Experimental evaluation of energy efficiency in a gas-heated self-contained steam jacketed kettle.

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Abstract. Gas Technological Development Center (CDT de GAS) has developed a new gas-heated self-contained steam jacketed kettle as a solution for temperature-controlled cooking of pulp fruit in the Colombian traditional candy-making industry. This initiative seeks to contribute to the promotion of natural gas as a cleaner and more efficient alternative to traditional fuels such as wood and coal in the Andean countries. Prototype follows the operational and safety rules provided by international and local standards: ASTM-F1602, ASME (section VIII, division 1), and NTC-4082. This paper presents the methodology, experimental setup and results obtained during the performance tests for heating efficiency evaluation of the kettle, according to the ASTM-F1785 standard, and the estimation of measurement uncertainty according to GUM method. The heating efficiency rate for this new prototype is higher to the convectional and commercial models of gas heated self-contained steam jacketed kettle. The results showed a heating efficiency of 63.83% ± 1.66% (k=2), whereas the emission of CO and NOₓ in stack gases was under the regulate limits for natural gas equipment.

1. Introduction

Traditional production of fruit candies is an important regional economic activity in Colombia. Hundreds of small and family businesses depend on this economic activity. For example, annual production of “bocadillo” of guava in Velez (Santander) and Ricaurte (Boyacá) regions amounts to some 24,000 to 35,000 ton a year, with a turnover of USD 24 million. Another example is the production of “arequipe” in Floridablanca (Santander) and “Manjar Blanco” in Valle del Cauca [1].

Basically, the production process consists of increasing the soluble solids concentration (Brix degree) by adding sugar (saccharose) and evaporating the water from the fruit pulp at a controlled temperature [2].

In the last decade this sector has been modernized by the introduction of best manufacturing practices (BMP) and the emergence of new lines of products and packages intended to reach international markets. Some technological improvements include the introduction of electric pulpers and the substitution of copper pots with stainless steel jacketed kettles whose steam supply comes from a steam boiler, usually fired by solid fuels such as coal or wood, because of their relatively lower price and its abundance in the region [3].
These advances have faced cultural and economic barriers hindering the sustainable development of this traditional sector. Public health issues, industrial safety and local air pollution are still of concern [4]. The Gas Technological Development Center (CDT de GAS in Spanish) seeks to contribute to the promotion of natural gas as a cleaner, safer and more efficient alternative to traditional fuels such as wood and coal. With that purpose, it is currently developing technological solutions for the sustainable use of natural gas in the traditional sectors described above.

2. Direct steam vs. gas-heated self-contained steam jacketed kettles

Direct steam kettles are semi-spherical-shaped containers, with a double bottom known as jacket. A heating fluid, e.g. water steam, flows through the jacket. The product is heated at steam saturation temperature, related to operating pressure in the jacket, typically 207 kPa - 276 kPa. The steam condenses and is drained off. Occasionally, this water is sent back to the boiler for a new cycle. Steam generation, distribution (pipes, control valves, etc.) and water return (pipes, pumps, valves, etc.) to the boiler demand extensive infrastructure under this production scheme.

Self-contained kettles, meanwhile, do not depend on an external boiler. The jacket contains water and an attached heating system (electric or gas). Steam is generated inside the jacket. Steam heats the product at the saturation temperature related to the operating pressure, but each time the condensed water drops into the jacket and boils again. In this case, the infrastructure for steam distribution and condensation return is not required [5].

This scheme is an innovative process vis-à-vis the traditional process, which relies on a boiler and a direct-steam kettle. Additionally, replacing coal and wood with natural gas has environmental, safety and operational benefits.

Since 2010 CDT de GAS, financially supported by the Colombian state science department COLCIENCIAS, has worked on the development of two self-contained steam jacketed kettles prototypes. The most important performance parameter is energy efficiency, since it is directly related to fuel costs [6]. These prototypes take into account the safety, control and performance requirements provided by ASTM F1602 [7], ASME Boiler & Pressure Vessel Code [8] and related Colombian Technical Standards (NTC in Spanish), such as NTC-4082 [9].

In 1997, a new ASTM standard for steam kettles, designed as ASTM F1785-97 [10]: Standard Test Method for Performance of Steam Kettles, was developed in the United States. This is a direct method that allows to evaluate and report the maximum energy consumption (firing rate), production capacity, heating efficiency and simmer energy rate [5]. The results, according to ASTM F1785 performance evaluation for the latest prototype developed by CDT de GAS, are shown hereafter.

3. Heating efficiency according with ASTM F1785

ASTM F1785 is a direct method for determining heating efficiency, as the ratio between the useful energy (sensible heat) and the supplied energy (chemical energy in the natural gas). Supplied energy is calculated from the natural gas volume (at standard conditions) and the High Heating Value. According to this procedure, the kettle pot is filled with clean water to 90 ±1% of the fill-to-spill volume. Water temperature is increased from 26.67 °C to 71.12 °C while natural gas pressure, temperature, volume and time are measured [10]. The mathematical expression for heating efficiency is:

\[ \eta = \frac{\text{Useful Energy}}{\text{Supplied Energy}} = \frac{m \cdot C_p (T_f - T_i)}{V_{\text{std}} \cdot H_V} \]  

(1)

Where \( m \) is the water mass, \( C_p \) is the specific heat of water, \( (T_f - T_i) \) is the temperature increasing, \( V_{\text{std}} \) is the natural gas volume at standard conditions, and \( H_V \) is the High Heating Value for natural gas.

3.1. Test conditions

The performance test for the self-contained steam jacketed kettle was developed using instruments and equipment from CDT de GAS. These instruments were selected following the appropriate range and metrological characteristics, including gas, temperature and volume of natural gas, mass and temperature of water. CDT de GAS Metrology Center is accredited by the National Accreditation
Agency of Colombia (ONAC in Spanish), according to ISO/IEC 17025:2005 [11] (Accreditation code: 10-LAB-013 [12]).

Figure 1 shows the schematic assembly for the test, and Table 1 shows the metrological characteristics of the instruments.

![Figure 1. Schematic assembly for the test.](image)

**Table 1. Measurement Instruments.**

| Instrument               | Range                  | Resolution |
|--------------------------|------------------------|------------|
| Scale                    | 0 kg - 260 kg          | 0.05 kg    |
| Barometer                | 81.1kPa - 106.1 kPa    | 1 Pa       |
| Diaphragm Flow Meter     | 0.025 m³/h - 4.0 m³/h  | 0.001 m³   |
| Differential pressure    | 0 kPa -5 kPa           | 0.03 kPa   |
| Temperature sensor       | 0 °C – 120 ºC          | 0.1 ºC     |
| Chronometer              | 0- (9h;59m;59.99s)     | 0.001 s    |

Natural gas used in the performance test is produced in *Gibraltar Well*, and supplied by natural gas transmission company TRANSORIENTE SA ESP. The composition and High Heating Value was evaluated by chromatography in the CDT de GAS Metrology Center following ASTM D3588 [13]. Table 2 shows the properties of the natural gas, and Table 3 summarizes other specific test conditions.

**Table 2. Fuel gas properties**

| Component                      | Formula | Molar concentration, % mol |
|--------------------------------|---------|----------------------------|
| Nitrogen                       | N₂      | 0.528                      |
| Methane                        | CH₄     | 89.178                     |
| Carbon dioxide                 | CO₂     | 1.850                      |
| Ethane                         | C₂H₆    | 5.759                      |
| Propane                        | C₃H₈    | 1.807                      |
| Iso-butane                     | C₄H₁₀   | 0.404                      |
| n-Butane                       | C₄H₁₀   | 0.341                      |
| Iso-pentane                    | C₅H₁₂   | 0.063                      |
| n-Pentane                      | C₅H₁₂   | 0.041                      |
Table 3. Test conditions

| Variable                        | Value       |
|---------------------------------|-------------|
| Average Atmospheric Pressure    | 90.5 kPa    |
| Average Local Temperature       | 299.2 K     |
| Water (mass)                    | 85.0 kg     |
| Water (Specific Heat)\(^b\)     | 4.18 kJ/(kg·K) |

\(^b\) Calculated using NIST Reference fluid thermodynamic and transport properties database - REFPROP

3.2. Results

Table 4 shows the results of the last 3 tests. However, 10 prior tests were carried out in order to tune and optimize the water level for boiling, and to estimate the correct position of gas injectors.

Table 4. Test Results

| Variable                          | Test 1 | Test 2 | Test 3 | Average |
|-----------------------------------|--------|--------|--------|---------|
| Injectors orifice (mm)            | 2.38   | 2.38   | 2.38   | 2.38    |
| Jacket vaporization water (dm\(^3\)) | 18    | 18    | 18    | 18      |
| Gas supply pressure (kPa)         | 1.47   | 1.37   | 1.39   | 1.41    |
| Gas supply temperature (K)        | 300.7  | 300.7  | 300.7  | 300.7   |
| Gas volume at supply conditions (dm\(^3\)) | 637   | 635   | 636   | 636.0   |
| Gas volume at standard conditions (dm\(^3\)) | 556.29 | 553.94 | 554.96 | 555.07  |
| Test time (s)                     | 1400   | 1432   | 1432   | 1421.3  |
| Supplied Energy rate (kW)         | 15.95  | 15.54  | 15.55  | 15.67   |
| Useful Energy rate (kW)           | 10.16  | 9.93   | 9.93   | 10.0    |
| Heating efficiency (%)            | 63.69  | 63.96  | 63.85  | 63.83   |

Heating efficiency was 63.83%, this a high efficiency according with previous benchmarking studies.

4. Uncertainty

ASTM F1785 suggests a method for uncertainty estimation, as the product of the Standard Deviation and an Uncertainty Factor, which depends on the number of results. The Standard deviation shows the dispersion from the representative value (arithmetic average). Accordingly, standard deviation shows the repetability of the test, but it does not take into account the uncertainty due to metrological performance of instruments [10].

4.1. Uncertainty calculated through ASTM F1785

Uncertainty for heating efficiency was estimated through the ASTM F1785 procedure. The arithmetic average for 3 results in Table 4 is 63.83 and the Standard Deviation is 0.136. For 3 results, the Uncertainty Factor is 2.48 (taken of Table A1.1 ASTM 1785 [10]). So Absolute Uncertainty is equal to the product of 0.136 and 2.48, 0.337. Finally, the expression of heating value should be (63.83 ± 0.337) % or, in relative terms, 0.638 ± 0.53%.

4.2. Uncertainty calculated through Propagation of Uncertainty

There are uncertainty sources that are not considered in the ASTM F1785 procedure. Figure 2 shows a schematic cause-and-effect diagram with the uncertainty sources related to each parameter included into the mathematical function of the heating efficiency.
As showed above, heating efficiency is a function of pressure, temperature, volume, heating value, specific heat, and mass. Each variable has uncertainties due to measurement instrument limitations or the quality of data acquired. Probability function associated to each uncertainty source can be a normal or rectangular distribution according to the data evaluation.

For example, the resolution of the scale used to measure the mass of water, limits the lower change in the mass of water that is possible to measure. Uncertainties due to repeatability refer to standard deviation of experimental values measured for a variable. Calibration uncertainties are derived by a calibration report for each instrument. Drift uncertainties refers to the stability of the instrument in a time line between calibrations. Uncertainties of High Heating Value of natural gas and Specific Heat of water depend on the calculation method.

Propagation of Uncertainty method takes into account the effect of each uncertainty variable on the result of the uncertainty function. Due to the statistical probability distribution of each variable that is known or can be assumed, it is possible to derive confidence limits to describe the region within the true value of the variable to be found [15]. Table 5 shows the uncertainties for each variable and the results obtained, according to (1).

### Table 5. Uncertainty Budget for heating efficiency measurement

| Input magnitude | Input estimate $x_i$ | Standard Uncertainty $u(x_i)$ | Sensitivity coefficients $C_{ij}$ | Contribution $C_i \cdot u(x_i)$ | Contribution (%) | Degrees of freedom $v_i$ |
|-----------------|---------------------|-------------------------------|-------------------------------|-------------------------------|------------------|-------------------------|
| Water mass (kg) | 85.00               | 0.0645                        | 0.00751                       | 0.00048                       | 0.81             | 3                       |
| Heat capacity (J/kg·K) | 4182.6          | 3.6                           | 0.00015                       | 0.00055                       | 1.05             | 149                     |
| Final temperature (K) | 70.0            | 0.18                          | 0.01596                       | 0.00280                       | 26.95            | 66                      |
| Initial temperature (K) | 30.0            | 0.18                          | -0.01596                      | -0.00280                      | 26.95            | 66                      |
| Gas volume (m³) | 0.55507             | 0.00202                       | 1.15002                       | 0.00232                       | 18.48            | 66                      |
| Heating value (J/m³) | 40135597         | 172093                        | 0.00000                       | 0.00274                       | 25.77            | 123                     |

**Combined standard uncertainty, $u_c(y)$** 0.0054

**Effective degrees of freedom, $V_{eff}$** 304

**Coverage factor, $k$** 1.97

**Expanded uncertainty, $U$** 0.0106

**Relative uncertainty, $U_{rel}$** 1.66%

**UNCERTAINTY REPORT**

Heating Efficiency $0.638 \pm 1.66\%$
Finally, heating efficiency was calculated as $(63.83 \pm 1.06)\%$ with a confidence interval of $95.5\%$ (in relative terms: $0.638 \pm 1.66\%$). This uncertainty estimated following the “propagation of uncertainty” method is higher than the uncertainty estimated through ASTM F1785. As explained earlier, uncertainty is higher due to the additional sources taken into account, but it provides a better outlook on the source of uncertainty and the best method to reduce the effect of the instruments on the measured results in order to increase the reliability of future tests.

5. **Boiler Efficiency evaluated through a gas analyzer**

*Boiler efficiency* assesses the use of the released energy in the combustion, and is equal to the product of the *combustion efficiency* and the *heat transfer efficiency* from flue gas to boiling water.

*Combustion efficiency* represents the ratio between the released energy by combustion and available energy in the fuel. This efficiency depends on the technology of the burner as well as the shape and size of the combustion chamber and the air/fuel ratio. Typically, the air excess must be 10-20\%, because deficiency of oxygen (contained in air) produces high carbon monoxide (CO) emissions. High excess of air and high temperatures produce nitrogen oxides (NOx) emissions.

High excess of air produces a high volume of inert products (as nitrogen) in the flue stack. The excess of flue gas reduces the heat available for transfer to vaporization water in the heat exchanger, as part of this energy is removed by the excess of nitrogen in flue gas [16].

Boiler efficiency can be evaluated with a *Flue Gas Analyzer*. This equipment measures the concentration of oxygen, carbon dioxide, carbon monoxide, nitrogen oxides and flue stack temperature. With these parameters, the Analyzer calculates the air excess in the flue gases, and the *boiler efficiency* of the self-contained steam jacketed kettle [17]. Table 6 shows the metrological characteristics of the Flue Gas Analyzer.

| Device | Gas Handheld Analyzer AMPRO 2000 |
|--------|-----------------------------------|
| Manufacturer | MRU Instruments, Inc. |

| Component               | Range           | Accuracy                  |
|-------------------------|-----------------|---------------------------|
| O₂ Oxygen               | 0-21 Vol.-% abs.| ± 0.2 Vol.-% abs.         |
| CO₂ Carbon dioxide      | 0 % -20 %       | ± 0.4 Vol.-% abs.         |
| CO Carbon monoxide      | 0ppm -4000 ppm  | ± 20 ppm o 5% reading < 4000ppm |
| NO Nitrogen monoxide    | 0ppm -1000 ppm  | ± 5 ppm o 5% reading <1000ppm |
| NO₂ Nitrogen dioxide    | 0ppm -200 ppm   | ± 5 ppm o 5% reading <200ppm |
| T-Gas Gas flue temperature | ≤ 650 °C       | ± 2.0°C <200°F/1% reading >200°F |
| T-Air Local Air temperature | ≤ 100°F        | ± 1.8°C                   |
| Boiler Efficiency       | 0 % - 100%      | -                         |
| Air excess              | 0 % - 99.9 %    | -                         |

Boiler efficiency was measured at the same conditions of the heating efficiency test. According to calculations made by the analyzer, excess air was set between 15-20%. Boiler efficiency decreased from 89% to 84% as flue stack temperature increased from 164°C to 210°C. Figure 3 shows this behavior: boiler efficiency is inversely proportional to flue stack temperature, because the temperature difference between the combustion gases and the vaporization water decreases during the test, so the heat transfer potential is lower at the end of the test.
Simmer Energy Rate

ASTM F1785 established a procedure to determine the simmer energy rate. It accounts for the firing energy rate necessary to hold the cooking product at set temperature for a period of time. This test is conducted after the heating efficiency test. The kettle temperature controller is set to 74 ± 0.5ºC. When the kettle reaches this temperature, the controller shuts off the main solenoid valve, and the gas burners turn off. When temperature is below the set point, the controller opens the solenoid valve, the burners turn on, and temperature increases again until the set point is reached. The simmer energy test was conducted for 3 hours, and several cycles of heating (burners being turned-on) and cooling (burners being turned-off) may occur during this time span. [10]

Figure 4 shows the temperature behavior during the test. Set-point temperature was 74ºC and the temperature controller had a minimum hysteresis of 1ºC, so the upper limit was 74.5ºC and the lower limit was 73.5ºC.

Water temperature changed from 73.3 ºC to 76.6ºC. Although the burners are turned off when temperature reaches 74.5ºC, temperature increases to 76.6ºC due to accumulated energy as steam pressure (latent heat). When temperature reaches the peak, it decreases as the internal pressure decreases due to boiling down of steam inside the jacket. It is important to remember that steam temperature (and cooking water) is directly related to and depend on the saturation pressure (operating pressure inside the jacket). Heating time (burners turned on) lasts 5 minutes, and cooling time (burners turned off) lasts 30 minutes, so keeping a given temperature requires that kettle stays off longer than it stays on, reducing fuel costs.
Simmer energy rate is calculated as the ratio between the net volume of natural gas and the test time (approx. 3 hours). In this case, the apparent energy rate is 2.19kW. Power is just 13% of the nominal energy rate for heating.

7. Conclusions

It was applied the method of “propagation of uncertainty,” as an alternative to the method proposed by the ASTM F1785, whereby a more reliable estimation of the results was obtained during test heating efficiency.

Energy efficiency of the self-contained steam jacketed kettle was assessed according to ASTM F1785 and two representative parameters were evaluated: (a) heating efficiency, with average value of 63.83±1.06% for a nominal firing rate of 15kW, and (b) simmer energy rate, with average value of 2.19kW.

The Boiler efficiency, for the new kettle, was measured at the same conditions of the heating efficiency test. With an excess air between 15%-20% the Boiler efficiency varied from 89% to 84% as flue stack temperature increased from 164ºC to 210ºC.

The performance is better than similar appliances. According to benchmarking published by the United States Food Service Technology Center (see the Steam Kettle Technology Assessment report [5]), same-size conventional self-contained kettles (gas-heated) with a similar size have a heating efficiency ranging between 39%- to 54%, as evaluated with ASTM F1785.

8. References

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