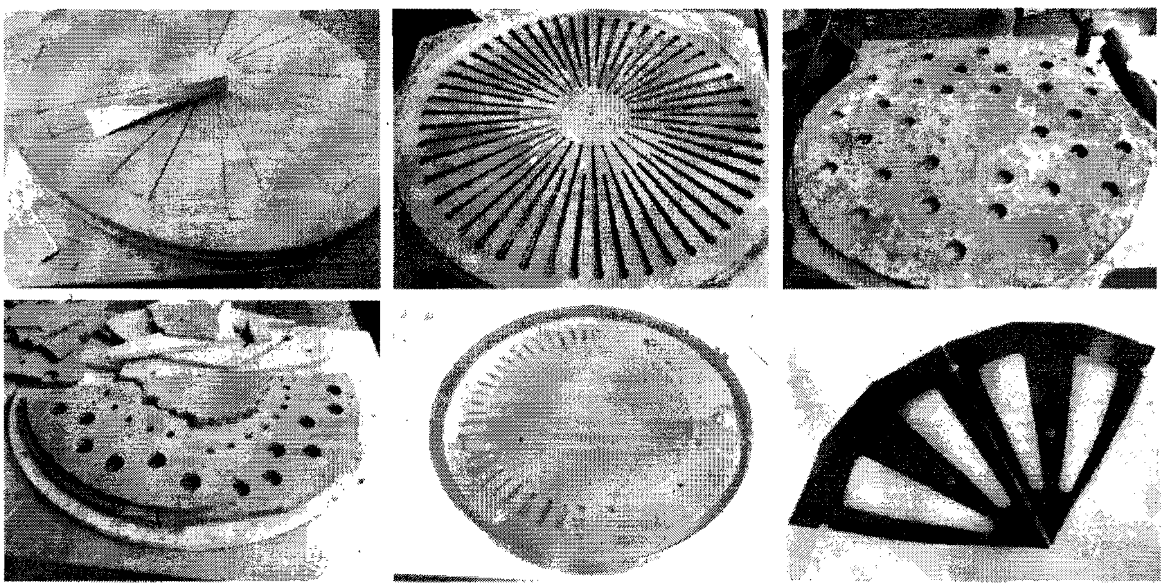

Figure 4: clay components to increase heat capacity of metal baking surface

## 3.5 Baking Test

Practical injera baking tests in Ethiopia showed that 137-140$^{0}$C is the ideal baking temperature. The actual baking time amounts to 2:30 min, but difficulties were mainly faced during removing the injera from the mitad. Often the baked injera stuck to the surface and could not be removed. This increased total baking time and reduced the efficiency. Typical baking test measurements of the mitad surface before and after baking as well as pictures of top and bottom of the baked injera are shown in Figure 5.

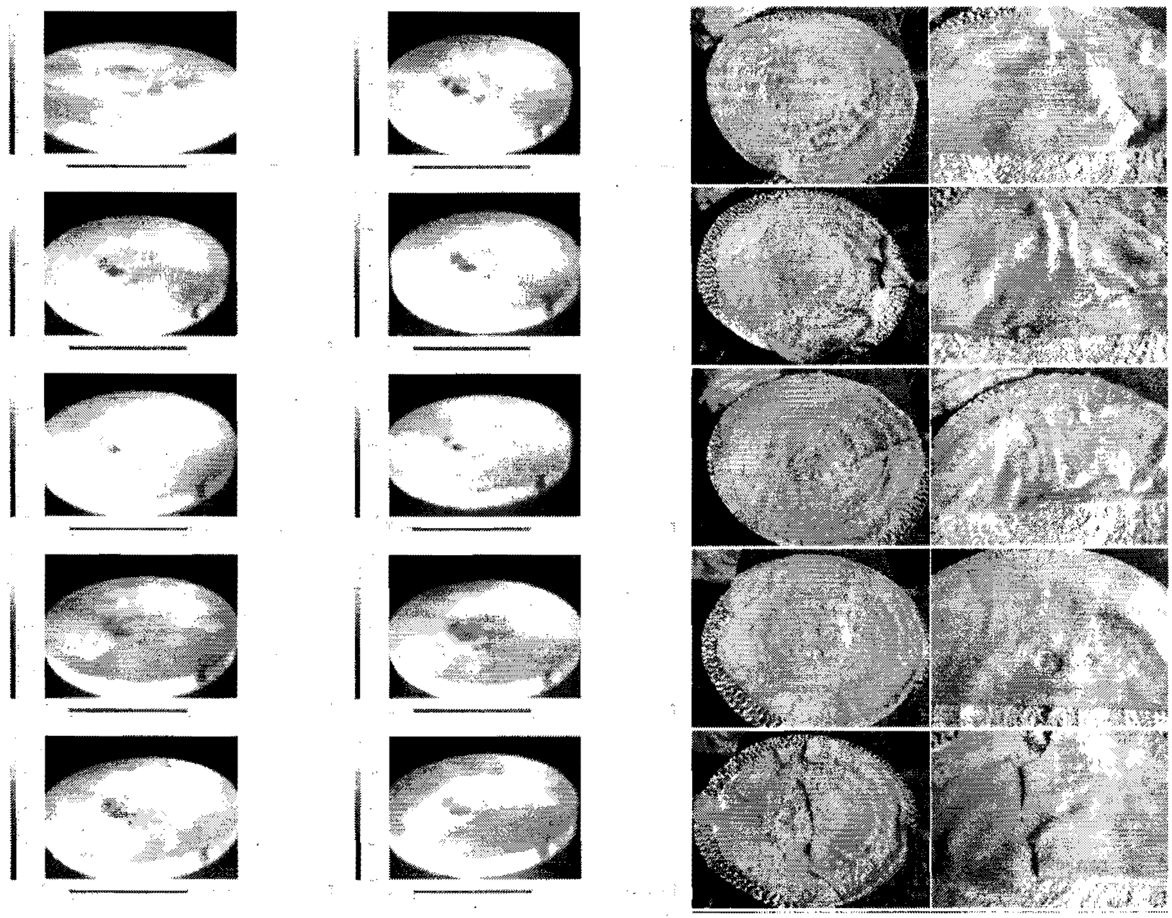

Figure 5: Example for Injera baking test results

# 4 FURTHER RESEARCH

During this study the multi fuel injera mitad could be further developed to a design, which works very well with the commonly used biogas stove. The injera quality is sufficiently good enough. The final mitad design is currently being reproduced by local manufacturers in Ethiopia. The first duplicate has been tested for heat distribution. The major problem remaining to be solved is the surface finishing of the metal mitad, which determines the total baking time. The formerly used method of seasoning the surface with oil has shown to be not smooth enough. In order to solve this problem HoA-REC at Addis Abeba University is currently employing an industrial designer from the Netherlands. He shall find a solution for an anti-sticky surface. He also prepares the design for industrial production and visits facilities to facilitate market entrance. A local investor has been found who is interested in producing and selling the current mitad version. Further baking tests as well as efficiency tests will be conducted as soon as the remaining minor modifications are made.

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