

# Torrefaction for Increasing Gross Heat of Combustion of Medical Cotton Waste

GEORGIOS E. GIAKOUMAKIS\*, DIMITRIOS K. SIDIRAS

Department of Industrial Management and Technology

University of Piraeus

80 Karaoli & Dimitriou, GR 18534 Piraeus, Greece

GREECE

[ggiakoum@unipi.gr](mailto:ggiakoum@unipi.gr), [sidiras@unipi.gr](mailto:sidiras@unipi.gr), <http://www.tex.unipi.gr/dep/sidiras/main.htm>

*Abstract:* - Cotton is a very popular material that has its own stock market. There are huge amounts of cotton waste and medical cotton waste that can be treated and become a considerable source of energy, instead of buried with other waste in the land-field or incinerated. The purpose of this study was first to examine and then to maximize, if possible, the efficiency of pretreated cotton waste, regarding its gross heat of combustion. More specifically we used a blast furnace in order to torrefy cotton. The cotton torrefaction was achieved through a non-isothermal heating up to 340 °C for 20-50 minutes. The effect of pretreatment conditions, i.e., reaction time and temperature, were investigated using a calorimeter. The diagrams show the heat energy curve and how gross heat of combustion is affected from the conditions applied.

*Key-Words:* - cotton, torrefaction, medical waste, gross heat of combustion, recycling, severity factor.

## 1 Introduction

Cotton is one of the oldest natural materials known to earth. Mexico started using it around 5800 BC.; Greeks and Arabs at 300 BC. Its first appearance in the medical and cosmetic sector is dated in 1880 when Samson Gamgee created Gamgee Tissue, an absorbent cotton wool and gauze surgical dressing [1]. Cotton has a huge production which is estimated at the amount of 106.7 million 480-lb. bales for 2016 [2]. As a result of this huge annual production is the existence of great amounts of cotton waste. Cotton waste exists in two forms. The post industrial waste and the post-consumer waste which consist the whole cotton waste volume. Cotton is almost entirely made of cellulose and this makes cotton recycling a matter of interest.

Recycling cotton is an issue that has occupied science through years. Recycling mainly refers to textile production (post industrial waste) and reused textiles (post-consumer waste). The post-consumer cotton waste includes also the medical cotton waste. This fraction of medical waste can also be recycled by being a source of biogas recovery [3]. Another approach is the use of this fraction as a material for biogas production [4]. With the suitable pretreatment it can also be used as a dye remover from aqueous solutions [5,6]. Each recycling method has the same purpose but a different effect to cotton waste.

Medical cotton waste is considered infectious and hazardous due to its usage like all kinds of medical waste. Infected blood and chemicals are attached to it [7]. Generally medical wastes get burned into incinerators. This method is the most common and most efficient. It reduces the waste volume up to 90% and it can treat all kinds of medical waste. Its significant problem is the dioxin, furans and mercury emissions produced during the procedure [8, 9]. There are many treatment methods acceptable and approved by global organizations. The majority of them include sterilization [10], autoclave waste treatment [11], pyrolysis, gasification, plasma treatment [12]. Sterilization process can be achieved in a temperature of 134 °C for 18 minutes and this is how surgical tools are sterilized generally [13]. Such method is used for sterilizing medical waste with similar temperatures applied.

The purpose of this study is to examine the feasibility of torrefying cotton in order to increase its thermal energy and use it as a heating material or as a supplementary material in energy production. This is a recycling procedure that will decrease the cotton waste volume and provide extra energy. This procedure sterilizes cotton simultaneously which make it harmless for people. Measurements were made on both untreated and torrefied cotton. The two varied process parameters that were chosen for

the experiment were time and temperature. Each experiment had different reaction time in the same heating curve, thus, different temperature. The reaction time was 20, 25, 30, 35, 40, 45, 50 minutes.

Torrefaction kinetics has been developed through years. A distributed activation energy model based on Avrami-Erofeev model has been used to reveal the torrefaction kinetics by Wang et al [14]. Doddapaneni et al [15] have used a combination of Arrhenius law with Coats and Redfern equation for the same purpose. Kinetics has been also simulated through a four-pseudo-component model [16]. Isothermal and non-isothermal torrefaction has been as well correlated with severity factor in order to examine its kinetics by Kim et al [17].

## 2 MATERIALS AND METHODS

### 2.1 Material Development

Cotton was bought from a Medical consumables Supplier in Greece. It was manually cut into small pieces. This fraction is preferred because this way we can achieve cottons' homogeneity after the torrefaction procedure. Cottons' moisture was 5% measured via oven. The heating conditions that applied in cottons' moisture measurement were 110 °C for 24 h in the oven

### 2.2 Torrefaction process

The torrefaction method used to treat cotton was performed in a blast furnace. Cotton was inserted in a weighted porcelain capsule and placed in the blast furnace. Blast furnace was in room temperature. The heat increase curve was from 23 °C up to 340 °C. Each experiment had different reaction time. The time was increased by 5 minutes from 20 minutes to 50 minutes (20, 25, 30, 35, 40, 45, 50 minutes). There wasn't preheating time. When torrefaction process was over, the porcelain capsule was removed immediately from the blast furnace. It was put in a dryer for 15 minutes. The porcelain capsule was weighted in order to measure the tare. Cotton has taken by hand and put in a weighted zip-lock bag for 24 hours. After 24 hours torrefied cottons' moisture was measured in the oven and the result was 3%. The heating conditions that applied in cottons' moisture measurement were 110 °C for 24 h in the oven.

### 2.3 Calorimeter usage

A Parr 1341 Plain Jacket Calorimeter was used to take the necessary measurements. 0.5 g of cotton

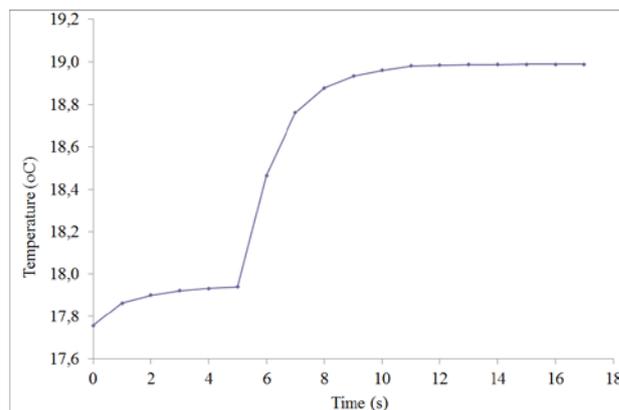


Fig.1: Temperature profile vs. time during the measurement of the gross heat of combustion.

was put in the combustion vessel. The combustion vessel was charged with oxygen to 25 atmospheres. The calorimeter bucket was filled with 2000 mL of distilled water. The bucket was attached in the calorimeter and then the combustion vessel was put in the bucket. The two ignition lead wires were pushed into the terminal sockets on the bombs' head. The cover was set on the jacket and the stirrer was turned manually to ensure that runs freely. If it turns normally then the drive belt is slipped onto the pulleys and the motor is started. The Temperature indications were taken via the 6775 Parr Digital Thermometer each minute for 5 minutes in order to achieve equilibrium into the calorimeter. At the start of the sixth minute the ignition button was pushed and temp measurements were taken each minute until the temperature was stable again. The rise of the temperature will be rapid during the first minutes and slow when we get close to the equilibrium. The diagram below shows how the temperature is affected from the stages explained above.

In Fig 1 temperature curve as affected in each stage of the gross heat of combustion measurement procedure inside the calorimeter is shown.

## 3 RESULTS AND DISCUSSION

The kinetics of gross heat combustion of untreated and torrefied cotton has been extensively studied using ISO 1716:2010 [18]. The widely used gross heat of combustion equation is shown below,

$$H_g = \frac{tW - e_1 - e_2 - e_3}{m} \quad (1)$$

where  $H_g$  represents the gross heat of combustion.  $m$  stands for mass of sample in grams.  $e_1$  refers to correction in calories for heat of formation of nitric

acid,  $e_2$  to correction in calories for heat of formation of sulfuric acid and  $e_3$  to correction in calories or heat of combustion of fuse wire. Both  $e_1$  and  $e_2$  are equal to zero since we use neither nitric acid nor sulfuric acid.  $W$  is the energy equivalent of the calorimeter, determined under standardization.  $t$  is the net corrected temperature rise. The equations below give more information about these variables,

$$t = t_c - t_a - r_1(b - a) - r_2(c - b) \tag{2}$$

$$e_3 = l_f \cdot x_{2,3} \tag{3}$$

$$W = 2426 \text{ cal/}^\circ\text{C} \tag{4}$$

Where  $a$  stands for time of firing,  $b$  for time when the temperature reaches 60% of the total rise and  $c$  for time at the beginning of period in which the rate of temperature change is constant.  $t_a$  represents temperature at firing time and  $t_c$  temperature at time  $c$ .  $r_1$  is the rate at which the temperature was rising until firing and  $r_2$  the rate at which the temperature rising during the 5-min period after the time  $c$ .  $l_f$  is the size of fuse wire consumed in firing. Severity factor was used to integrate the effects of reaction times and temperature into a single variable during torrefaction.

Through years a ‘combined severity factor’ is introduced for isothermal reactions [19] as follows.

$$R_0' = 10^{-pH} \cdot t \cdot e^{\frac{T-100}{14.75}} \tag{5}$$

where  $t$  is the reaction time in min and  $T$  is the reaction temperature in degrees Celsius.

Moreover, in torrefaction studies the following severity factor has been used [17].

$$SF = \text{Log} \left[ t \cdot e^{\left( \frac{T_h - T_R}{14.75} \right)} \right] \tag{6}$$

where  $t$  is the reaction time of the torrefaction in min,  $T_h$  the reaction temperature and  $T_R$  the reference temperature, both in degrees Celsius.

A combined severity factor for non-isothermal reaction conditions was introduced [20].

$$R_0^* = 10^{-pH} \cdot \int_0^t e^{\frac{T_\theta - 100}{14.75}} dt \tag{7}$$

where  $T_\theta$  is the reaction temperature in degrees Celsius. Since in this work variables used are time

and temperature, pH was removed from the equation. The simplified severity factor used herein for non-isothermal reaction conditions is shown below.

$$R_0 = \int_0^t e^{\frac{T_\theta - 100}{14.75}} dt \tag{8}$$

The Severity factor values according to eq. (8) for each experiment are estimated in Table 1.

In Table 2, is shown, for each experiment carried out, how mass at starting time ( $m_0$ ) lowers to mass at the end of each experiment ( $m_t$ ). Yield% shows the shrinkage percentage of the mass through time.

Figure 2, as it can be seen below, displays how yields’ percentage decreases rapidly for small severity factor values and as severity factor

Table 1: Severity factor values for each experiment.

t(min)	R <sub>0</sub>	logR <sub>0</sub>
20	2.12E+07	7.33
25	6.87E+07	7.84
30	1.16E+08	8.07
35	1.61E+08	8.21
40	1.87E+08	8.27
45	1.93E+08	8.29
50	2.02E+08	8.31

Table 2: The table shows the mass decrease during the torrefaction process.

R <sub>0</sub>	LogR <sub>0</sub>	t(min)	yield%
2,12E+07	7,33	20	75.87
6,87E+07	7,84	25	62.36
1,16E+08	8,07	30	49.49
1,61E+08	8,21	35	41.75
1,87E+08	8,27	40	40.20
1,93E+08	8,29	45	39.80
2,02E+08	8,31	50	39.41

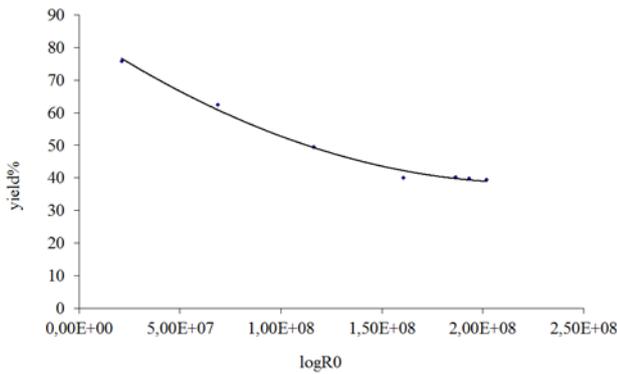


Fig.2: Torrefacted cotton mass yield as affected by severity factor.

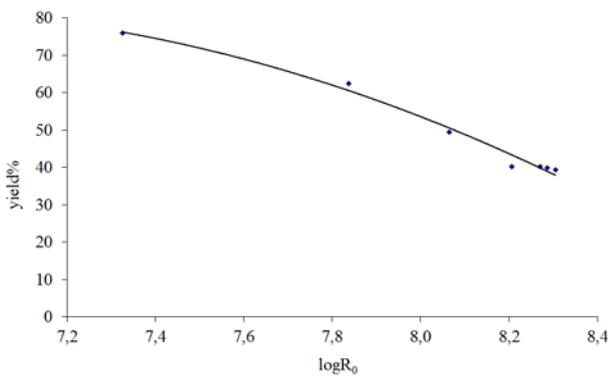


Fig.3: Torrefied cotton mass yield as affected by severity factor in logarithmic form.

increases this decrease shortens and it becomes more stable. The equation that shows how yield is affected by severity factor is the following.

$$yield\% = 9E - 16R_0^2 - 4E - 07R_0 + 84.9347 \quad (9)$$

The coefficient of variation was  $R^2 = 0.9936$ .

In Figure 3 the percentage of loss of mass during the torrefaction procedure compared to logarithm of severity factor is presented. As it can be seen as time rises yield is less affected. The kinetic equation that shows mass decreasing as logarithm of severity factor increases is given below.

$$yield\% = -18.248R_0^2 - 246.12R_0 - 747.53 \quad (10)$$

The coefficient of variation was  $R^2 = 0.9854$ .

Table 3, shows, how gross heat of combustion ( $H_g$ ) increases for different torrefying reaction time. The ideal time that gives the biggest output ( $\Delta H_g\%$ ) is 30 minutes were  $H_g$  increased 23.06%. The

Table 3: Gross Heat of Combustion changes through time.

$R_0$	$\log R_0$	$H_g$ (MJ/kg)	$\Delta H_g\%$
2,12E+07	7,33	17.2	5.31
6,87E+07	7,84	17.7	8.37
1,16E+08	8,07	20.1	23.06
1,61E+08	8,21	19.9	21.84
1,87E+08	8,27	19.2	17.55
1,93E+08	8,29	19.6	20.00
2,02E+08	8,31	19.5	19.39

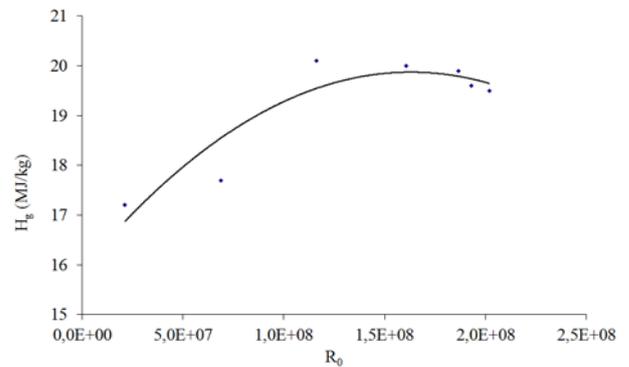


Fig.4: Gross heat of cimbustion vs severity factor.

gross heat of combustion for the untreated medical cotton was measured 3 times. Its average found 16.3 MJ/kg and its standard deviation 0.3 (1.9%).

Figure 4 shows the dependence of gross heat of combustion from the severity factor. As it seems a moderate torrefaction optimizes the procedure since maximum  $H_g$  is found at 30 minutes reaction time. This dependence is given from the following equation.

$$H_g = -1E - 16R_0^2 + 5E - 08R_0 + 15.912 \quad (11)$$

The coefficient of correlation was  $R^2 = 0.8576$ .

Figure 5 shows how gross heat of combustion grows as logarithm of severity factor increases. The kinetic equation that describes this figure is shown below.

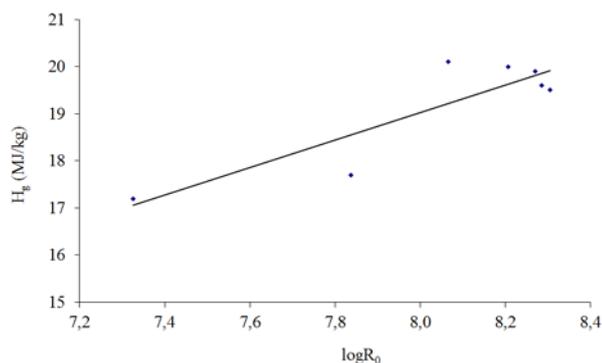


Fig. 5: Gross heat of combustion compared to logarithm of severity factor

$$H_g = 2.9182R_0 - 4.3259 \quad (12)$$

The coefficient of correlation was  $R^2 = 0.773$ .

#### 4 Conclusion

In this study, torrefaction conditions were investigated for enhancing medical cotton waste heating value. Moderate treatment conditions were found to maximize gross heat of combustion of torrefied cotton. In conclusion, medical cotton becomes sterilized at these conditions and has 23% higher gross heat of combustion compared to untreated medical cotton. That makes it a suitable recycled material that can be used for energy production instead of being incinerated.

#### References:

- [1] J.C. Lawrence, A Century after Gamgee, *Burns*, Vol. 13, No.1, 1986, pp. 77-79.
- [2] Monthly Economic Letter. October 2017 <http://www.cottoninc.com/corporate/market-data/monthlyeconomicletter/pdfs/monthlyeconomicletter-english.pdf> (access 14 Oct 2017)
- [3] Z.Z. Ismail, A.R. Talib, Recycled medical cotton industry waste as a source of biogas recovery, *Journal of Cleaner Production*, Vol. 112, 2016, pp. 4413-4418.
- [4] A. Isci, G.N. Demirer, Biogas production potential from cotton wastes, *Renewable Energy*, Vol. 32, 2007, pp. 750-757.
- [5] M. Ertas, B Acemioglu, M Hakki Alma, M. Usta, Removal of methylene blue from aqueous solution using cotton stalk, cotton waste and cotton dust, *Journal of Hazardous Materials*, Vol. 183, 2010, pp. 421-427.
- [6] M. Baghdadi, B. Alipour Soltani, M. Nourani, Malachite green removal from aqueous solutions using fibrous cellulose sulfate prepared from medical cotton waste: Comprehensive batch and column studies, *Journal of Industrial and Engineering Chemistry*, 2017, in press.
- [7] H. Taghipour, M. Mosafieri, Characterization of medical waste from hospitals in Tabriz, Iran, *Science of the Total Environment*, Vol. 407, 2009, 1527-1595.
- [8] E. A. Windfeld, M. Su-Ling Brooks, Medical waste management - A review, *Journal of Environmental Management*, Vol. 163, 2015, pp. 98-108.
- [9] Y. Chen, L. LIU, Q. Feng, G Chen, Key issues study on the operation management of medical waste incineration disposal facilities, *Procedia Environmental Sciences*, Vol. 16, 2012, pp. 208-213.
- [10] J. Dengchao, B. Zhenbo, Y. Xinping, Effects of Vacuum on Sterilizing Rate in Medical Waste Steam Treatment Process, *Procedia Environmental Sciences*, Vol. 11, 2011, pp. 1407-1411.
- [11] A. Graikos, E. Voudrias, A. Papazachariou, N. Iosifidis, M. Kalpakidou, Composition and production rate of medical waste from a small producer in Greece, *Waste Management*, Vol. 30, 2010, pp. 1683-1689.
- [12] Dimitrios P. Komilis, Issues on medical waste management research, *Waste Management*, Vol. 48, 2016, pp. 1-2.
- [13] JJ Perkins, *Principles and Methods of Sterilization in Health Sciences*, Charles C. Thomas, 1969.
- [14] S. Wang, G. Dai, B. Ru, Y. Zhao, X. Wang, G. Xiao, Influence of torrefaction on the characteristics and pyrolysis behaviour of cellulose, *Energy*, Vol. 120, 2017, pp. 864-871.
- [15] T.R.K.C. Doddapaneni, J. Kontinen, T. Hukka, Influence of torrefaction pretreatment on the pyrolysis of Eucalyptus clone: A study on kinetics, reaction mechanism and heat flow, *Industrial Crops and Product*, Vol. 92, 2016, pp. 244-254.
- [16] Q-V. Bach, K-Q Tran, dry and wet torrefaction of woody biomass – A comparative study on combustion kinetics, *Energy Procedia*, Vol. 75, No.1, 2015, pp. 150-155.
- [17] Y-H. Kim, B-II. Na, B-J. Ahn, H-W. Lee, J-W Lee, Optimal condition of torrefaction for high energy density solid fuel of fast growing tree species, *Korean Journal of Chemical Engineering* Vol.32, No.8, 2015, pp. 1547-1553.

- [18] ISO 1716:2010 Preview Reaction to fire tests for products -- Determination of the gross heat of combustion (calorific value).
- [19] R. Overend, E. Chornet., Fractionation of lignocellulosics by steam-aqueous pretreatments, *Philosophical Transactions of the Royal Society of London*, Vol. 321, No.1, 1987, pp. 523-536.
- [20] D. Sidiras, F. Batzias, R. Ranjan, M. Tsapatsis, Simulation and optimization of batch autohydrolysis of wheat straw to monosaccharides and oligosaccharides, *Bioresource Technology*, Vol. 102, No.1, 2011, pp. 10486-10492.

## 5 Acknowledgements

Financial support provided by the Research Centre of the University of Piraeus is kindly acknowledged.