Thermal Performance of Improved Charcoal Stove as a Clean Development Mechanism Project – A Case Study of Bauchi

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Abstract- Improved cook stoves (ICS) are known to ensure efficiency in the use of traditional fuels, reduce smoke emission and associated health hazards during cooking and reduce cooking time. Another benefit of ICS is in mitigating the effects of climate change. This paper presents the thermal performance and achievable emission reductions by ICS for daily cooking in households around Bauchi. It evaluates an ICS using the International Workshop Agreement (IWA) which rates cook stoves on four indicators (Indoor emission, total emission, efficiency/fuel use and safety) each indicator is rated along five tiers (0: lowest performing to 4: highest performing). The evaluation focused on efficiency/fuel use. The benchmark values for thermal efficiency, fuel use and energy use are 35%, 0.310kg and 7928kJ respectively. This shows that the ICS offers modest improvements in fuel use and it is rated as a tier 3 ICS. A carbon savings of 0.9 x 10^4 tCO_2 can be achieved on an annual basis assuming all rural and urban households in Bauchi employ ICS for their daily cooking.

Keywords- Improved charcoal stove (ICS), Water Boiling Test (WBT), climate change, Clean Development Mechanism (CDM), Thermal efficiency.

1 INTRODUCTION

Every day, three billion people in the world cook their food on open fires or traditional cookstoves. They burn solid fuels such as wood, crop residues, dung, coal, and charcoal, producing smoke that kills more than four million people annually and sickens millions more (Barnes et al., 2009). In addition to the enormous health toll, this cooking method carries an enormous environmental burden; the emissions from the combustion of unsustainably harvested wood fuel alone accounts for roughly 2% of global greenhouse gas emissions (IPCC 5th assessment report, 2014). The result is that one of our most fundamental activities – cooking a meal – is a major global health and environmental issue, as well as a significant barrier to sustainable economic development. Though cleaner, more efficient cooking technologies have been developed, they are often out of reach for families in developing countries due to cost or lack of availability in their local marketplace.

Over 95,000 Nigerians, mostly women and children die annually from smoke in the kitchen (Osita et al., 2013). This is Nigeria’s third highest killer after Malaria and HIV/AIDS (WHO, 2012). In addition, Nigeria loses 3% of its forests annually partly as result of the cutting of trees for firewood (Al-Amin, 2014). Clean Development Mechanism (CDM) projects aims to assist developing countries in achieving sustainable development and to help developed countries fulfil their commitments to reduce emissions by investing in climate change mitigation projects in developing countries (CDM Benefits, 2012).

2 THEORETICAL BACKGROUND

The stove performances with respect to the type of fuel used can be analysed using energy audit method. It is assumed that no heat is lost from the stove combustion chamber to the outside, and with this assumption, the result is compared to the benchmark values from the same fuel utilized in simmers tests. Default heating values of charcoal are given as 31,000kJ/kg for Higher Heating Value (HHV), 29,800kJ/kg for Lower Heating Value (LHV), and charcoal carbon content Cc = 95%. However, due to the presence of some water content in the charcoal, the accessible heating values are lowered to an effective heating value (EHV) which is given with reference to the moisture content as (Morgan et. Al, 2010).

\[
EHV = LHV * (1 - MC) - MC * [(Ta - Tb) * 4.2 + 2260]
\]

Where LHV is the Net calorific value,

- MC is the moisture content,
- \(T_a\) is the local boiling temperature and
- \(T_b\) is the reference air temperature.

The total heat extracted from the charcoal is the product of the EHV and the quantity of charcoal consumed \(f_m\) measured in grams, obtained as the difference between the initial weight \(f_i\) and final weight \(f_f\) of the charcoal:

\[
f_m = f_i - f_f
\]

In addition to changes in weight of charcoal, there is also net change in weight of the charcoal \(\Delta C_x\) given as

\[
\Delta C_x = C_x - K
\]

Where \(C_x\) is the weight of container plus charcoal and \(K\) is the weight of dry container.

The equivalent dry charcoal consumed \(f_d\) is given as (Morgan et. Al, 2010)

\[
f_d = \frac{f_m [LHV * (1 - MC) - MC * (4.186 * (T_a - T_b) + 2257)] - \Delta C_x * CCV]}{LHV}
\]

Where \(f_m\) is the quantity of charcoal consumed in grams,

- \(LHV\) is the lower heating value of charcoal
- \(MC\) is the moisture content,
- \(T_a\) is the local boiling temperature and

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$T_i$ is the reference air temperature

$\Delta C_T$ is the net change in weight of charcoal, and

$CCV$ is the char calorific value

The effective mass of water boiled $w_b$ is given as (Morgan et. al, 2010):

$$w_b = \sum w_i \left( P_{w,i} - P_{d,i} \right) \ast \left[ \left( T_{f,i} - T_{i,i} \right) / (T_{f,i} - T_{i,i}) \right]$$

Where $P_{w,i}$ is the weight of pot + water;

$P_{d,i}$ is the weight of empty pot

$T_{f,i}$ is the temperature at finish

$T_{i,i}$ is the temperature at start, and

$T_i$ is the local boiling temperature.

During heating, the weight of evaporation $w_v$, which takes place is given as (Morgan et. al, 2010):

$$w_v = \sum w_i \left( P_{w,i} - P_{d,i} \right)$$

Where $w_v$ is the weight of water evaporated,

$P_{w,i}$ is the weight of pot with water and

$P_{d,i}$ is the weight of dry pot.

The required time $\Delta t$ to boil the water in the pot is given as the difference between the start time $t_i$ and the stop time $t_f$ defined as:

$$\Delta t = T_f - t_i$$

Where $\Delta t$ is the time required to boil water in the pots,

$t_i$ is the stop or finish time, and

$t_f$ is the start or initial time

With reference to normal boiling condition from a temperature of 25 °C to 100 °C temperature correction factor is (Morgan et. Al, 2010):

$$\Delta t^2 \Delta t \ast 75 / (T_{f,i} - T_{i,i})$$

Where $\Delta t^2$ is the temperature correlation time to boil water in the pots,

$T_{i,i}$ is the temperature at finish in the pots,

$T_{f,i}$ is the water temperature in the pot before commencing boiling.

Thus the thermal efficiency of the stove is obtained from (Morgan et. Al, 2010):

$$h_{th,b} = \frac{4.186 \ast \sum (P_{w,i} - P_{d,i}) \ast (T_{f,i} - T_{i,i}) + 2260 \ast w_v}{f_d \ast LHV}$$

Where $h_{th,b}$ is the thermal efficiency,

$P_{w,i}$ is the weight of pot + water;

$P_{d,i}$ is the weight of empty pot

$T_{f,i}$ is the temperature at finish

$T_{i,i}$ is the temperature at start

$w_v$ is the weight of water vaporized from the pots,

$f_d$ is the mass of equivalent dry fuel consumed, and

$LHV$ is the lower heating value of charcoal.

The thermal efficiency above is used for the high power phase (cold and hot start) with the following (Morgan et. al, 2010):

$$h_{th,h} = \begin{cases} \frac{h_{th,c}}{2} & \text{for } \Delta t_h = 0 \\ \frac{h_{th,c} + h_{th,h}}{2} & \text{for } \Delta t_h > 0 \end{cases}$$

Where $h_{th,h}$ is the thermal efficiency of the simmer test,

$h_{th,c}$ is the thermal efficiency for cold start test,

$h_{th,h}$ is the thermal efficiency for hot start test,

$\Delta t_h$ is the difference between start and finish for hot start test.

The rate of burning the fuel over the test period is:

$$\eta_b = f_d / \Delta t$$

Where $\eta_b$ is the burning rate,

$f_d$ is the mass of dry fuel consumed,

$\Delta t$ is the duration for boiling water in the pots.

The theoretical specific fuel consumption is given as:

$$SC = \frac{1000 \ast f_d \ast w_b}{w_v}$$

Where $SC$ is the theoretical specific fuel consumption,

$f_d$ is the mass of equivalent dry fuel consumed, and

$w_v$ is the equivalent mass of water boiled.

This value is normalized by temperature correction factor to give the effective specific consumption as:

$$SE = \frac{SC \ast 75}{(T_f - T_{i,i})}$$

Where $SE$ is the effective specific consumption,

$SC$ is the theoretical specific fuel consumption,

$T_f$ is the local boiling temperature, and

$T_{i,i}$ is the water temperature in the pot before commencing boiling.

Corresponding specific energy consumption is:

$$SE = \frac{SC \ast 1000 \ast LHV}{w_v}$$

Where $SE$ is the specific energy consumption, and

$SC$ is the effective specific consumption.

The fire power of charcoal is defined as (Morgan et. al, 2010):

$$FP = \frac{f_d \ast LHV}{\Delta t \ast 60}$$

Where $FP$ is the fire power of charcoal,

$f_d$ is the mass of equivalent dry fuel consumed, and

$\Delta t$ is the duration for boiling water in the pots.

The energy turn down ratio is given as the ratio of the fire power for cold start to fire power for simmer test:

$$TDR = FP_c / FP_s$$

Where $TDR$ is the energy turn down ratio,

$FP_c$ is the fire power of charcoal in cold start test,

$FP_s$ is the fire power of charcoal in simmer test.

Low power specific consumption based on simmer test values is defined as (Morgan et. al, 2010):

$$SC_{LP} = \frac{(f_d \ast LHV)}{(w_b \ast \Delta t \ast 1000)}$$

Where $SC_{LP}$ is the low power specific consumption,

$f_d$ is the mass of equivalent dry fuel consumed in simmer test,
\[ w_{5,3} \] is the equivalent mass of water boiled in Simmer test.

The fuel consumption benchmark is based on the utilization of 5 litres of water and is given by (Morgan et al., 2010):

\[ BF = 5*SC_{T, C} + SC_{T, h} forSC_{T, h} = 0 \]  \hspace{1cm} (17)

\[ BF = 5*SC_{T, C} + SC_{T, h} + SC_{T, s} forSC_{T, h} > 0 \] \hspace{1cm} (18)

Where \( BF \) is the fuel consumption benchmark,

\( SC_{T, C} \) is the temperature correlation specific consumption for cold start,

\( SC_{T, h} \) is the temperature correlation specific consumption for hot start,

\( SC_{T, s} \) is the temperature correlation specific consumption for simmer test,

The corresponding energy benchmark to complete 5 litres is (Morgan et al., 2010):

\[ BE = BF = LHV/1000 \] \hspace{1cm} (19)

Where \( BE \) is the energy benchmark, 

\( BF \) is the fuel consumption benchmark, and

3 METHODOLOGY
The Water Boiling Test (WBT) protocol developed by the Global Alliance for Clean Cooking (GACC) has been adopted. The WBT consists of three phases.

3.1 Cold start high power phase
Water at room temperature is poured in a sauce pan (three quarters full) and weighed. Charcoal pieces (of uniform size) completely filling the combustion chamber of the ICS but not touching the base of the sauce pan was weighed and put into the combustion chamber. The insulation foam was placed on the sauce pan and the thermocouple/thermocouple holder was passed through an opening on the foam into the sauce pan allowing a gap of about 5 cm from the base of the sauce pan and tip of the thermocouple. The stove was lit by using a kindler and the sauce pan placed on the ICS. The starting time was immediately recorded using a digital timer. Time at the pre-determined local boiling point was recorded, the remaining charcoal was removed from the ICS and weighed (separate from the ash). The weight of the sauce pan plus water was also recorded.

3.2 Hot start high power phase
This phase begins immediately after the cold start high power phase. With the stove still hot, the hot saucepan was refilled with the same quantity of water as in the first phase. The saucepan containing the water was weighed and the weight recorded in the calculation sheet. The foam insulation was placed on the surface of the water and the thermocouple holder placed in the sauce pan. The thermocouple was placed in the saucepan by passing it through a small opening on the insulation foam leaving a gap of 5 cm between the tip of the thermocouple and the base of the sauce pan. Temperature of water was measured and recorded in the calculation sheet. Quantity of charcoal that can fill the combustion chamber of the ICS was put in a weighing container and weighed. The weight of the charcoal was recorded in the calculation sheet. The charcoal was poured into the combustion chamber and the stove was lit. The saucepan containing water and covered with insulation foam (thermocouple inserted) was placed on the ICS. The time was noted on the digital timer and recorded on the calculation sheet. At the pre-determined local boiling point, the time and temperature was recorded. The weight of the saucepan and boiling water was also recorded (this is also the starting weight in phase 3), the charcoal in the combustion chamber was removed, weighed and recorded in the calculation sheet.

3.3 Simmering phase
The saucepan containing the hot water was immediately placed back on the ICS after the remaining hot charcoal in phase 2 has been poured back into the combustion chamber of the ICS. The water temperature did not drop 6 degrees Celsius below the local boiling point during the transition from phase 2 to phase 3 and also during the simmering process (this would have rendered the test results invalid). The temperature at the start of simmering was recorded as well as the weight of saucepan and boiling water. Simmering was carried out for forty five (45) minutes with the heat from the charcoal able to keep the water at the pre-determined local boiling point. At the end of 45 minutes, the temperature of water, weight of saucepan and the weight of charcoal remaining in the combustion chamber were recorded. WBT protocol version 4.2.2 was used to determine the efficiency of the ICS (GACC, 2013).

3.4 Drawing of ICS

![Fig. 1. Oblique Projection of the Cooking Stove](image)

![Fig. 2. Orthogonal Views and Sectional View of the Cooking Stove](image)
4 RESULT AND ANALYSIS
The result is split into three components: cold start, hot start and simmer test.

| Table 4.1 High Power Test Result for Cold Start |
|------------------------------------------------|
| Cold Start Performance | units | Test 1 | Test 2 | Test 3 | ... | Test 9 | Test 10 | Test 11 | Average | St. Dev | COV |
| Time to boil Pot #1 | min | 27 | 31 | 39 | ... | 35 | 33 | 33 | 38.64 | 7.27 | 0.188 |
| Temp-corrected time to | min | 30.09 | 34.39 | 43.85 | ... | 35.67 | 32.40 | 33.54 | 40.96 | 7.85 | 0.19 |
| boil Pot #1 | g/min | 5.78 | 5.55 | 3.69 | ... | 4.12 | 5.50 | 4.23 | 4.20 | 1.00 | 0.24 |
| Burning rate | % | 28.7% | 26.2% | 30.9% | ... | 32.6% | 29.0% | 33.9% | 31.8% | 4.8% | 0.15 |
| Thermal efficiency | g/liter | 39.17 | 42.97 | 36.27 | ... | 36.21 | 46.11 | 35.03 | 35.97 | 4.21 | 0.11 |
| Specific fuel consumption | g/liter | 43.65 | 47.67 | 40.78 | ... | 36.90 | 45.27 | 35.60 | 41.97 | 4.71 | 0.11 |
| Temp-corrected specific | kj/liter | 1124 | 1228 | 1050 | ... | 987 | 1211 | 952 | 1074 | 121 | 0.11 |
| energy cons. | watts | 2483 | 2383 | 1585 | ... | 1839 | 2451 | 1886 | 1798 | 461 | 0.26 |
| Firepower | |

| Table 4.2 High Power Test Result for Hot Start |
|------------------------------------------------|
| Hot Start Performance | units | Test 1 | Test 2 | Test 3 | ... | Test 9 | Test 10 | Test 11 | Average | St. Dev | COV |
| Time to boil Pot #1 | min | 28 | 24 | 38 | ... | 21 | 21 | 23 | 29.55 | 6.35 | 0.215 |
| Temp-corrected time to boil | min | 31.34 | 26.83 | 42.47 | ... | 21.55 | 21.84 | 23.41 | 31.75 | 7.27 | 0.23 |
| Pot #1 | g/min | 4.51 | 5.38 | 2.93 | ... | 4.79 | 7.28 | 4.25 | 4.43 | 1.14 | 0.26 |
| Burning rate | % | 35.2% | 34.6% | 40.8% | ... | 47.0% | 33.0% | 48.4% | 39.0% | 5.9% | 0.15 |
| Thermal efficiency | g/liter | 31.60 | 32.38 | 27.93 | ... | 25.30 | 38.93 | 24.55 | 31.72 | 4.62 | 0.15 |
| Specific fuel consumption | g/liter | 35.38 | 36.19 | 31.22 | ... | 25.95 | 40.50 | 24.98 | 34.03 | 5.25 | 0.15 |
| Temp-corrected specific | kj/liter | 911 | 932 | 804 | ... | 694 | 1083 | 668 | 870 | 131 | 0.15 |
| energy cons. | watts | 1936 | 2309 | 1257 | ... | 2137 | 3246 | 1896 | 1898 | 540 | 0.28 |
| Firepower | |

| Table 4.3 Simmer Test Result for Input Variables |
|------------------------------------------------|
| Low Power Simmer Performance | units | Test 1 | Test 2 | Test 3 | ... | Test 9 | Test 10 | Test 11 | Average | St. Dev | COV |
| Burning rate | g/min | 30 | 30 | 30 | ... | 30 | 30 | 30 | 30 | 7E-14 | 2E-15 |
| Thermal efficiency | % | 46.5% | 49.3% | 49.0% | ... | 52.6% | 60.9% | 54.6% | 51.9% | 4.4% | 0.084 |
| Specific fuel consumption | g/liter | 27.66 | 25.13 | 17.47 | ... | 18.05 | 28.58 | 17.81 | 24.04 | 5.517 | 0.23 |
| Temp-corrected specific | kj/liter | 712.4 | 647.3 | 449.9 | ... | 483.0 | 764.6 | 476.4 | 613.7 | 134.1 | 0.219 |
| energy cons. | watts | 1378.4 | 1258.0 | 910.0 | ... | 959.8 | 1383.1 | 945.6 | 1181.0 | 220.9 | 0.187 |
| Firepower | |
| Turn down ratio | -- | 1.80 | 1.89 | 1.74 | ... | 1.92 | 1.77 | 1.99 | 1.55 | 0.402 | 0.258 |

| Table 4.4 Benchmark Values for 5 Liters IWA Performance Result in Metric |
|------------------------------------------------|
| Units | Test 1 | Test 2 | Test 3 | ... | Test 9 | Test 10 | Test 11 | Average | St. Dev | COV |
| Fuel Use Benchmark Value | g | 335.9 | 335.3 | 267.3 | ... | 247.4 | 357.3 | 240.5 | 310.2 | 45.5 | 0.147 |
| Energy Use Benchmark Value | kj | 8651 | 8637 | 6886 | ... | 6619 | 9560 | 6434 | 7928 | 1113 | 0.14 |

| Table 4.5 IWA Performance Comparative Result in Metric |
|------------------------------------------------|
| IWA Metrics Values | Units | Test 1 | Test 2 | Test 3 | ... | Test 9 | Test 10 | Test 11 | Average | St. Dev | COV |
| High Power Thermal Efficiency | % | 31.9% | 30.4% | 35.8% | ... | 39.8% | 31.0% | 41.1% | 35.4% | 4.7% | 0.132 |
| Low Power Specific Fuel Consumption | MJ/(min.L) | 0 | 0 | 0 | ... | 0 | 0 | 0 | 0.02 | 0.005 | 0.225 |

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4.1 Carbon Savings

Possible carbon savings that can be achieved with the use of an ICS is calculated from default values of parameters published by the United Nations Framework Convention on Climate Change, thermal efficiency of ICS and statistical data obtained from study area as shown in the table below.

| Parameters | Description of Quantity | Value | Source |
|------------|-------------------------|-------|--------|
| $F_{NBS}$ | Fraction of non-renewable biomass for Nigeria | 93% | [https://cdm.unfccc.int/Panels/ssc_wg/meetings/037/ssc_37_an14.pdf](https://cdm.unfccc.int/Panels/ssc_wg/meetings/037/ssc_37_an14.pdf) |
| $NCV_{Biom}$ | Net Calorific Value of Biomass | 15MJ/kg | [https://cdm.unfccc.int/methodologies/088](https://cdm.unfccc.int/methodologies/088) |
| $EF_{fossil}$ | Emission factor of projected fossil fuel | 81.6 tCO2/TJ | [https://cdm.unfccc.int/methodologies/DB](https://cdm.unfccc.int/methodologies/DB) |
| $B_{old}$ | Average charcoal consumption | Calculated | Survey data |
| $\eta_{old}$ | Thermal efficiency of traditional charcoal stove | 11.46% | Adeyemi (2010) |
| $\eta_{new}$ | Thermal efficiency of improved charcoal stove | 35% | WBT results |

The population of Bauchi State is 4,653,066 (NPC, 2006 census) and with a growth rate of 3.2%, population is estimated at 5,931,594 in 2015. Total number of regular households is 847,731. More than 90% of the household depend on biomass for their daily cooking. Average daily charcoal consumption per household is 0.64kg in urban areas and 4.353kg in the rural areas (Adeyemi and Asere, 2007). Annual average charcoal consumption per household is estimated at 1.588 tonnes per charcoal stove. The baseline consumption for charcoal, $B_{old}$, therefore becomes:

$B_{old} = \text{Number of appliance} \times \text{estimated average annual consumption of charcoal per appliance} = 762,958 \times 1.588 = 1.21$ Million tonnes of charcoal

Biomass saved from the use of improved charcoal stove:

$B_{saving} = B_{old} \times (1 - \eta_{old}/\eta_{new})$

$= \frac{0.93 \text{ Millions tonnes of Biomass}}{0.94 \times 10^6 \text{ tCO}_2/\text{t}}$

5 CONCLUSION

This research work has looked into the biomass that can be saved by the use of ICS. The Biomass saved translates directly to carbon savings that can mitigate the effects of climate change. The thermal analysis was aimed at determining the thermal efficiency of the ICS as compared to the traditional charcoal stove as indicated in Table 4.6. The thermal efficiency of 35% (as analysed in the equations and tables above) shows possible reduction in the quantity of charcoal consumed for daily cooking. This is in comparison to the traditional stove with efficiency of 11.46% which was determined in previous work. The importance of this analysis is that the thermal performance of ICS is related to climate change mitigation. Sustainable development in the domestic energy sector by the use of ICS in households can be achieved if the biomass savings is converted to emission reductions. These reductions can be traded in what can be referred to as the carbon market as a CDM project. This would generate additional income and benefits for households and also mitigate the effects of climate change.

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WHO (2012) Study Report
# Definition of Terms/Symbols

| Symbol | Meaning |
|--------|---------|
| BE     | Energy benchmark |
| CCV    | Char calorific value |
| \( C_c \) | Weight of container plus charcoal |
| FPc    | Fire power of charcoal in cold start test |
| FPs    | Fire power of charcoal in Simmer test |
| \( f_w \) | Quantity of charcoal consumed |
| \( f_i \) | Initial quantity of charcoal |
| \( f_f \) | Final quantity of charcoal |
| FP     | Fire power of charcoal |
| \( f_s \) | Mass of equivalent charcoal consumed |
| \( f_{ds} \) | Mass of equivalent dry fuel consumed in Simmer test |
| \( f_d \) | Mass of dry fuel consumed |
| \( h_{th} \) | Thermal efficiency |
| \( h_{th,s} \) | Thermal efficiency for Simmer test |
| \( h_{th,c} \) | Thermal efficiency for cold start test |
| \( h_{th,h} \) | Thermal efficiency for hot start test |
| \( K \) | Weight of dry container |
| \( LHV \) | Lower heating value of charcoal |
| \( MC \) | Moisture content |
| \( P_{w,i} \) | Weight of pot + water |
| \( P_{di} \) | Weight of empty pot |
| \( r_b \) | Burning rate |
| \( SE \) | Specific energy consumption |
| \( SC \) | Theoretical specific fuel consumption |
| \( SC_e \) | Effective specific fuel consumption |
| \( SC_{TC} \) | Temperature correlation specific consumption for cold start |
| \( SC_{Th} \) | Temperature correlation specific consumption for hot start |
| \( SC_{Ts} \) | Temperature correlation specific consumption for Simmer test |
| \( SC_{LP} \) | Low power specific consumption |
| \( T_b \) | Local boiling temperature |
| \( T_r \) | Reference air temperature |
| \( T_f \) | Temperature at finish |
| \( T_i \) | Temperature at start |
| \( T_0 \) | Local boiling temperature |
| \( TDR \) | Energy turns down ratio |
| \( t_f \) | Stop or finish time |
| \( t_i \) | Start or initial time |
| \( w_{bs} \) | Equivalent mass of water boiled in Simmer test |
| \( w_v \) | Weight of water vaporized from all the pots |
| \( \Delta T \) | Time required to boil water in the pots |
| \( \Delta C \) | Change in weight of container plus charcoal |
| \( \Delta t_i \) | Temperature correlation time to boil water in the pots |
| \( \Delta t_h \) | Duration of heating in hot start |