African Journal of Science, Technology, Innovation and Development
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rajs20

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Published online: 24 Jul 2015.

To cite this article: Clément Ahouannou, Fidèle Tchobo, Emile A. Sanya, Christa Lokossou & Mohamed Soumanou (2015) Performance and design optimisation of an apparatus for distilling palm wine (Elaeis guineensis) by controlling thermal operations, African Journal of Science, Technology, Innovation and Development, 7:3, 165-176, DOI: 10.1080/20421338.2015.1031460

To link to this article: http://dx.doi.org/10.1080/20421338.2015.1031460

African Journal of Science, Technology, Innovation and Development, 2015
Vol. 7, No. 3, 165–176, http://dx.doi.org/10.1080/20421338.2015.1031460

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Performance and design optimisation of an apparatus for distilling palm wine (*Elaeis guineensis*) by controlling thermal operations

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Mastery of thermal control in the craft distillation processing operations of fermented wine from *Elaeis guineensis* is needed to improve and enhance the resulting Beninese alcoholic drink, *sodabi*. In this study, craft distillation of palm-wines from three municipalities of southern Benin was investigated and the influences of wine vapour temperature on some physical-chemical parameters of the liquor produced were analysed. Palm wines, handcraft distilled, presented relative density values between 0.90 to 0.96, volumetric alcoholic strength from 35.16 to 46.29% (v/v), acetic acid content of 1.17 to 3.29 g/l and pH-values of 3.7– 4.2. A series of palm-wine distillations, from liquor-producing farms, controlled by maintaining the heating temperature at 94 ± 1 °C, was also performed. The values of characteristic parameters were then respectively 0.84 to 0.93, 38.05 to 52.72% (v/v), 0.35 to 0.39 g/l and 4 to 4.25. From analysis of these results, we conclude that the high values of wine heating temperature, well above 100 °C, induce a significant increase in relative density and acetic acid content of *sodabi* and a decrease of its volumetric alcoholic strength and pH-value. Controlled laboratory distillation yielded a distillate which has the best features of spirituous and thermal efficiency.

Keywords: Palm-wine, heating, *sodabi*, characteristics, quality

JEL classification: O30, O31, O55

Introduction

The distilled product from fermented wine extracted from the oil palm-tree *Elaeis guineensis*, a hard liquor, is known by many names in West Africa, for example, *akpeteshie* in Ghana, *matango* in Cameroon, and *ogogoro* in Nigeria, plays a central role in traditional West African society (Béhi et al. 2002, 8, Ukhun et al. 2005: 4, Amoa-Awua et al. 2006: 8). Prepared for the first time in Benin by brothers Gbèhalaton and Bonou Kiti Sodabi in Sedje Houègoudo village, a former subdivision of Allada and currently belonging to the municipality of Zê (Aionou 1993, 120, Ade et al. 2010, 8), *sodabi* (its Beninese designation) is defined by Nago et al. (1994, 59) as a 'water of life' originally obtained by distilling fermented palm wine.

The *sodabi* became the most locally popular prized spirituous drink and its production is of paramount importance in the lives of most people of southern Benin (Ade et al. 2010: 8). In Côte d'Ivoire, the same liquor, called *koutoukou*, occupies a prominent place in both the consumption of alcohol and in the socio-cultural habits of the people's beverages (Camara 2002: 6). According to a study, *koutoukou* has been proved to be as beneficial as any other alcoholic beverage for liver functions as well as lipid metabolism, if consumed in moderation, about 125 ml per day (Tehoua et al. 2011, 8). However, it's shown, among other things, that the heating of palm wine based entirely on sensory assessment does not effectively allow for control of the influence of temperature gradient (Aiounou 1993, 120), while Okechukwu et al. (1984, 3) and Olasupo and Obayori (2003, 8) revealed the positive impact of controlled heating of palm wine on the quality of *ogogoro*, the Nigerian equivalent of Beninese *sodabi*. The traditional process used in Benin for *sodabi* has remained unchanged in its design and is consistent with the description given by Aiounou (1993, 120). This reflects the non-improvement of this technology over the past quarter century, although some variations in the conduct of operations were noted from one region to another.

The international literature reveals very little information on this traditional technique of distilling wine of the oil palm (*Elaeis guineensis*). However, it was possible to improve and standardise the distillation process for Nigerian *ogogoro*, which become a favourite imported spirit (Olasupo and Obayori 2003, 8). This study therefore aims to improve the quality of the process of distillation and obtain better added value for *sodabi* in Benin.

Material and methods

Areas of study and equipment

The reported investigation was conducted in three local *sodabi* producers' communities of southern Benin: Bonou in Ouémé Department, Dogbo in Couffo Department and Abomey-Calavi in Atlantic Department. This choice of study areas and producers was made following the non-probabilistic statistical method, known as rational choice, after conducting a preliminary investigation. In this study, we used mainly four different types of material:

- Fresh palm wine was taken from oil palm trees *Elaeis guineensis* in the above three different localities. The chemical analysis of freshly collected palm sap shows that it is made of 16% solid matter, 13% sugars, 0.30% proteins, 100 to 200 mg/l of vitamin C and 10^8/ml yeast (Aiounou 1993, 120, Ezeagu and Fafunso 2003, 10, Ukhun et al. 2005, 4). However, after 24 hours of natural fermentation at 28–30 °C, according to the same authors, the sugars have virtually disappeared with the advent of alcohols and acids in following proportions: 6.70% alcohol, 0.69% acids and 0.58% of remaining sugars (Nwachukwu et al. 2006, 9).
- The wine distillation craft device, illustrated in Figure 1, is a thermal physical method for separation of constituents of a 'zeotropic' mixture. The provided materials, as well as some details of used operations, can vary in time and space, but the basic principle remains the same. It consists of a rustic 'alembic', usually manufactured from recycled materials: one or two steel drums of 200 liters each, 2 to 4 earthenware jars or half drums containing cooling water and a copper pipe for condensing the *sodabi* vapour. The whole drum, sealed and placed on a hearth stone, functions as a boiler (hence drum-boiler). A long copper tube of about 4 m, fashioned in a spiral of three to five turns per jar in each cooler, ducts the *sodabi* steam or mixture of steam and condensate, depending on the stage of cooling.
- The conventional distillation apparatus of the Research Laboratory Unit in Enzymatic and Food Engineering (URGEA) is made up of a heating mantle, a round-bottom flask, a distillation column, water condenser, a container for collecting distillate and a classical water supply.
- The temperature measuring device consists of set of five thermocouples K (Ni-Al) type that can withstand temperatures of about 1260 °C and a brand OXFORD tenth digital temperature reader.

Method

The drum that serves as a boiler is filled with fermented wine (substrate) to a quarter or a third of its capacity. Some farmers fill it to half or two-thirds capacity. After filling, the drum is sealed to prevent leakage of *sodabi* steam. The fire is lit and fanned if needed. The operator continually monitors the temperature of cooling water in each of four condensing tanks (Figure 1). During the distillation process, the operator ensures the constancy of temperature in the drum-boiler, checking regularly on the fire. The vapour gradually formed on top of the boiled palm wine escapes, passing through the copper pipe. This *sodabi* vapour flows through the spiral copper pipe, which is laid in condensing tanks filled with cold water, where it loses heat and then condenses and becomes liquid alcohol locally called *sodabi*. This liquid is collected at the free end of the copper tube into containers, either by range of alcoholic degrees (for example, after passing through one or more of the three condensers), or all at once (at the last condenser ending). This recovered alcohol is distilled once again, either alone or in combination with new fermented palm wine. This second distillate is of high quality and highly prized by consumers. Samples from the palm wine and resulting distilled *sodabi* are collected at each distillation site, at regular intervals (every 10 minutes), for determination of their thermal and physicochemical characteristics.

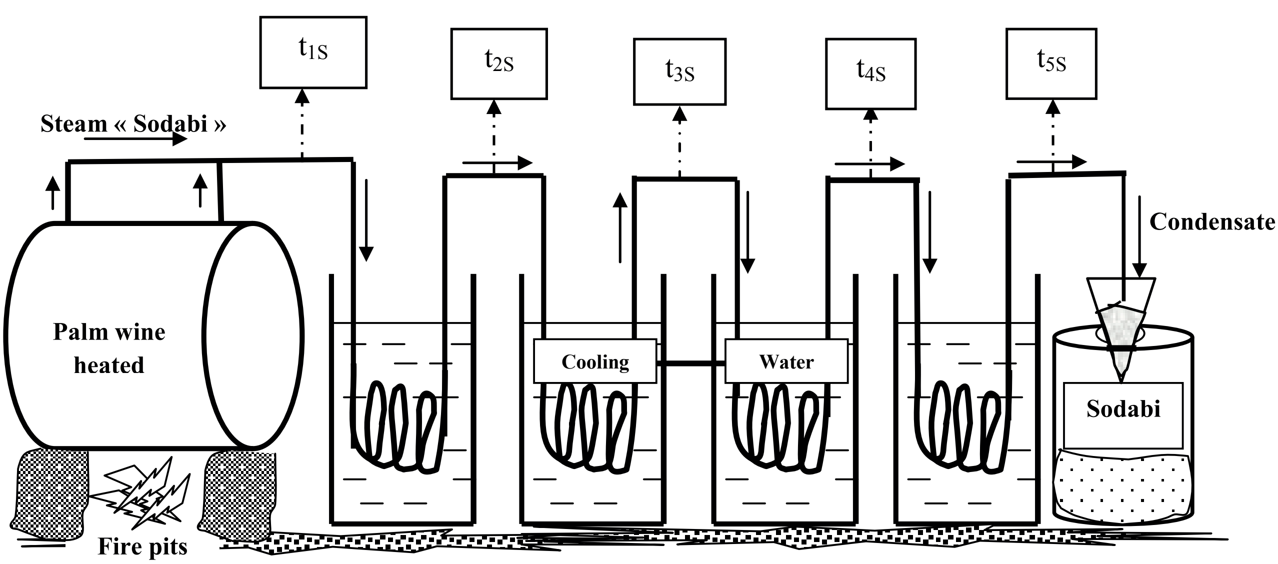


Figure 1: Physical representation of the distillation unit of palm wine and arrangement of thermocouples.

Heating temperature of the palm wine

Controlled production of *sodabi* was conducted to assess the influence of heating control of the wine on the physical-chemical characteristics of the product. Thus, distillation was done by heating modulation in order to maintain the palm wine temperature, from its first boiling bubbles, at 94 °C ± 1 °C for the two hours distillation duration.

Indeed, a very low temperature during distillation prolongs the process while a very high temperature could lead to excess water evaporation of (Olasupo and Obayori 2003, 8). The temperature must be kept between two values: one located around the boiling point of ethanol, 75–80 °C, and the other below the boiling point of water (100 °C).

Balance of heat exchange at the distillation process

The distillation process is described in three main stages and Figure 2 shows these steps and the thermal operations associated with it.

We are interested in the heat exchanges balance at the process level during the various rounds of distillation to account for the thermal efficiency of the device, its production performance and the quality of the produced *sodabi*. Thus, we followed the temperature evolution of the fermented palm wine and formed *sodabi* steam (tS) during the distillation process, by means of thermocouples installed at different locations as indicated by t1S to t5S in Figure 1. These thermocouples allowed for direct recording of temperatures of the distillation apparatus, every ten (10) minutes for 2 h 20 min. We estimated the initial temperature of *sodabi* steam t1S as equal to the measured temperature of heated palm wine (liquid-vapour equilibrium phase) for establishing done balances below (Mafart 1980, 164, Visser and Frederiks 2006, 158).

The quantity of heat supplied by the biomass-energy for distillation cycle is given by the following expressions:

$$m = m_\upsilon \cdot \upsilon \quad (1)$$

$$Q_{sup,\ bio} = \eta_{com} \cdot m_h \cdot PCI \quad (2)$$

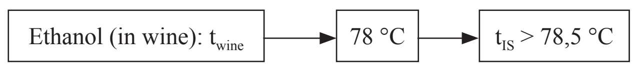
$$Q_{receiv} = \eta_{foy} \cdot Q_{sup,\ bio} \quad (3)$$

All energy quantities transferred or received by the distillation system are determined using the Joule relationship $Q = m \cdot C_p \cdot \Delta t$ (4)

Thus, different quantities of heat received or supplied by the system to achieve the production of *sodabi* are obtained by the mathematical models below:

- Quantity of heat received by the ethanol which is vaporised

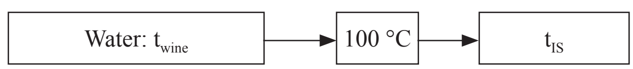
The amount of heat received during the various stages of processing undergone by ethanol, which is vaporised, are presented as follows:



$$Q_{eth} = m_{eth} \cdot [(Cp_{eth,\ liq}\ (78{,}5 - t_{wine})] + L_{v,\ eth} + [Cp_{eth,\ vap} \cdot (t_{1S} - 78{,}5)] \quad (5)$$

- Quantity of heat received by the water which is vaporised

The different states of transformation undergone by the water spray are presented as follows:



$$Q_{water} = m_{water} \cdot \{[Cp_{water,\ liq}\ .\ (100 - t_{wine})] + L_{v,\ water} + (Cp_{water,\ vap} \cdot (t_{1S} - 100)]\} \quad (6)$$

- Quantity of heat stored in the vinasse (residue of palm wine at the end of the process)

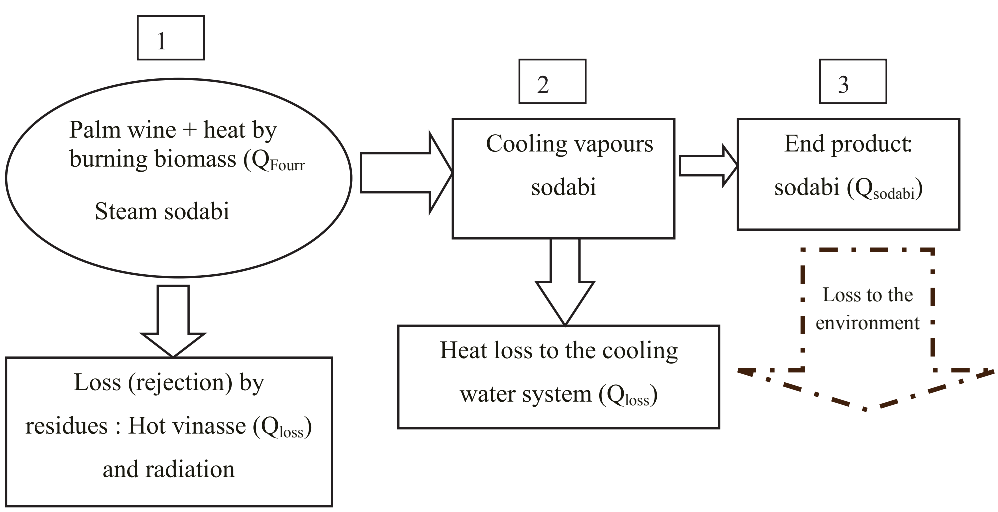


Figure 2: Thermal model of the distillation system (The three stages of thermal operations)

The different states of transformation undergone by vinasse are presented as follows:

$$Q_{vinas} = m_{vinas} \cdot [Cp_{vinas} \cdot (t_{vinas} - t_{wine})] \quad (7)$$

- Quantity of heat stored in the accessories of the distillery

$$Q_{access} = \sum_{i=1}^{n} m_{i,\ access} \cdot Cp_{i,\ access} \cdot (t_{if} - t_{ii}) \quad (8)$$

- Quantity of heat used to the vaporisation

$$Q_{vap} = Q_{eth} + Q_{water} \quad (9)$$

- Total quantity of heat received by the distillation system

$$Q_{syst} = Q_{eth} + Q_{water} + Q_{vinas} + Q_{access} \quad (10)$$

- Quantity of heat transferred from the system to the environment (Q_{env})
  - *Quantity of heat transferred to the cooling water*

$$Q_{cool} = \sum_{1=n}^{n} m_i \,.\, Cp_{water,\ liq} \cdot (t_{if} - t_{ii}) \quad (11)$$

  - *Quantity of heat transferred from the environment to the sodabi*

$$Q_{sod} = (m_{water,\ sod} \cdot Cp_{water,\ liq} + m_{eth} \cdot Cp_{eth,\ liq}) \cdot (t_{nS} - t_{amb}) \quad (12)$$

Therefore the quantity of heat liberated to the environment through the distillation process, to ensure the production *sodabi* is given by the following expression:

$$Q_{env} = Q_{cool} + Q_{sod} + Q_{access} + Q_{vinasse} \quad (13)$$

The quantity of heat actually used for the extraction to the *sodabi* is:

$$Q_{use} = Q_{receiv} - Q_{env} \quad (14)$$

  - *Calculation of theoretical thermal efficiency of distillation*

$$\varepsilon_{th,\ syst} = \frac{Q_{reveiv}}{Q_{supp,\ bio}} \quad (15)$$

- *Calculating the thermal performance of process and vaporisation*

$$\varepsilon_{th,\ proc} = \varepsilon_{real} = \frac{Q_{use}}{Q_{reveiv}},\ \varepsilon_{th,\ vap1} = \frac{Q_{vap}}{Q_{receiv}},\ \varepsilon_{th,\ vap2} = \frac{Q_{use}}{Q_{vap}} \quad (16)$$

Physicochemical characteristics of sodabi

These characteristic were determined with OIV (2012, 509):

- the pycnometer (for relative density DR) according to OIV-MA-AS2-01A method: R2009. In the absence of a pycnometer, a 5-ml volumetri(c flask was used.
- pH-meter (for pH) previously calibrated with standard solutions of pH 4 and 7 respectively, using the OIV-MA-BS-13: R2009 with a brand HANNA (HI96107).
- The volatile acidity (AV) was determined by titration of 5 ml of each sample with a standard solution of sodium hydroxide at NaOH concentration of 0.1 N in the presence of an indicator, phenolphthalein 1% according to standard method-OIV MA-AS313-02, and
- the volumetric alcoholic titration (TAV %v/v) is calculated from results of ethanol dosage according to Cordebard nitro-chromic method. This is based, on one hand, on cold ethanol oxidation by potassium dichromate excess solution in an acidic medium and, on the other hand, on the back-titration of excess dichromate ions by iodometry.

The Principal Component Analysis (PCA), a statistics exploratory method that allowed describing a wide array data of individuals/variables type, was performed using the SPAD version 5.5 software. The analysis of variance (ANOVA) was realised on it with the SPSS Version 16.0 software.

Results and discussion

In the real environment, ie at the producer farmers, the recorded values of physico-chemical parameters (DR, pH, AV and TAV) were determined as described for wines palm of different origins, and are as shown in Table 1. Thus, the listed characteristics are obtained under thermal conditions presented for the case of the village of Bonou, in Figure 3.

Influence of the duration of the fermentation process

Analysis of data in this table shows that Dogbo's palm wine undergoing fermentation period of eight (08) days is the one that presented the best characteristics in terms of density and alcohol content. The alcohol contents of the studied wines vary between 8.95% and 12.45%, values which are consistent with those from Aiounou (1993,

Table 1. Physico-chemical characteristics of palm wine distilled.

Municipal cities	DR	pH	AV (%)	TAV (%v/v)
Bonou	1,00 ± 0,01 (b)	4,05 ± 0,01 (c)	0,74 ± 0,01 (a)	10,70 ± 0,22 (b)
Dogbo	0,99 ± 0,01 (a)	3,5 ± 0,05 (b)	1,17 ± 0,01 (b)	12,45 ± 0,22 (c)
Abomey−Calavi	1,00 ± 0,01 (c)	3,3 ± 0,01 (a)	1,67 ± 0,01 (c)	8,95 ± 0,22 (a)

Note**:** The carrying values in the same column, different letters are significantly different at the 5% level.

120). The other obtained a rate of 6.70% after 24 hours of fermentation. The recorded results for volatile acidity (AV) also show very consistent values with those from the same author, who estimates the acid content to 0.58% after 24 hours of fermentation. Note however that the observed differences for these three wines should not be solely attributed to change in duration of fermentation, since the initial composition of fermenting palm wine and occasional addition of "chila", a distillate of latter category of very low alcohol content, have influenced the values of physicochemical characteristics (case of Dogbo distillation).

Influence of temperature on the physico-chemical characteristics

Figure 4 illustrates the evolution of the temperature of the steam *sodabi* the boiler outlet, for the three different study areas. It presents the respective boiling points early palm wine marked by coordinates (time, temperature). The gap between the different boiling points shows the difference in the conduct of three distillation of palm wine. For the same flow rate of distilled wine (0,833 l/min), the heat inputs required are respectively 681 kJ/l of wine (for Bonou) 636 kJ/l (Dogbo) and 660 kJ/l (Abomey-Calavi), an average of 11 kW/l of palm wine for extraction *sodabi* of 0.20 l/min.

All figures identified Figure 5, showed a generally increasing trend of t_{1S} temperature and the physico-chemical characteristics of *sodabi* for the three distillations.

The relative density of samples from Bonou *sodabi* ranged from 0.92 to 0.99, those of Dogbo 0.88 to 0.91 and Abomey between 0.91 and 0.97. The highest densities have been obtained for distillation of Bonou palm wine. But the latter also presented the higher temperature values: between 107 °C and 118 °C. The lowest values were obtained for distillation of Dogbo palm wine with the lowest temperature values: 94 °C to 109 °C. Very high

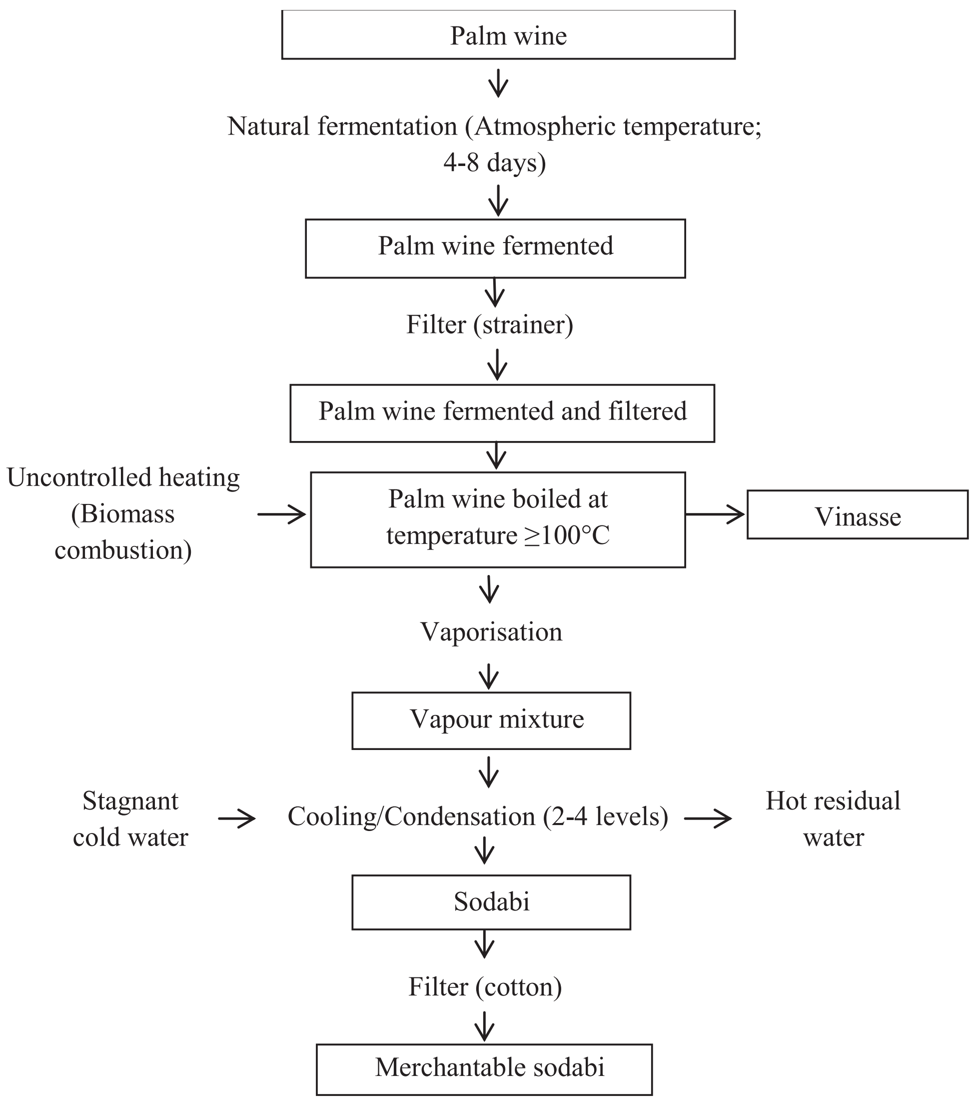


Figure 3: Technological diagram of artisanal *sodabi* production

temperature values t_{1S} during palm wine distillation have led to a large increase in relative density value. This could be justified by a greater amount of water vaporisation when the temperature reaches and exceeds 100 °C.

The obtained curves for variation of volatile acidity (Fig. 5b) showed the same increasing pace trend as for associated temperature curves of Figure 5. This could be justified by vaporisation of acid when temperature is around 118 °C. The lowest values of volatile acidity 0.10 to 0.13% were recorded from distillation of Dogbo palm wine. Obtaining lower acetic acid content *sodabi* is thus conditioned by lower temperatures t_{1S} during the wine heating.

Changes in temperature and pH of *sodabi* over time (Fig. 5c) show that, for the three palm wines distillations, an instantaneous rise in temperature leads to a decrease in pH. Indeed, the pH ranged from 4.75 to 3.25 for Bonou wine, 4.75 to 4.10 for Dogbo one and 4.10 to 3.20 for Abomey wine. Samples of *sodabi*, from Dogbo palm wine distillation at the lowest t1S values were found to be the least acidic of the three studied areas.

The recorded curves in Fig. 5d reflect a decrease of *sodabi* TAV for the studied palm wines from the three distillation sites over the time. This could be justified by the scarcity of ethanol vapours when temperature rises and exceeds 78.5 °C during the process. At Bonou and Abomey, the alcoholic TAV significantly decreased respectively from 46.09 to 7.64% and 46.80 to 14.85% while at Dogbo, it has changed little, only from 48.11 to 35.23%.

It would have been possible to combining the high values of TAV for Dogbo samples only to high alcohol content of its palm wine (12.45%). However, by considering that there is a significant difference at the 5% confident level between alcohol content of Bonou palm wine (10.70%) and Abomey (8.95%), we could have wait to get *sodabi* having a higher TAV from Bonou palm wine.

The opposite result was noted that better highlighting the impact of very high temperatures on significant decrease in TAV values. Therefore, regardless of alcohol content of palm wine, very high t1S temperatures during heating led to a significant decline in quality of resulting spirituous.

Statistical studies of the values of the characteristic parameters obtained sodabi

The results of existing correlations study between measured different characteristics on different samples are shown in Table 2.

The analysis of data in Table 2 shows that there are strong correlations between the six (06) studied variables. These correlations are confirmed by results of Principal Component Analysis (PCA) shown in Fig. 6 and 7. Applied PCA analysis to different physical chemical characteristics and initial temperature of *sodabi* steam, indicates that the first factorial axis alone explains almost 82 % of the total inertia of cloud points, which is widely sufficient to ensure accurate analysis.

This factorial axis (Figure 6) takes into account both the variables pH and volumetric alcoholic titration (TAV) negatively correlated with relative density (RD), volatile acidity (VA) and temperature.

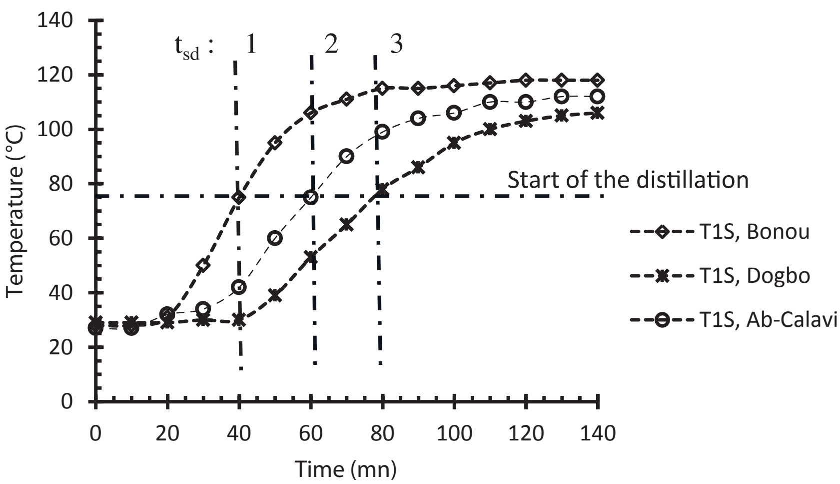


Figure 4: Temperature (T1S) of *sodabi* steam during distillation process on the three sites for testing

Table 2: Correlation between variables.

Variables	TjS	DR	AV	pH	TAV
TjS	1,00				
DR	0,75**	1,00			
AV	0,33	0,74**	1,00		
pH	−0,62**	−0,87**	−0,86**	1,00	
TAV	−0,84**	−0,92**	−0,57**	0,83**	1,00

**Correlation significant at the 1% (Pearson).

The produced *sodabi* samples which presented a pH and a high TAV are, at the same time, those which have submitted the lower values for the three variables as initial steam temperature, relative density and volatile acidity.

The projection of all samples of *sodabi* from all three studied palm wine regions on the factorial design graph gave results of Figure 7. Overlaying figures 6 and 7, four major *sodabi* clusters were formed. The first group contains A4 to A8 samples observed between 40 and 80 minutes at Abomey-Calavi mainly characterised by high volatile acidity. Samples A0, A1, A2 and A3, also observed at Abomey-Calavi in the first 30 minutes, constitutes those of second group and are mainly characterised by high alcohol content. The third group, consisting of samples B2, B3, B4, B5 and B6, is that of obtained *sodabi* samples between 20 and 60 minutes at Bonou. They are mainly characterised by a high initial temperature of *sodabi* steam. Finally, the obtained samples D2, D3, D4, D5, D6, D7 and D8 at Dogbo between 20 and 80 minutes on the one hand, and B0 sample from Bonou, as observed early of processing on the other hand, form the last group essentially characterised by their high pH-values.

In general manner, combinations of these tested *sodabi* samples were made by region. Therefore, there is a high variability as well, between the physicochemical characteristics of *sodabi* samples of the three regions, as those for inner samples from Abomey-Calavi region. Only samples from Dogbo, less scattered, showed some consistency in the evolution of physicochemical characteristics and temperature.

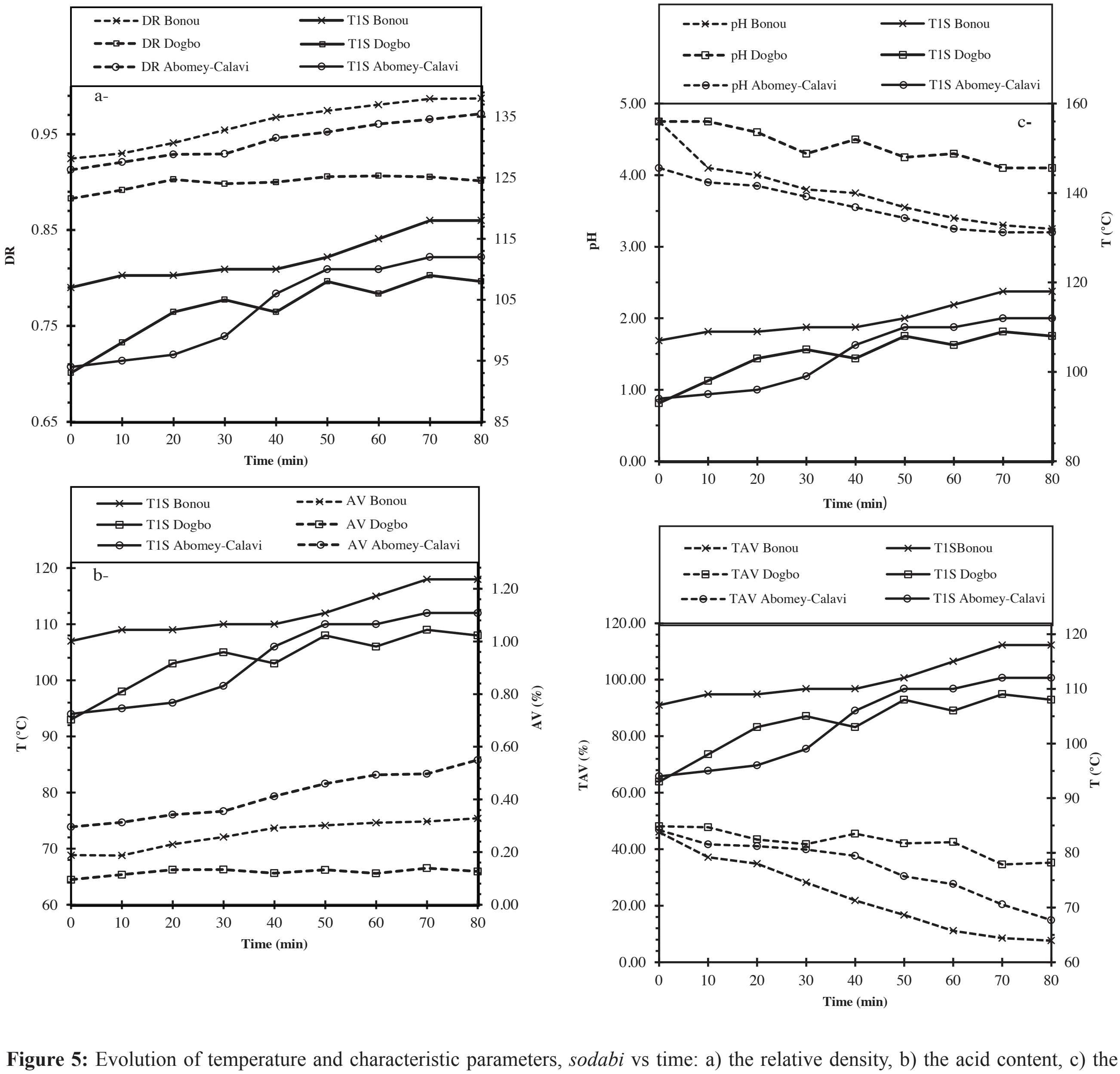


Figure 5: Evolution of temperature and characteristic parameters, *sodabi* vs time: a) the relative density, b) the acid content, c) the pH, d) the alcoholic strength

Evaluation of the heat inputs required for the distillation

The study of the thermal behavior of the distillation apparatus was made using the average values of different characteristic parameters below:

For one (01) kg of produced *sodabi*, the quantity of lost energy in distillation processes for the three sites are significantly different, the highest value observed at Abomey-Calavi (2086.56 kJ). Yields thermal distillation operations are calculated: apparatus ($\varepsilon_{th,syst}$), process (εth,proc), vaporisation 1 ($\varepsilon_{th,vap1}$) and vaporisation 2 ($\varepsilon_{th,vap2}$). The values obtained are given in Tables 3 and 4. These values obtained from the three test areas are acceptable agreement and averages for each operation are respectively 80.51, 41.16, 61.15 and 67.35, with a mean difference of 10.45, 0.82, 1.29 and 2.02.

The process Dogbo with a yield of about 63.1%, was more energy efficient than the two others. This is mainly due to moderation of wine heating in this locality. Figure 8 shows the state of the thermal exchanges made during the distillation of the various areas of study. It highlights the loss of stored energy in a thermal operation of a craft or industrial equipment (Mafart 1980: 164). In the case of

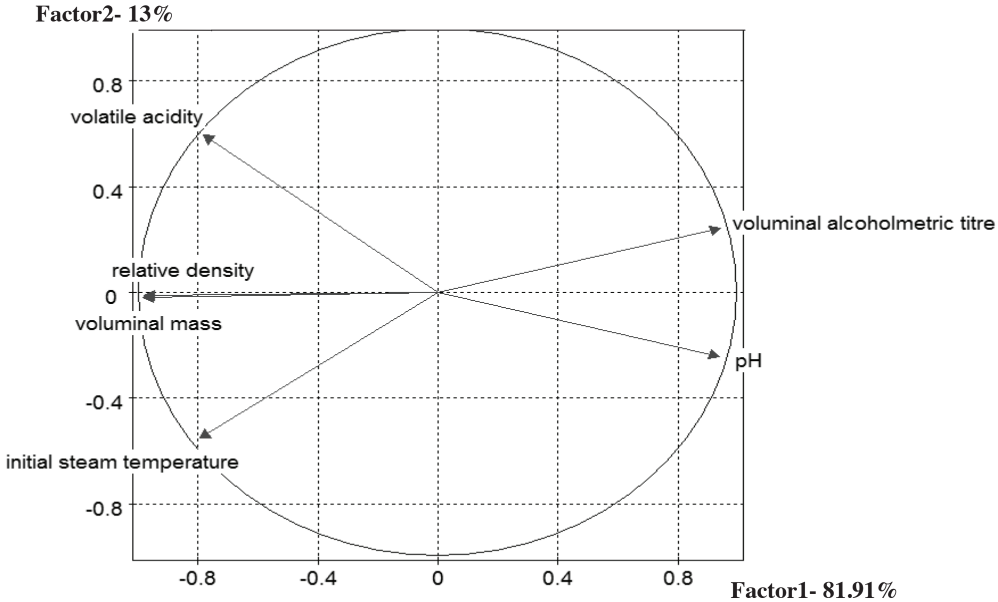


Figure 6: Representation of the physico-chemical characteristics and the temperature in the factorial

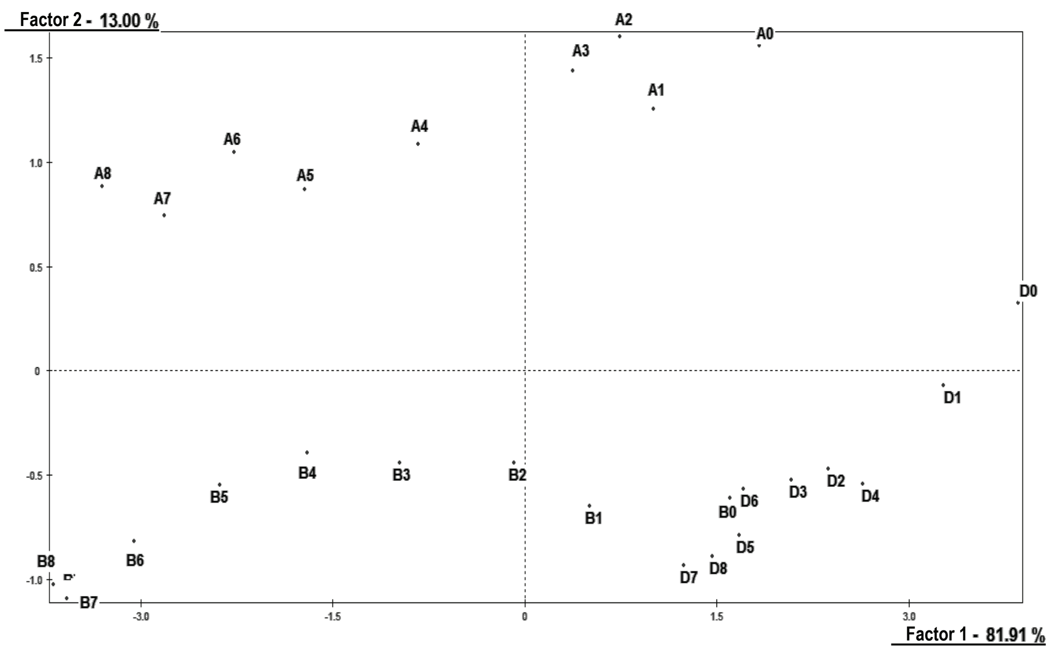


Figure 7: Representation of *sodabi* samples in factorial

Table 3. Mean values of various parameters thermophysical characteristics of the components of palm wine

Components	Physical state	Mv (kg/m³)	Cp (kJ/kg. °C)	Lv (kJ/kg °C)
Water	Liquid	1000,00	4,18	–
	Vapour	–	1,92	2257,90
Wine	Liquid	996,26[1]	4,42*	–
Ethanol	Liquid	780,00*	2,84*	–
	Vapour	–	1,88*	855,00*
Vinasse	Liquid	994,00*	4,35*	–

Source: www.crdp-montpellier.fr/ressources/examens/sujet/04/400/2200200/E2/u02_n1_d01.pdf

Table 4. Efficiency of thermal operations on three test areas (%)

Locality	^syst	^proc	^vap1	^vap2
Bonou	70,96	42,39	60,31	70,29
Dogbo	96,17	40,58	63,09	64,32
Ab–Calavi	74,38	40,50	60,04	67,45
Average	80,51	41,16	61,15	67,35
Mean deviation	10,45	0,82	1,29	2,02

our study, the heat loss is very important and justifies the appropriateness of the study.

The arrangement of the four yield curves and their evolution as a function of temperature reveal a normative trend of the yield curve. In Figure 9, three yield curves are significant ($\varepsilon_{th\,syst}$, $\varepsilon_{th\,proc}$ and $\varepsilon_{th\,vap1}$) to predict the energy needs of the thermal system and the technological improvement contributions may be applied. We found that the thermal efficiency of the traditional process (system) is very high compared to the distillation process. All performance curves actually reflect the efficiency of a thermal system is best when the operating temperature is carefully chosen.

Every produced final *sodabi*, from studied palm wines of the tested three areas, has a density which varies from 0.90 to 0.96, a pH from 3.7 to 4.2, acetic acid content from 1.17 to 3.29 g/L and alcohol content between 35.16 and 46.29 %. There is a significant difference at 5 % confident level for all parameters. Found values for volumetric alcoholic titration are higher than those proposed (26.8 and 39.9 %) in Nigeria (Olasupo and Obayori 2003, 9, Ogbulie et al. 2007, 8).

Only the alcoholic strength value of *sodabi* from Dogbo palm wine is consistent with the obtained values by Aiounou (1993, 120) for which, *sodabi* in its commercial form, has from 40 to 60% ethanol. The values of volatile acidity provided by wines from Bonou and Abomey are greater than the published value of 1.42 g/l from the same author, while acidity value of Dogbo wine below this value. It is noted, however that, obtained *sodabi* from Bonou and Abomey was intended to undergo further distillation, their respective alcohol degrees have been recognised as insufficient.

Each sample of fermented palm wine was twice distilled. Two (02) types of *sodabi* are obtained from each palm wine. Each analysis was twice performed on each produced type of *sodabi*. For every physicochemical characteristic, the retained results represent the mean of obtained mean-values for the two *sodabi* types from each sample.

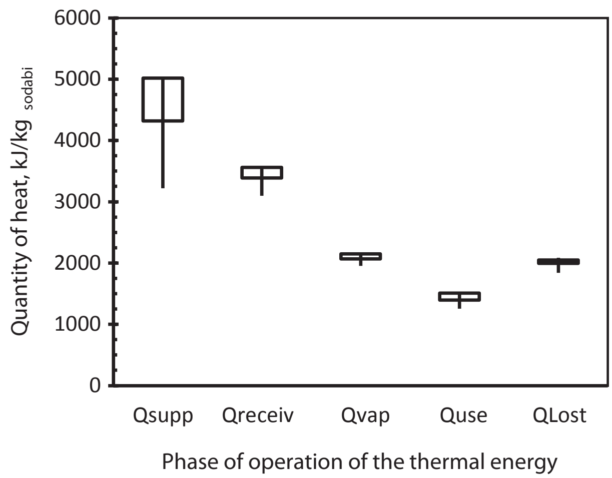


Figure 8: Heat balance per unit mass of the three test areas

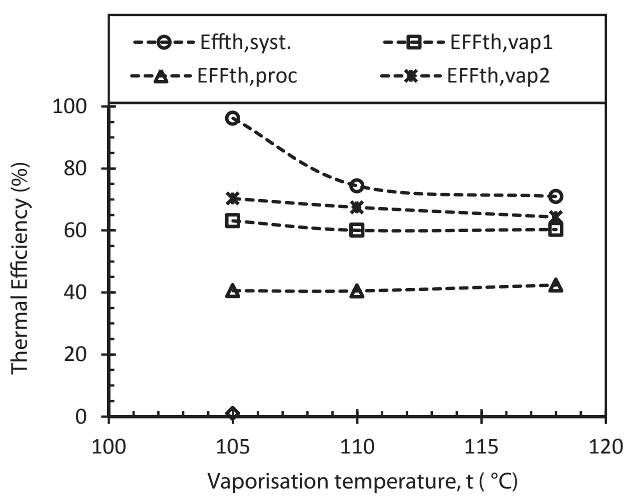


Figure 9: Thermal efficiency as a function of the vaporisation temperature at the areas of study

The relative density of improved *sodabi* varied between 0.84 and 0.93. However, these values are still lower than those obtained for the "traditional" *sodabi*: ranging from 0.99 to 1.00 per locality. The volatile acidity, expressed as acetic acid content varied between 0.35 and 0.39 g/l, well below the volatile acidity values (AV) of "traditional" *sodabi* which is between 1.17 and 3.29 g/l. These values of acidity are also well below the found value by Aiounou (1993, 120), who estimates the volatile acid content *sodabi* equal to 1.42 g/l. For recorded pH-value of "improved" *sodabi* samples, it varied from 4 to 4.25 showing that improved *sodabi* is less acidic than "traditional" *sodabi* with pH between 3.7 and 4.2. In general, the obtained *sodabi* volumetric alcoholic strength (TAV) varied between 52.72 and 55.12 %. These values are higher than "traditional" *sodabi* TAV whose highest value was 46.29 %. These results are consistent with those found by Olasupo and Obayori (2003, 8) for which, the temperature control, in production of Ogogoro in Nigeria, played a key role in its high alcohol content (55%) compared with that of traditionally distilled Ogogoro. The obtained volumetric alcoholic strength values for improved *sodabi* samples are also consistent with those from Aiounou (1993, 120). This author considers that, *sodabi*, in its commercial form, must be between 40 and 60% alcohol.

These *sodabi* improved obtained, which are produced respectively from distillation of Dogbo and Abomey palm wines, meet all requirements of wine spirits, as defined by the International Organisation of Vine and Wine. Therefore, *sodabi* can be considered without misnomer, as a generated "water-of-life" from palm wine.

Optimum operating conditions

The *sodabi* is a "Water-of-life" Benin wine obtained from the distillation of palm wine, which performed under suitable conditions for fermentation and heating can titrate more than 60% (v/v). Fermentation duration of three days (03), the setting temperature of the heated palm wine in the range of 78 °C ≤ *t* ≤ 100 °C during the distillation process and system for continuous cooling, are the best production conditions for obtaining a *sodabi* quality with a high production yield. Distillation temperature *sodabi* must be between two values, one located around the boiling point of ethanol (78 °C) and the other below the boiling point of water (100 °C), as shown in Figure 10.

Indeed, for Olasupo and Obayori (2003, 8), a very low temperature during distillation prolong the distillation time while a very high temperature cause vaporisation of excess water. In their report: study on the development of the ethanol industry /gel fuel as cooking energy in space "UEMOA", Visser and Frederiks, in (2006, 158) claimed that the reduction of the fermentation of wine is a very important parameter. Finally, a continuous cooling prevents the heating of the water and thereby assures a better condensation of the *sodabi* vapour.

Furthermore, local producers can get from the first distillation *sodabi* a better quality with a small amount of biomass instead of getting a distillate which requires further distillation with a large amount of wood used. They could therefore save time and produce a greater quantity of *sodabi* high quality at an affordable price.

Note also that a misuse of wood energy has a very negative impact on the vegetation especially in areas of study. Improving the energy performance of production systems, such as artisanal distillation apparatus lead to a rational use of biomass energy in these areas. General, to improve the distiller's output, it would suit to use:

- improved stoves,
- kettles achieved with selective materials, that keep the heat better;
- very well insulated pipings for *sodabi* steam's conveying;
- and finally, continuous cooling system for *sodabi* vapour's condensation.

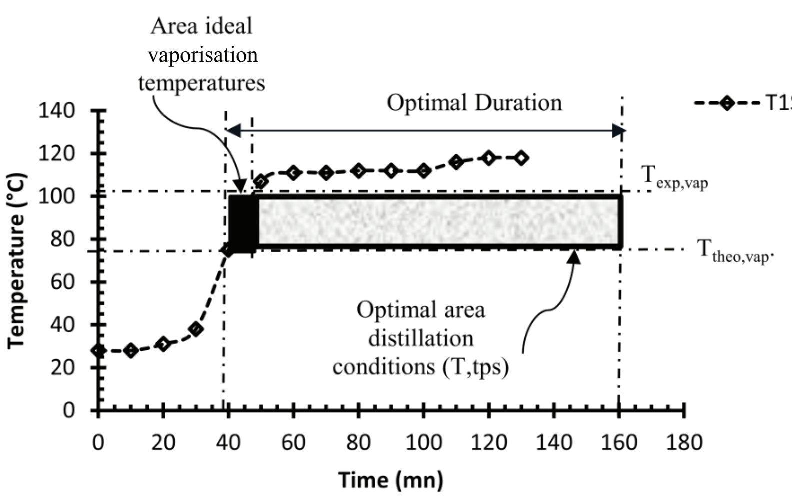


Figure 10: Optimal extraction conditions for *sodabi* during the distillation of palm wine

Conclusion

The *sodabi* is a "water of life" distilled obtained from the distillation of wine palm in Benin and West Africa. Distillation of palm wine requires the use of biomass-energy, the control of biochemical operations and essential thermo-physical parameters to *sodabi* better.

Today, the average value of the thermal efficiency of traditional distillation apparatus used is less than 50%. The lack of control of the distillation temperature of palm wine has a negative impact on the quality of the distillate (*sodabi*). When the duration of the fermentation of palm wine is a maximum of 3 days and the distillation temperature between 78 °C and 100 °C (lower bound), better quality *sodabi* we obtain (best values of the characteristic parameters of the liquor), and a good yield.

When the distillation of palm wine is produced under appropriate conditions of fermentation duration and temperature of heating, duration of extraction (2 to 4 hours max.), wine producers can extract up to 60% (v/v) of spirituous to the first distillation; a rate that shows some improvement in the production performance.

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Appendix: Abbreviations

Cp	specific heat at constant pressure, $J.kg^{-1}.K$
Lv	enthalpy vaporisation, $J.kg^{-1}$
m	mass, kg
PCI	net calorific value, $J.kg^{-1}$
Q	heat, J
T1S	temperature of sodabi, K

Subscripts

Amb	Ambient
Access	Accessory
Bio	Biomass
Cool	Cooling
Eth	Ethanol
I	Initial, sequence number
F	Final
Foy	Fireplace
H	moisture (%)
liq	liquid
n	sequence number
proc	process
prod	production
receiv	received
sd	start of distillation
sod	sodabi
sup	supplied
th	thermal
theo	theoretical
vap	vaporised
vinas	vinasse
env	environment

Greek symbols

η	performance
ε	efficiency
Δ	delta