DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

INVESTIGATION OF DRYING POTENTIAL OF MUNICIPAL TREATMENT SLUDGES

by

Didem MUŞLU

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İZMİR

INVESTIGATION OF DRYING POTENTIAL OF MUNICIPAL TREATMENT SLUDGES

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"INVESTIGATION OF DRYING POTENTIAL OF MUNICIPAL TREATMENT SLUDGES"** completed by **DİDEM MUŞLU** under supervision of **ASSOC.PROF.DR. AZİZE AYOL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

ASSOC.PROF.DR. AZİZE AYOL

Supervisor

(Jury Member)	(Jury Member)

Prof.Dr. Mustafa SABUNCU
Director
Graduate School of Natural and Applied Sciences

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DİDEM MUŞLU

INVESTIGATION OF DRYING POTENTIAL OF MUNICIPAL TREATMENT SLUDGES

ABSTRACT

Wastewater treatment plants (WWTP), while treating wastewater, have produced huge amounts of sludge which should diligently be disposed. Among the different disposal alternatives, landfilling has been widely applied for many years and the necessity of the area for sludge disposal has increased day by day with the rise of the populations especially in metropolitan areas. Beyond this, disposal of sludge has always been seen as a big problem for the municipalities and industries due to the high transportation costs for sludge.

In order to find effective solutions for sludge related problems in WWTPs,different sludge treatment processes including sludge thickening, stabilization, conditioning and dewatering have been applied to improve the sludge quality while decreasing the amount of processed sludges. To end this, each treatment process has specific functions. For example, sludge stabilization aims to reduce organic matter content of sludges and also elimate pathogenic content of sludge, while sludge dewatering aims to increase dry solids content of sludge to decrease the sludge amounts to be disposed. In addition to these auxiliary treatment processes, sludge drying processes have recently used in practice as a new alternative to reduce the sludge amount in WWTPs and also evaluate the processed sludges for possible beneficial alternatives. Although the number of full-scale sludge drying applications have been increased within a few years, this technology is quite new for Turkey.

Thermal drying processes intend to enhance water removal from dewatered solids which attains both volume and weight reductions. Beyond this, thermal drying of sludges can provide in a product with significant energy and nutrient value.There are many scientific studies about sludge drying techniques that prove thermal drying efficiency on sludge cakes. In order to extend the use of this technology in the field of sludge management, the market dryer producing companies have also been doing research and pilot scale applications to improve their technologies.

This research study conducted in Department of Environmental Engineering at Dokuz Eylul University aimed to review different types of dryers with their heat transfer methods used in sludge treatment and to investigate sludge's drying abilities under the different temperature and drying time conditions. In addition, the current situation of sludge drying technology in Turkey as well as in the World has been examined. In order to carry out the experimental studies, the sludge cake samples were taken from IZSU (Administration on Water and Sewage Systems of City of Izmir) Çiğli Municipal Wastewater Treatment Plant located in Çiğli, Izmir, Turkey. The parameters – pH, temperature, dry solid contents of sludge cakes (DS%), volatile solid contents of sludge cakes (VS%), calorific values of sluge cakes, and thermal gravimetric analysis were analyzed to determine the sludge cake characteristics. Experimental studies were designed by using the Box Wilson experimental statistical method for the achieved data to be evaluated. Experimental studies were done as two series. In the first experimental study, the retention time range of 10-120 minutes and the temperature range of 50-180 ^{o}C were selected as operational while the retention time range of 10-180 minutes and the temperature range of 80-250 ^{o}C were selected for the second experimental study. Experimental results showed that the increasing of time and temperature increased the both dry solid contents and calorific value of the final sludge product.

This thesis presents the detailed research results on sludge drying applications and debugs them in a quantitive manner for full-scale applications.

Keywords: Sludge drying, sludge dewatering, sludge's water fractions, drying technology, direct dryers, indirect dryers, time effect, temperature effect, calorific value of sludge, thermal gravimetric analysis.

KENTSEL NİTELİKLİ ARITMA ÇAMURLARININ KURUTMA POTANSİYELİNİN ARAŞTIRILMASI

ÖZ

Uzun yıllardan bu yana, atıksu arıtma tesisleri, atıksuyun arıtımı esnasında bertarafı zor olan büyük miktarlarda çamur üretmektedir. Çamurun depolama alanlarında bertaraf edilmesi için gerekli olan alan ihtiyacı, şehirlerdeki nüfusun çoğalmasıyla birlikte artmaktadır. Bununla birlikte, çamurun taşınmasının yüksek maliyetlerinden dolayı, çamurların bertaraf edilmesi hem belediyeler ve hem de endüstriler için büyük bir problem olarak görülmektedir.

Atıksu arıtma tesislerinde, arıtma çamurlarıyla ilgili olarak problemlere etkin çözümler bulmak hem işlenmiş çamurların kalitesinin arttırılması hem de çamur miktarlarının azaltılması için çamur yoğunlaştırma, çamur stabilizasyonu, şartlandırma ve susuzlaştırma işlemleri gibi her biri farklı bir amaca hizmet eden farklı çamur arıtma prosesleri uygulanmaktadır. Örneğin, çamur stabilizasyonunda arıtma çamurunun organik madde içeriği ve patojen mikroorganizma içeriğinin indirgenmesi hedeflenirken, çamur susuzlaştırma işlemleriyle arıtma çamurundaki su içeriğinin ve dolayısıyla bertaraf edilecek çamur miktarının azaltılması amaçlanmaktadır. Bu uygulamada olan konvansiyonel çamur işleme proseslerine ilave olarak, son dönemlerde çamur kurutma teknolojileri yeni bir uygulama alternatifi olarak atıksu arıtma tesislerinde yerini almıştır. Çamur kurutma uygulamalarıyla, susuzlaştırılmış çamurundan ilave su alımı sağlanmakta ve aynı zamanda çamurlara uygulanabilecek farklı yararlı kullanım alternatifleri için bu çamurlar kurutulmak suretiyle bir ön işleme tabi tutulmaktadır. Arıtma çamurunun kurutulmasıyla ilgili olarak tam ölçekli uygulamaların sayısı tüm dünyada son birkaç yıl içinde artmakla birlikte, Türkiye'de bu teknoloji oldukça yeni bir uygulamadır. Termal kurutma prosesleri susuzlaştırılmış arıtma çamurundan mekanik yöntemlerle alınamayan suyu uzaklaştırırken hem hacimsel hem de ağırlıkça arıtma çamuru miktarıda azalma sağlamaktadır. Bunun ötesinde termal kurutma işlemi sonrasında elde edilen ürün genellikle önemli bir besin ve enerji değerine sahip olmaktadır.

Arıtma çamurlarının termal olarak kurutulmasına ilişkin verimliliğinin belirlendiği bilimsel araştırma çalışmaları vardır. Bununla birlikte, gerçek ölçekte çamur kurutma ünitelerini tasarlayan üretici firmalar da teknolojilerini geliştirmek adına araştırma ve pilot ölçekli çalışmalarını sürdürmektedir. Dokuz Eylül Üniversitesi, Çevre Mühendisliği Bölümü'nde gerçekleştirilen bu tez çalışmasında, uygulamada kullanılan farklı ısı transfer metodlarına sahip farklı tipteki çamur kurutucu üniteleri incelenmiş ve yürütülen deneysel çalışmalarda, arıtma çamurunun farklı sıcaklık ve farklı kurutma sürelerinde kurutulabilme potansiyeli araştırılmıştır. Bunun yanı sıra, dünyadaki ve ülkemizdeki arıtma çamuru kurutma uygulamaları irdelenerek, çamur kurutma teknolojilerinde mevcut durumunu ortaya konması amaçlamıştır. Deneysel çalışmalarda, İzmir Büyükşehir Belediyesi, İzmir Su ve Kanalizasyon İdaresi Genel Müdürülüğü (İZSU) sorumluluğunda işletilen Çiğli Kentsel Atıksu Arıtma Tesisi'nden alınan çamur keki örnekleri ile çalışılmıştır. Çamur keki karakterizasyonunun belirlenmesinde, pH, sıcaklık, çamur katı madde miktarı, organik madde miktarı, kalorifik (ısıl) değer ve termal gravimetrik analiz parametreleri analiz edilmiştir. Deneysel çalışmanın tasarımında ve elde edilen verilerin değerlendirilmesinde Box Wilson İstatiksel Deney Yöntemi uygulanmıştır. Deneysel çalışmalarda bu uygulama, iki seri olarak gerçekleştirilmiştir. Birinci seri deneysel çalışmalarda, işletme şartları olarak alıkonma süresi aralığı 10-120 dakika ve sıcaklık aralığı 50-180 °C olarak; ikinci deneysel çalışma serisinde ise alıkonma süresi 10-180 dakika ve sıcaklık aralığı 80-250 °C olarak seçilmiştir.Deneysel çalışmaların sonuçları, artan sıcaklık ve alıkonma süreleri için hem çamurun katı madde içeriğinin hem de son ürünün ısıl değerinin arttığını göstermektedir.

Bu tez çalışmasında, arıtma çamurlarının kurutulmasına ilişkin elde edilen deneysel veriler detaylı olarak sunulmakta ve tam ölçekli uygulamalara yönelik tartışılmaktadır.

Anahtar kelimeler: Çamur kurutma, çamur susuzlaştırma, arıtma çamuru su bileşenleri, direk kurutma, indirek (dolaylı) kurutma, zaman etkisi, sıcaklık etkisi, çamurun ısıl değeri, termal gravimetrik analiz.

CONTENTS

CHAPTER ONE
INTRODUCTION

1.1 Introduction

Huge amounts of sludge have been produced in wastewater treatment plants (WWTP) during the wastewater treatment. The treatment and disposal of sludges have been seen a great problem due to the high treatment and disposal costs. Depending on the increasing number of treatment plants, the amount of sludge produced in WWTPs have increased. Therefore, sludge management is being an important issue in Turkey as well as all over the World. Sludge is a complex material and a great problem to be faced from many view of points: first cause is the difficulties in the sludge characterization; second cause is that the material properties can change with the time; third cause is that sludge treatment and disposal need high technological information and most of them are high costly processes.

In sludge management field, among the different disposal alternatives, landfilling has been widely applied for many years and the necessity of the area for sludge disposal has increased day by day with the rise of the populations especially in metropolitan areas. Beyond this, disposal of sludge has always been seen as a big problem not only for the municipalities, but also the industries due to the high transportation costs for sludge.

Sludge management is also receiving great attention in Turkey for a variety of reasons that all are in accordance with the environmental health criteria and developed environmental policy of Turkey based on many regulations and legislations. Wastewater treatment technologies have been widely accepted and the most of the metropolitans of Turkey like Ankara, Istanbul, Izmir, and many others have municipal wastewater treatment plants. Most of them are facilitated with conventional treatment processes as physical and biological treatment units except for a few treatment plants that have advanced treatment technologies (Filibeli and Ayol, 2007). However, most of the treatment plants have recently been constructed including advanced biological treatment units in Turkey. The produced sludges have been processed using auxiliary sludge treatment processes. Commonly used sludge processes are thickening (gravity thickening, flotation thickening, and centrifuge) and dewatering (sludge drying beds, belt press filters, centrifuges, and plate press filters).

Following dewatering units, depending on the final product quality, the sludges can be stored in landfill areas and/or used for beneficial usage alternatives. Due to the fact that sludge consist of roughly 70-80% dry solids after dewatering process, it is stil a big problem to be dealt with the transportaion and disposal or beneficial usage alternatives. To solve this problem, some techniques like sludge drying technology have been improved. Heat drying technology involves the application of heat to evaporate water and to reduce the moisture content of biosolids that is not achievable by conventional dewatering methods. The advantages of heat drying include reduced product transportation costs, further pathogen reduction, improved storage capability, and marketability (Metcalf & Eddy, 2003).

Thermal drying is a process for the reduction of the volume of sludges, by removing the water and achieving dry solids content more than 90%. This process is applicable not only for volume reductions of sludges produced at WTTPs but also for some industries, such as chemical, pharmaceutical, food processing and minerals processing. In the thermal drying process, the final product is stabilized in a dry granular form that simplifies the storage, delivery, use or disposal (EPS-SLUDGEDRY-USA-BR-0908, www.siemens.com).

It is known that the costs for sludge treatment and disposal have a ratio ranged between 40-60% of whole treatment costs. Although sludge is considered as a waste, it is also thought as a valuable product because of its high nutrient content and heating value. Due to the fact that sludge has commercial value, it can be used both fertilizer or like a fuel. Therefore, sludge producers make also efforts to improve the sludge quality by using different techniques and make a profit. Thermal drying of sludges can provide in a product with significant energy and nutrient value. There are many scientific studies on sludge drying techniques that prove thermal drying efficiency of sludge cakes and it has been still under research to improve sludge drying performance.

This scientific research study conducted in Department of Environmental Engineering at Dokuz Eylul University aimed to emphasize the importance of the sludge drying technology to investigate sludge's drying abilities under the different temperature and drying time conditions at laboratory conditions. This thesis presents the detailed research results on sludge drying applications.

1.2 Scope and Research Objectives of the Thesis

The application of laboratory tests for sludge drying evaluations is a great need since the information obtained from such tests will help to select appropriate technology for sludge drying and to describe sludge as a material which is being dried. However, there is no sufficient information which could help with that problem. All the literature concerning sludge issue is focused mostly on the sludge treatment processes like thickening, dewatering and also on different methods of sludge utilization. There is an unquestionable demand for more information in sludge drying. This study was carried out with the aim of determining the drying potential of sludges at laboratory conditions. The research objectives of this thesis are therefore:

- To review the existing drying technologies and full-scale applications with their advantages and disadvantages, to determine the current situation in terms of using different drying process in Turkey,
- to investigate the time and temperature effects on sludge drying efficiency,
- to examine the calorific values of sludg e after drying process.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter gives some information about the sludge treatment methods and sludge drying technology.

In this chapter, background information about sludge drying technology, some lab-scale dryers used for sludge drying purpose is given in details to understand the role of heat drying process in the sludge management. All technologies used for sludge drying with the aim of showing the developments in this field are summarized as possible as in details. In addition, some kind of examples on drying processes, which were globally studied in different area will be given.

2.2 General View of Final Sludge Treatment Methods

Sludges related problems arising from wastewater treatment plants have led to develop efficient sludge treatment processes, which each of them has a unique function. Sludge treatment methods are given in Table 2.1. Among the processes, thickening, conditioning-dewatering, and drying are the primarily methods used for removing water from sludge. Digestion, composting, and incineration are the methods used primarily for stabilization purpose to reduce the volatile solids and pathogenic microorganism contents of sludge (Metcalf & Eddy, 2003).

There are a few final treatment methods for sludge management as summarized in Table 2.1 Sludge drying process is an advanced treatment method to be used after dewatering systems. In this method, thermal energy has been applied to the sludge cake in order to evaporate the remaining water in the sludge after dewatering unit. Due to the drying process is an effective method regarding the high dry matter content of sludges, this technology has recently come forward. In the course of this process, pathogenic microorganisms in the sludge can also be removed with the help of high heating temperature.

Table 2.1 Solids processing methods (Metcalf&Eddy, 2003)

Unit operation, unit process, or treatment method	**Function**
Pumping	Transport of sludge and liquid biosolids
Preliminary operations:	
Grinding	Particle size reduction
Screening	Removal of fibrous materials
Degritting	Grit removal
Blending	Homogenization of solids streams
Storage	Flow equalization
Thickening:	
Gravity thickening	Volume reduction
Flotation thickening	Volume reduction
Centrifugation	Volume reduction
Gravity – belt thickening	Volume reduction
Rotary – drum thickening	Volume reduction
Stabilization:	
Alkaline stabilization	Stabilization
Anaerobic digestion	Stabilization, mass reduction
Aerobic digestion	Stabilization, mass reduction
Autothermal aerobic digestion (ATAD)	Stabilization, mass reduction
Composting	Stabilization, product recovery
Conditioning:	
Chemical conditioning	Improve dewaterability
Other conditioning methods	Improve dewaterability

Table 2.1 (Continued) Solids processing methods (Metcalf&Eddy, 2003)

Dewatering:	
Centrifuge	Volume reduction
Belt – filter press	Volume reduction
Filter press	Volume reduction
Sludge drying beds	Volume reduction
Reed beds, Lagoons	Storage, volume reduction
Heat drying:	
Direct dryers	Weight and volume reduction
Indirect dryers	Weight and volume reduction
Incineration:	
Multiple – hearth incineration	Volume reduction, resource recovery
Fluidized – bed incineration	Volume reduction
Co-incineration with solid waste	Volume reduction
Application of biosolids to land:	
Land application	Benefical use, disposal
Dedicate land disposal	Disposal, land reclamation
Landfilling	Disposal
Conveyance and storage	Solids transport and storage

2.3 Review of Thermal Processes Applied in Sludge Management

Various modern technologies have been introduced as an alternative approach to the sewage sludge disposal, especially with the decreasing land availability for landfilling. These technologies can be categorized as thermal utilization processes of sludge including pyrolysis, gasification, wet oxidation, combustion. Thermal processes remove the organic part of the sludge and leave only the ash component for final disposal. Sewage sludge is a type of biomass fuel with its calorific value as in coal. Table 2.2 shows the typical heating values of different kinds of sludges. The main aim of the sludge thermal processing is the utilization of the sludge’s stored energy. However, it is well known that sludge contains high water content.Therefore the majority of energy released during thermal processes is consumed for reducing the water content of sludge (Fytili, D. and Zabaniotou, A. , 2008).

Table 2.2 Typical heating values for different types of sewage sludge (Fytili, D. and Zabaniotou, A. , 2008)

Type of sludge	**Heating Value (MJ/ kgDS)**	
	Range	**Typical**
Raw sludge	23-29	25.5
Activated sludge	16-23	21
Anaerobically digested primary sludge	9-13	11
Raw chemically precipitated primary sludge	14-18	16
Biological filter sludge	16-23	19.5

2.4 Definition of Water Fractions in Sludge

The water in sludge is existed in the following four categories and repsesented in Figures 2.1 and 2.2 (Vesilind, 1994; Lowe,1995; Chen et al., 2002; Vaxelaire and Cezac, 2004) :

- **Free water,** the limit being the first critical water content; water non-associated with solid particles and including void water not affected by capillary force -the constant drying-rate period-.

- **Capillary (interstitial)water,** i.e. water held between the first and second critical water content; water trapped inside crevices and interstitial spaces of flocs and organisms - the first falling-rate period of the drying curve and usually associated with the removal of water from the capillaries in the sludge cake-.
- **Floc or particle (surface) water,** i.e. water held within the individual sludge particles represented by the water content below the second critical water content; water held on to the surface of solid particles by adsorption and adhesion - the second falling-rate period of the drying curve- and

- **Chemically bound water,** i.e. water held at a moisture content somewhere below the equilibrium water content - not removed by the drying experiment evaluation procedure and usually associated with the chemically bound water to the solid particles-.

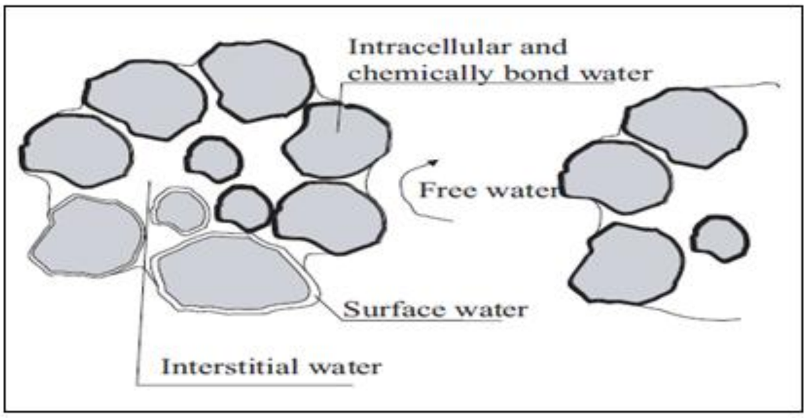

Figure 2.1 Water Distribution in Sludge (Chen et al., 2002)

The bound water content can be determined by methods such as dilatometric determination, vacuum filtration, expression, drying, and thermal analysis (Chen, et al., 2002).

2.5 Sludge Drying Studies

In the world, drying technologies have been used for many years in different industrial sectors including chemical, pharmaceutical, food and mineral processing. There are many studies on drying technology which has also the technological efficiency on sludge drying.

Yan et al. (2009) developed a lab-scale cylindrical paddle dryer shown in Figure 2.2 to study the drying kinetics of sewage sludge under partial vacuum conditions. Lower heating values of dried sludge and condensate properties for different drying conditions is given in Table 2.3. The researchers used a penetration model which is valid for past materials since dewatered sludge behaves like a pasty material. Their results showed good agreements between the model drying kinetics and experimental data.

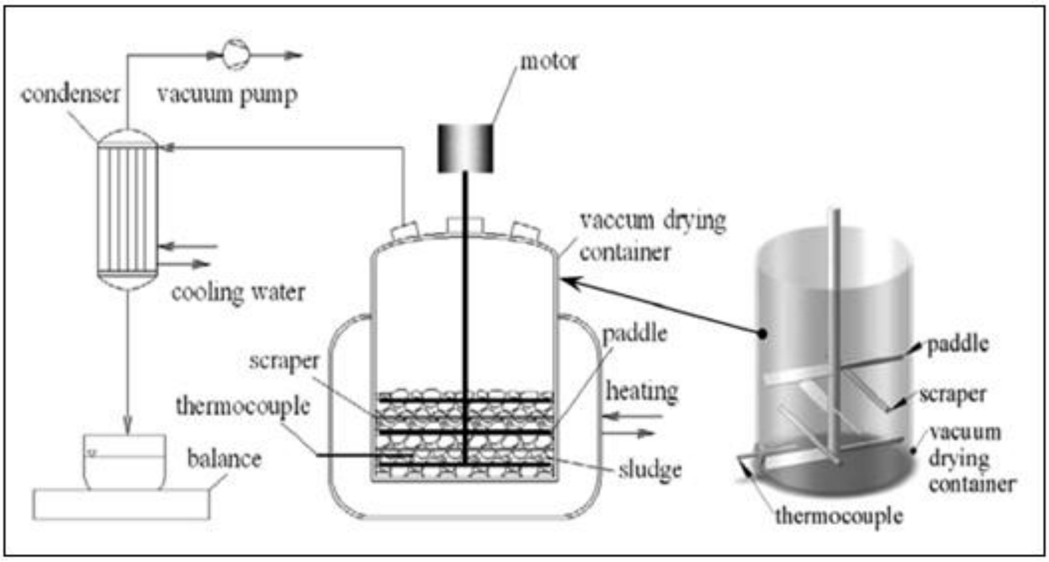

Figure 2.2 Cylindrical lab-scale paddle dryer by Yan et al. (2009)

Table 2.3 Lower heating values of dried sludge and condensate properties for different drying conditions (Yan et al. , 2009)

Lower heating values (LHVs) of dried sludge and properties of condensate for different drying conditions					
Atmospheric contact drying					
T/^{o}C	120	130	140	150	160
LHVs of dried sludge (J/g)	9038	9013	8904	8872	8710
COD of the condensate(mg/L)	57.14	58.65	64.58	85.71	100.8
pH of the condensate	10.27	10.30	10.34	10.30	10.25
Partial vacuum contact drying					
T/^{o}C	80	80	80	80	90
P/mbar	268.03	139.6	103.5	73.76	123.4
ΔT/^{o}C	13.5	27.5	33.5	40	40
LHVs of dried sludge (J/g)	9063	8841	8823	8891	8945
COD of the condensate(mg/L)	ND	9.023	ND	ND	1.054
pH of the condensate	10.15	10.18	9.81	10.02	9.68
ND:Not detected					

Wang and Li (2009) used a cylindrical sludge drying chamber for dewatered sludges taken from Dalian WWTP located in China. The main properties of sewage sludge are given in Table 2.4 and the schematic view of the reactor is shown in Figure 2.3 Dewatered sludge was spread on a salver that is supported by an electronic scale (PL202- S, Mettler Toledo, Switzerland). The sludge was dried in a drying chamber, which is made of a cylindrical steel tube coiled by a resistance coil and wrapped by heatproof asbestos and sheet iron. The temperature of the whole heater was controlled by a temperature control unit connected with a thermal-couple. The scale was connected to a computer measuring and recording the mass of sludge on-line every 6 s, and was able to obtain the mass loss curve of sludge drying. The mass loss curve of cylindirical sludge with different diameters drying at 120 ^{o}C is shown in Figure 2.4 (Wang and Li, 2009).

Table 2.4 Main properties of dewatered sludge from Dalian WWTP (Wang and Li, 2009)

Sample	Approximate analysis/wt.%				Ultimate analysis/wt%					LHV/(10^6 J*kg^{-1}
	Moisture	Volatile matter	Fixed carbon	Ash	C	H	O	N	S	
Sludge	86.48	88.25(db)	2.74(db)	9.00(db)	46.847	7.495	37.013	7.302	1.343	19.368(db)
Notes: LHV is lower heat value, db is dry basis										

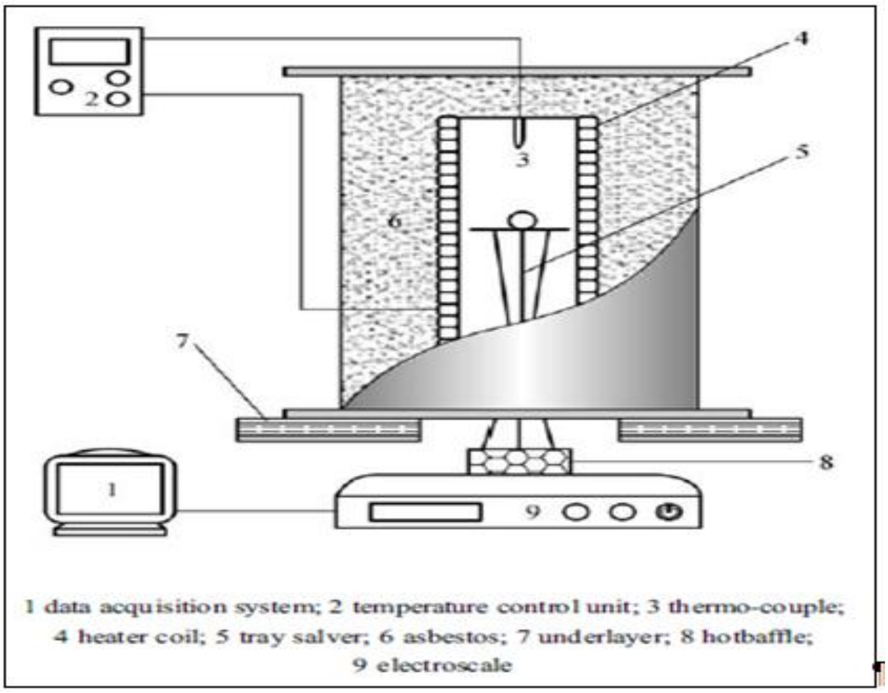

Figure 2.3 Drying equipment used in experimental studies (Wang and Li, 2009)

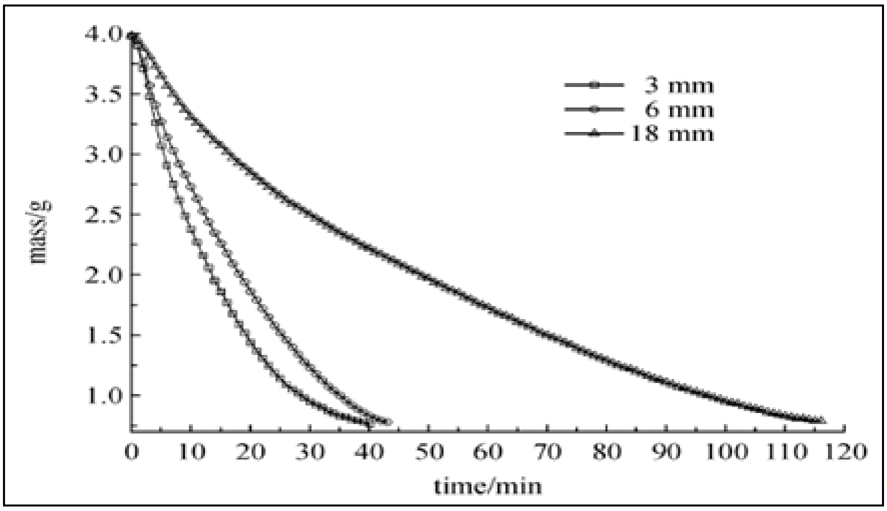

Figure 2.4 Mass loss of cylindrical sludge with different diameters drying at 120°C (Wang and Li, 2009)

Sewage sludge drying and hygienization system with a heat pump, which is an alternative for the traditional method of sludge drying was introduced by Flaga and Schnotale(nd, http://www.lwr.kth.se/Forskningsprojekt/Polishproject/rep14/Flaga14p25.pdf). This system is shown in Figure 2.5 .

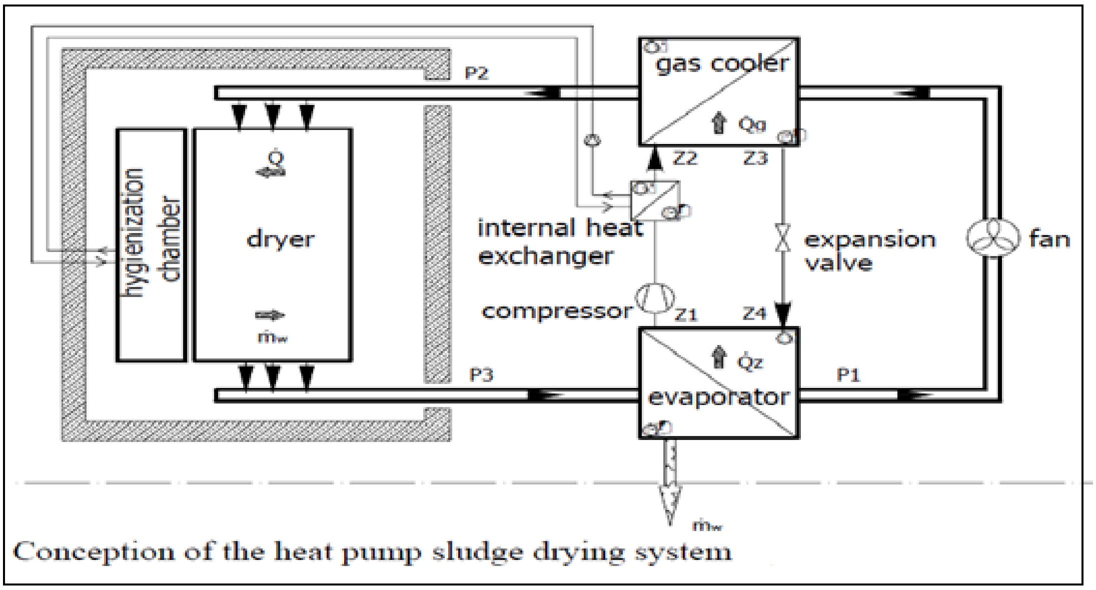

Figure 2.5 Heat Pump Sludge Drying System (Flaga and Schnotale, nd; http://www.lwr.kth.se/Forskningsprojekt/Polishproject/rep14/Flaga14p25.pdf)

Flaga and Schnotale performed the sludge drying tests at laboratory. They dried the sludge samples controlled temperature and relative humidity. The results from the first test series conducted are given in Figure 2.6. Sludge sample was dried by the air of 63 ^{o}C. After 22 hours, during which the sample reached the stabilized state with the surrounding environment, the temperature of the process air was changed to 72 ^{o}C. They calculated the DS values of sludge samples during the whole process of drying. The results of the calculation showed that the initial concentration of DS in sludge taken to dry was approximately 85%. The mass of water removed during drying was approximately 109g.

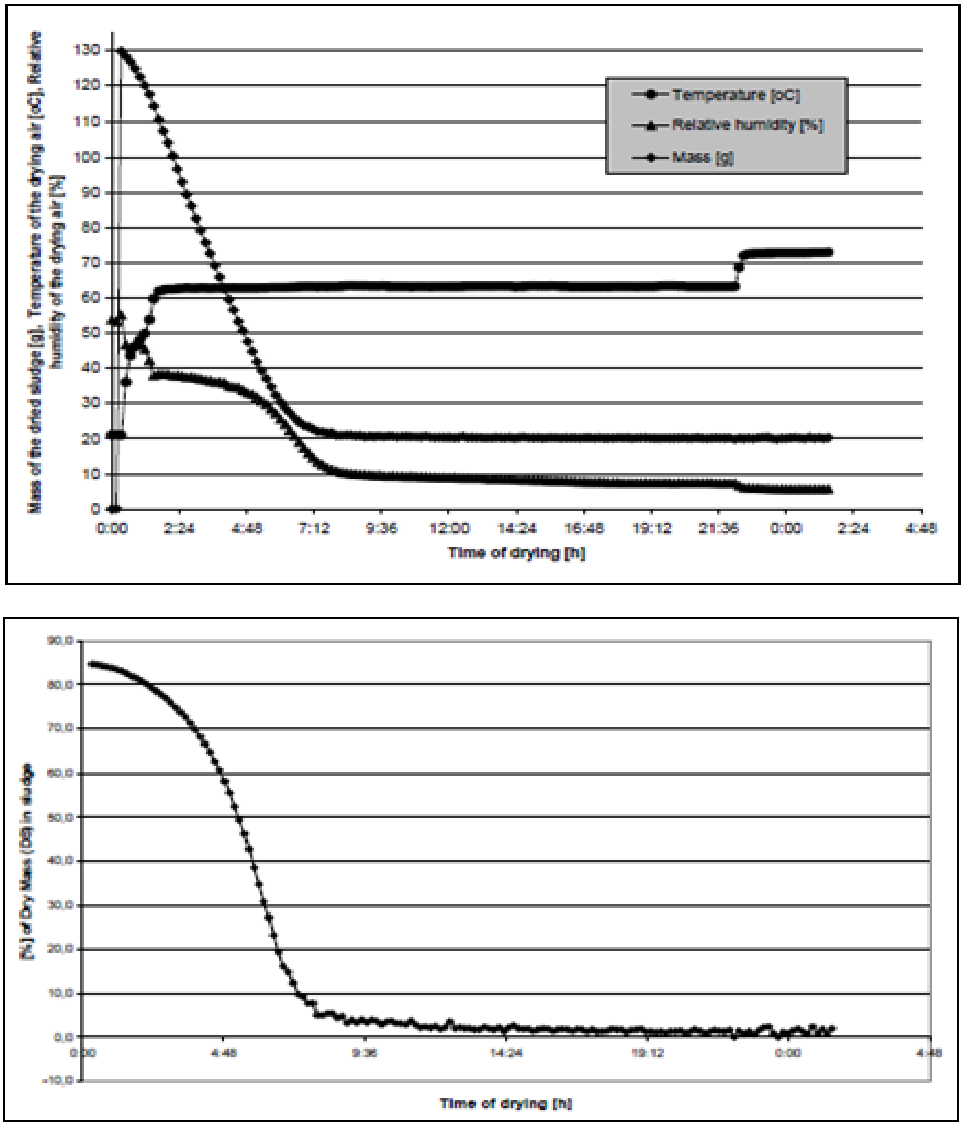

Figure 2.6 Drying test results and DS content in sludge during (Flaga and Schnotale, nd,http://www.lwr.kth.se/Forskningsprojekt/Polishproject/rep14/Flaga14p25.pdf)

Chen et al. (2004) presented some research results from drying tests, using a convective dryer at laboratory conditions. Convective drying was characterized by crack formation, which could enhance the drying rate of sewage sludge. Chun and Lee (2004) studied the drying characteristics of sludge using a combined reactor system composed of a contact dryer and a fluidized bed dryer. Their results indicate that the overall thermal efficiency of the combined system can reach approx. 76% and that the combined system causes less air pollution and attains a higher energy efficiency (Yan et al., 2009).

As another lab-scale example, a convective dryer was also used Leonard et al. (2004). They carried out the convective drying experiments in a 'micro-drier' specially designed for handling small extruded samples with a mass between 0.5 and 5 g. The micro-drier is a classical convective rig controlled in relative humidity, temperature and air velocity. Drying curves representing the drying rate (kg/s) versus the water content on a dry basis W (kg/ kg) are calculated from these mass versus time data. Dividing the drying rate by the external exchange area yields the so-called Krisher's curves commonly used to study drying, i.e., the mass flux (kg/ m^2. s) versus water content (kg/ kg). Results reported in this study refer to the following operating conditions: temperature of 160°C, superficial velocity of 3 m/s, ambient humidity. Ambient humidity fluctuates from one day to another one, ranging between 0.004 and 0.010 kg/ kg. Such variations can however be neglected, at a high temperature, when compared to the external driving force (Léonard et al., 2004).

Dewila et al. (2005) used a multiple hearth dryer system shown in Figure 2.7. This sytem consisted of several hollow plates placed horizontally above each other. The energy required to preheat the sludge and to evaporate the sludge water was supplied by means of thermal oil flowing through the sandwich heat exchanging plates. The sludge was added to the dryer on the top-plate. A continuously rotating rake mechanism transports the sludge from plate to plate. The dried sludge was evacuated at the bottom. After being mechanically dewatered, the sludge reached the mixer-pelletizer where the dewatered sludge was mixed with an amount of dried sludge to reach a DS content of 70%. The mixed sludge was fed to the dryer where it was dried to 90% DS. The sludge temperature in the drier was approximately 100 ^oC, except for the first plate where the sludge was preheated, causing only little evaporation. All other plates were required for evaporation of sludge water (Dewila et al., 2005).

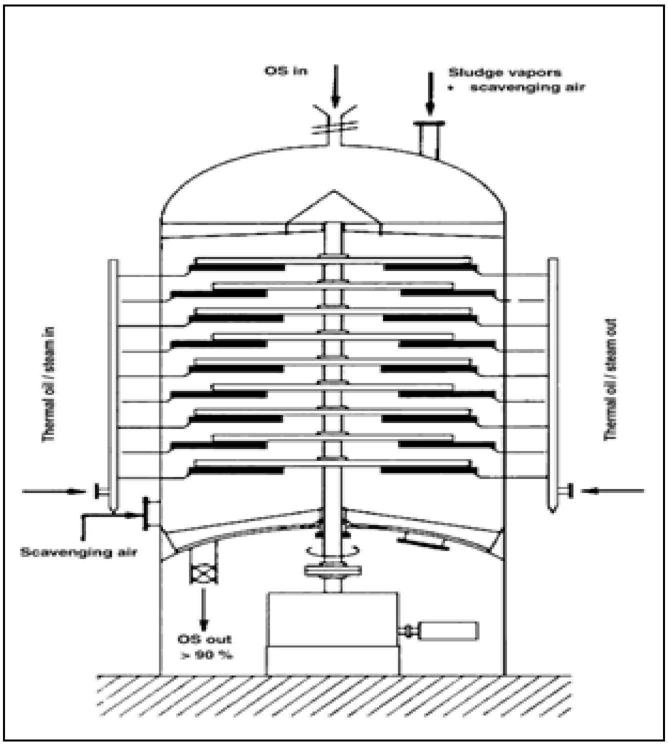

Figure 2.7 Multiple hearth dryer used by Dewila et al. (2005)

Hassebrauck and Ermel (1996) investigated two full-scale sludge drying plants: Darmstadt sludge drying plant (2 lines with a 2 stage dryer) and Frankfurt (1 line with a drum dryer) (Figure 2.8). For the first plant, the input and the output solid concentrations of sludge were given as 35% and 90%, respectively. As similarly with the first plant, the input and the output dry solid concentrations of the sludge in Frankfurt drying plant were about 35% and 90%, respectively. In Frankfurt plant, almost dustless granules with a grain size of 2-4 mm were produced trough the drum dryer, and final product could be available to be used in agricultural areas. In these plants, product quality, building situation on site, opportunity of using waste heat, integration into existing plant conception, and also economic viability were the criteria for choosing adequate drying method (Figure 2.9) .

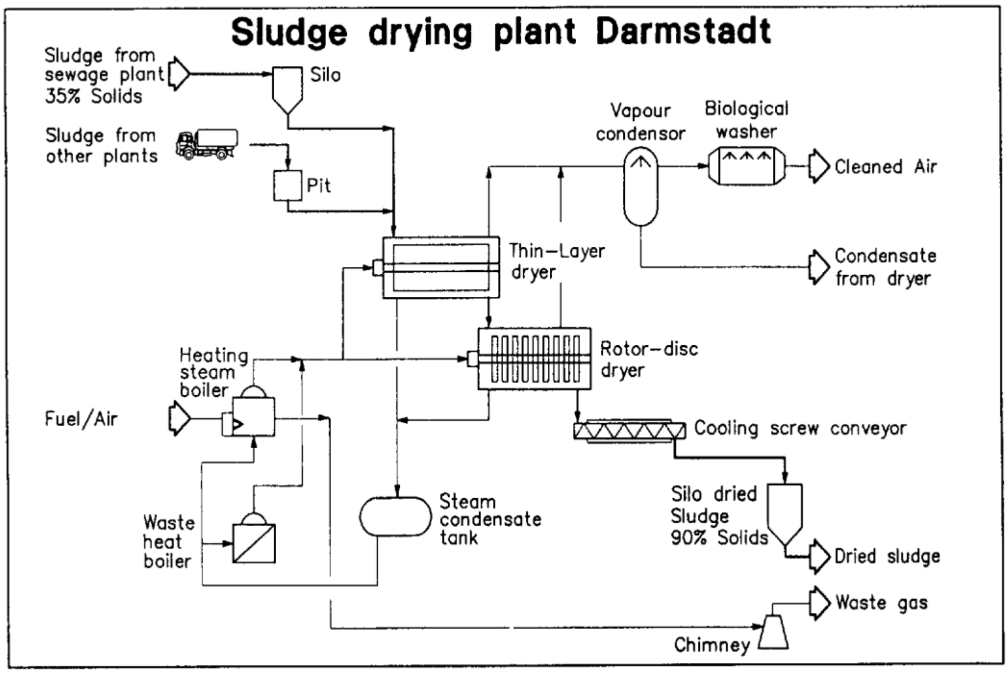

Figure 2.8 Sewage sludge drying plant at Darmstadt (Hassebrauck and Ermel, 1996).

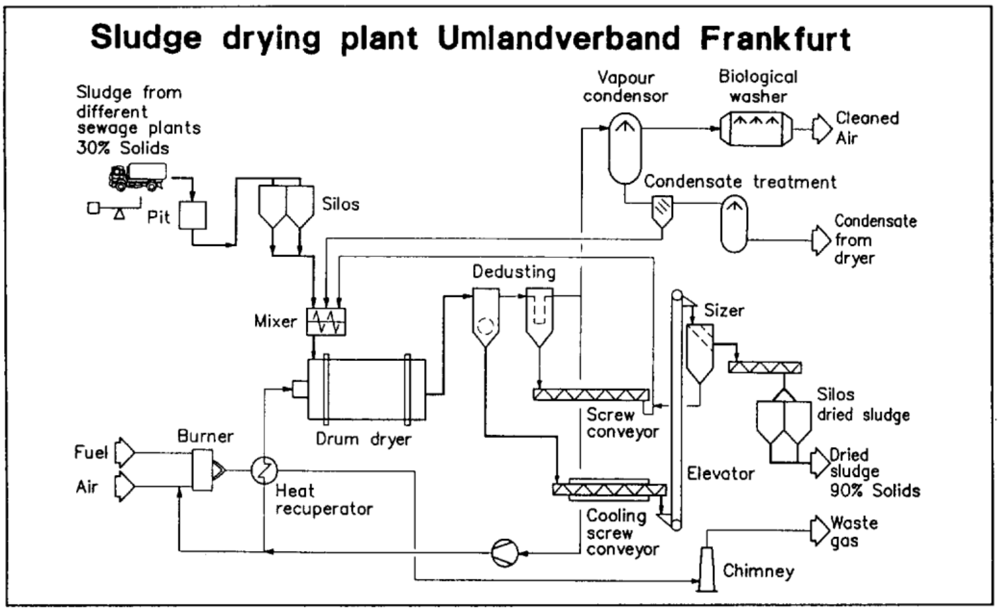

Figure 2.9 Sewage sludge drying plant of the Umlandverband Frankfurt (Hassebrauck and Ermel, 1996)

There is also solar sludge drying technology in practice. Because natural air drying is a long process and incomplete in the winter months, it needs additional thermal drying, thus reducing not only the final moisture content of discharged solids but also reducing the content of pathogens (Chen et al., 2002). For instance, taking into consideration fecal coliform removal, Salihoğlu and Pınarlı (2007) showed that solar sludge drying of sludges in closed system was more effective method than open solar drying method (Salihoglu and Pinarli, 2007).

2.6 Review of Present Situation in Turkey regarding the Sludge Drying Technology

Based on 2004 Statistical Energy and Environmental Data of TUIK, the ratio of population served wastewater treatment plants to total population is considered as 37% and the assuming solids production as 60 g/c/d, the amount of municipal sludges can be estimated as 1,600 t/d (Filibeli and Ayol, 2007). The target rate of population served by wastewater treatment plants in total municipal population is about 73% for 2010. However, Ministry of Environment and Forestry (MoEF) has recently declared that this ratio will be increased up to 81% by the year 2012. Regarding this ratio, the total sludge production produced at municipal/domestic plants is expected about at 3,500 t/d by the year 2012 (Ayol and Filibeli, 2010).

By-Law on Urban Wastewater Treatment Regulation established in 2006 has an article "all municipalities having WWTPs serving 1 million Population Equivalent should be dry their sludges up to 90% ds by the year 2010. However, MoEF revised this regulation and Soil Pollution Control Regulation (SPCR). MoEF separated SPCR as Soil Pollution Control and Point Source Contaminated Sites Regulation and Land Application of Stabilized Domestic/Municipal Sludge Regulation. In the second regulation, MoEF recommends the drying units for the municipalities serving 1 million Population Equivalent (Filibeli and Ayol, 2010). Therefore, many municipalities have opened tenders for sludge drying plants. In the near future (within 3 years), it is expected to increase the number of sludge drying units in WWTPs to reduce the sludge amounts and increase their energy contents (Ayol and Filibeli, 2010).

Sludge drying process are considered for the most suitable way of overcoming the cost of storage and transportation problems in order to dispose the excessive sludge from the wastewater treatment plants of the big cities with high population. Furthermore, this waste considered as a toxic and harmful can be converted into useful product through the medium of sludge drying systems, so it can be used as a source of energy in plants or marketed as soil fertility for the farmers (Water Environment Federation Residuals and Biosolids Committee Bioenergy Technology Subcommittee [WEF-RBC-BTS], 2004; Bux et al.,2002).

In Turkey, the sludge drying process is a quite new technology. Some municipalities and industries have applied this technology for sludge produced at their wastewater treatment plants. Municipalities and some industries have been tended to use sludge drying methods on sludge to ensure the limits in conformity with the legal legislations and also to get more competitive advantage on the global market with the increasing environment-conscious.

When taking into account of the the current situation in Turkey, it can be said that the first drying unit was established in Antalya. However, many municipalities like İzmir, Bursa, Gaziantep are also planning the construction of sludge drying units. After the drying unit application in Antalya, the Administration of Water and Sewage of City of Istanbul (ISKI) built some full-scale sludge drying units in some WWTPs like Tuzla, Pasakoy, and Atakoy WWTPs. Some details about the units will be given within this section.

The Administration on Water and Wastewater in Antalya (ASAT) made tender to build the sludge drying unit in Hurma WWTP in 2008. The sludge drying plant with a 4900 kg/h water evaporation capacity accepts sludges coming from two wastewater treatment plants: Hurma and Lara in city of Antalya, which their sludge production is about 110 tonnes/day with 18%DS. Dried Solid contents of the sludges have been increased up to app. 92% DS. The sludge cake with 20% DS has been produced about 80-100 ton/ day in Hurma WWTP located in the west side of Antalya. The sludge cake with 25% DS has also produced approximately 30-50 ton/ day in the Lara WWTP located in the east-side of Antalya, which the produced sludges are transferred to the sludge thermal drying and cogeneration plant in Hurma WWTP.

For the first studies regarding the solving sludge disposal problem in Antalya, solar drying technique was thought. However, due to the feasibility study revealed that it required app. 9.000 m^2 storage place and it can be only achieveable 55-65% DS in sludge after solar drying, it was given up (Yıldız, and Minta, 2009).

In 2008, thermal sludge drying plant was built. By the process of thermal sludge drying which enables the sludge volume to be diminished 3-4 times, storage and transport problems have been solved or minimized in Antalya. By using this process, the sludge’s calorific value has been also increased while the water content of the sludge was decreased and to be hygienic by decontaminating pathogens.

In Hurma WWTP, after the thermal drying plant, there is also a cogeneration plant. The dry solid matter content of the product obtained at the output of the process is 92%DS. The product obtained after drying of the sludge has been utilized as fertilizer for municipal service areas. In the ASAT presentation submitted to the Second National Sludge Treatment Symposium held in Izmir, it was reported that the thermally dried sludge’s calorific value was 3950 kCal/kgDS on average basis (Yıldız, and Minta, 2009). Figure 2.10 has showed the schematic diagram of the Hurma drying plant and a picture from the first full-scale municipal sludge drying unit in (www.asat.gov.tr).

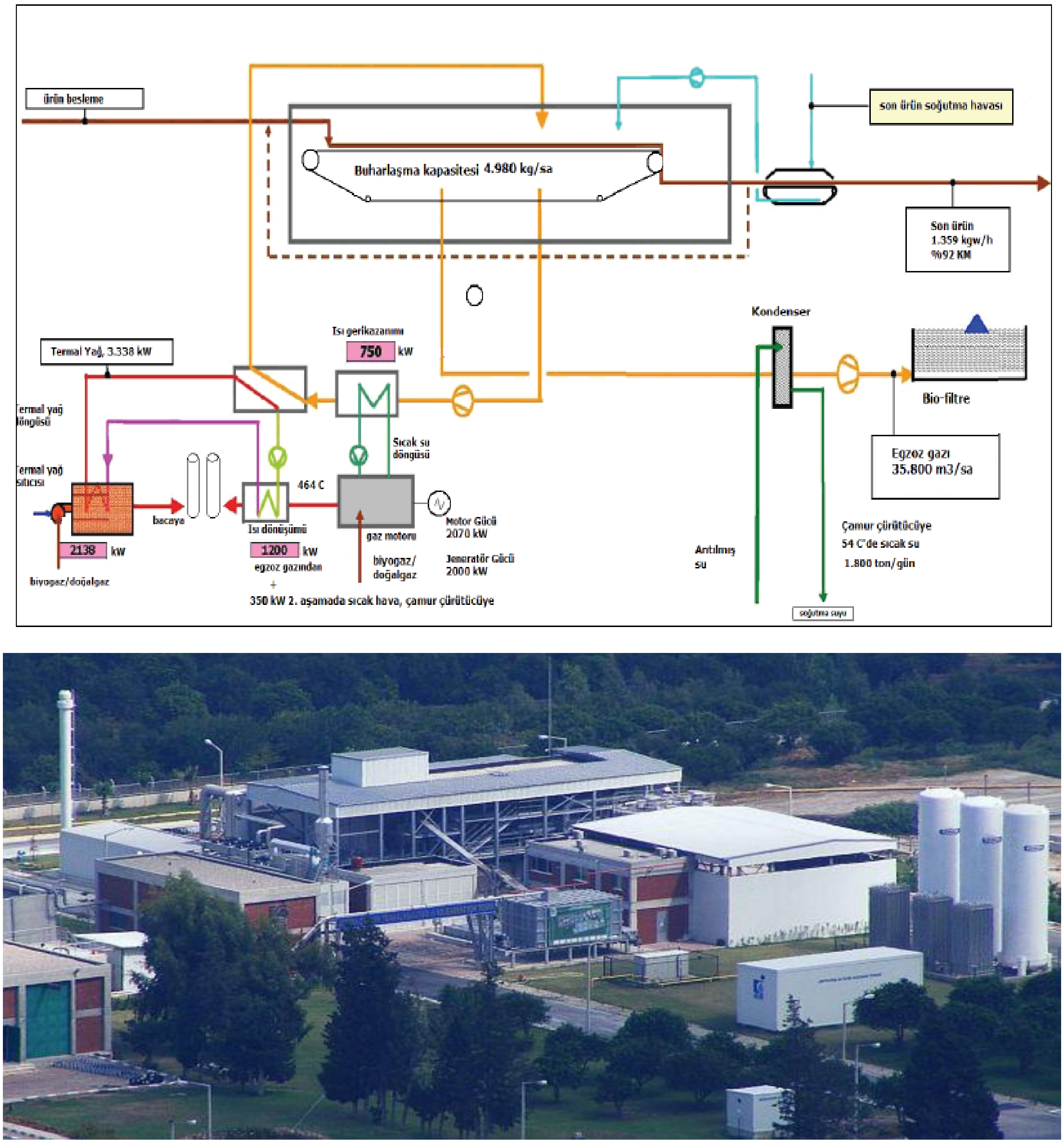

Figure 2.10 The Flow Schema of Hurma Sludge Drying Plant and a view from the plant (www.asat.gov.tr)

In Istanbul Metropolitan Municipality, ISKI built a few sludge drying plants in Tuzla, Pasakoy, and Atakoy WWTPs. In Tuzla WWTP’s drying plant shown in Figure 2.11, the dryer capacity is 300 tonnes/day and the dewatered sludge with 25%DS content has been fed to the system and dried product has about 90%DS, which is transferred to cement factories as a supplementary fuel (Demir et al., 2010).

Figure 2.11 Tuzla WWTP Sludge DryingUnit (Demir et al., 2010)

The dryer capacity in Pasakoy WWTP is 200 tonnes/day and the DS content of the dewatered sludge has been increased from 25%DS upto 90%DS, which is transferred to cement factories as a supplementary fuel. In this plant, there is a cogeneration plant with a capacity of 4.2 MW, which is used for plant energy comsumption and waste steam has been used in drying unit. The plants are shown in Figure 2.12 (Demir et al., 2010).

Atakoy WWTP has six sludge dryers, which they increased the DS content of sludges from 25% to 90%. The total amount of produced sludge in Atakoy WWTP is about 15083 m^3/d, which is reduced to 140 m^3/d after drying application. The dried products have been used as a fertilizer and/or supplementary fuel in cement factories since their high calorific values are about 3000 kcal/kg (Demir et al., 2010). The drying plant and some pictures from dewatered sludge cake and dried sludge are given in Figure 2.13 .

Figure 2.12 Pasakoy WWTP Sludge Drying Unit and Cogeneration Plant

Figure 2.13 Atakoy WWTP Sludge Drying Unit an a view of a dewatered sludge cake and dried product (the upper pics).

Beyond the constructed sludge drying plants, many municipalities have been making preparations to open tenders for drying plant establishments. For example, Izmir Metropolitan Municipality have started this study for approximately 800 tonnes/day sludge to be dried and reduce the amount 120 tonnes/d. They are planning to establish this drying plant in Cigli Municipal WWTP, which 94% of the total amount of sludges produced at municipal WWTPs in Izmir belong to Cigli WWTP (http://www.izmir.bel.tr/Details.asp?textID=7443).

Formerly, the officers of Bursa municipality have also worked on a thermal sludge drying plant for the east part and the west part WWTPs of the city. However, there is stil no any clear project declarated on the sludges produced in these WWTPs.

The administration of Water-Wastewater Management of Gaziantep city (GASKI) has recently opened a tender to construct sludge thermal drying plant. GASKI is planning to increase the DS content of the sludges from 16-18% to 90 % DS (http://www.insaatdergisi.com/insaat-gaziantepsuvekanalizasyonidaresiaritmacamurutermalkurutmaveyakmatesisiinsaatiihalesi-haberayrinti-24533-insaatihaleleri.html).

In addition to municipial sludge drying plants, there are some examples from private sectors. For example, a plant with sludge-burner licensed namely Nuh Cement Inc. in Kocaeli has also a burning capacity for the sludge from outside of the company. Meanwhile, KTS group, carrying on with its studies in İzmir, has been producing the sludge drying systems for industrial factories lately.

Nuh Cement Inc. established a sludge drying plant in Hereke, which its cost is about 40 million USD. This plnat accepts the sludges from domestic WWTP in Kocaeli and 60 factories between Trakya and Adapazarı. After drying, the output dried product is burned again with coal in the plant, so the calorific value of the sludge is used for energy obtaining purpose.The system is working at full capacity with 250 ton waste sludge drying (http://www.borsagundem.com/haber/oku/manset/18189/nuh_atik_camur_icin_40_milyon_$_yatirdi__/print).

Bumerang Waste Disposal and Recovery Plant located in Kocaeli is the only licenced firm in Turkey. This plant has enable to dispose all kinds of sludge such as hazardous, non-hazardous, industriel, domestic, pigment, phosphate, and the other process sludge by drying. The treatment plant sludges from factories, organized industrial areas, free zones, and settling areas have been dried up to 80-90%DS. The sludge drying capacity is about 80 tonnes/day (http://www.kobiden.com/haber.asp?id=2025).

KTS Group Drying Technology Systems established in Kemalpaşa, İzmir has started to construct drying plant sludge produced atFord Otosan’s plant in Kocaeli in

2009. With this process, it’s the amount of treatment sludges is reduced and also its calorific value is increased. The dried product has been used in cement factories. In addition to this, KTS group has announced trough the internet website that they have started to build a sludge drying plant in Efes Pilsen plant, Izmir, as of 01.01.2009 (http://www.dryerturk.com/Default.asp?L=TR&mid=167&nid=75&action=NewsDetail).

When the current situation is examined in Turkey, it can be said that there are much more efforts on sludge drying technology. In terms of quite positive point of view, energy recovery from sludge and/or other beneficial usage alternatives have been recently receiving much more attention in Turkey for both municipalities and industries.

CHAPTER THREE

THERMAL DRYING

3.1 Introduction

This chapter gives the information about thermal drying process, heat transfer methods, dryer types, and advantages –disadvantages of sludge dryers.

3.2 Thermal Drying of Sludge

The term "**drying**" is defined as a mass transfer process comprising the water or moisture removal by evaporation from a solid, semi-solid or liquid (http://en.wikipedia.org/wiki/Drying). According to the Water Environment Federation Residuals and Biosolids Committee Bioenergy Technology Subcommittee, thermal drying refers to the technology is based on removal of water from dewatered solids which accomplishes both volume and weight reduction (WEF-RBC-BTS, 2004).

Thermal drying can be considered as a final treatment method in sludge management field. Although it is very effective process from the view of reducing the sludge amount and pathogenic microorganism in sludge, its capital cost is quite high. Taking into consideration of many advantages of the thermal drying process, it is an effective final step for beneficial usage of sludges like energy recovery from sludges or usage for agricultural purpose. It can indeed lower the water content in sludge, which is usually below 5% dry solids (DS). This obviously reduces the mass and volume of sludge and, consequently, the cost for storage, handling and transport. The water removals to such a low level increases the calorific value, transforming the sludge into an acceptable combustible. In addition, the dried sludge is a pathogen-free, stabilized material due to high-temperature treatment (Léonard et al., 2008). Final product coming from thermal drying process can be considered as a suitable product for both using in agricultural areas and landfilling. In addition to this, it is also an important step before further thermal treatment like incineration, pyrolysis, and gasification.

3.2.1 Heat Transfer Methods

Heat transfer or transfer of thermal energy is known as the movement of heat from one place to another. *When an object is at a different temperature from its surroundings, heat transfer occurs so that the body and the surroundings reach the same temperature at thermal equilibrium. Such spontaneous heat transfer always occurs from a region of high temperature to another region of lower temperature as required by the second law of thermodynamics* (DOE-HDBK-1012/2-92,1992; Lienhard IV and Lienhard V; 2008).

Fundamental methods for heat transfer in engineering can be classified as three ways: conduction, convection, and radiation. *Energy transfer by heat between objects is classified as either* ***heat conduction*** *or diffusion, of two objects in contact;* ***by fluid convection****, which is the mixing of hot and cold fluid regions; and* ***by thermal radiation****, the transmission of electromagnetic radiation described by black body theory. In addition to three methods, engineers also consider the mass transfer of differing chemical species, either cold or hot, to achieve transfer of heat* (DOE-HDBK-1012/2-92, 1992; Chris and Sayma, 2009).

However separate physical laws have been knownto describe the behavior of each method, in nature, real systems may exhibit a complicated combination of them (http://en.wikipedia.org/wiki/Heat_transfer; Chris and Sayma, 2009).

- Conduction or diffusion: Transfer of energy between objects by the means of physical contact,
- Convection: Fluid motion leads to transfer of energy between an object and its environment,
- Radiation: *Transfer of energy from or to a body by the emission or absorption of electromagnetic radiation*

- Mass transfer: *Movement of physical objects represents a movement of their internal energy* (DOE-HDBK-1012/2-92, 1992; Cengel,2003)

3.2.1.1 Conduction

On a microscopic scale, heat conduction occurs as hot, rapidly moving or vibrating atoms and molecules interact with neighboring atoms and molecules, transferring some of their energy (heat) to these neighboring atoms. Conduction is the most important method of heat transfer within a solid or between solid objects in thermal contact. Although fluids (and especially gases) are less conductive, thermal contact conductance is the study of heat conduction between solid bodies in contact. In steady state conduction, the amount of heat entering a section is equal to amount of heat coming out. However, transient conduction occurs when the temperature within an object changes as a function of time (http://en.wikipedia.org/wiki/Heat_transfer; DOE-HDBK-1012/2-92, 1992).

3.2.1.2 Convection

Convective heat transfer is the second method, in which transfer of heat from one place to another by the movement of fluids. It is described by Newton's law of cooling, which states that the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings.

The presence of bulk motion of the fluid enhances the heat transfer between the solid surface and the fluid. Convection is usually the dominant form of heat transfer in liquids and gases. However, convection actually describes the combined effects of conduction and fluid flow (Cengel, 2003).

Free or natural convection occurs when the fluid motion is caused by buoyancy forces that result from the density variations due to variations of temperature in the fluid. Forced convection is when the fluid is forced to flow over the surface by external sources such as fans, stirrers, and pumps, creating an artificially induced *convection current* (http://www.engineersedge.com/heat_transfer/convection.htm; Faghri, et al.,2010).

3.2.1.3 Radiation

Thermal radiation is the transfer of heat energy through empty space by electromagnetic waves.

Thermal radiation is a direct result of the movements of atoms and molecules in a material. Since these atoms and molecules are composed of charged particles (protons and electrons), their movement results in the emission of electromagnetic radiation, which carries energy away from the surface. At the same time, the surface is constantly bombarded by radiation from the surroundings, resulting in the transfer of energy to the surface. Since the amount of emitted radiation increases with increasing temperature, a net transfer of energy from higher temperatures to lower temperatures results (http://en.wikipedia.org/wiki/Heat_transfer; Faghri, et al.,2010).

3.2.1.4 Mass Transfer

In mass transfer, energy, including thermal energy, is moved by physical transfer of a hot or cold object from one place to another. This can be as simple as placing hot water in a bottle and heating a bed or the movement of an iceberg and changing ocean currents (http://en.wikipedia.org/wiki/Heat_transfer#Conduction).

Considering the fact that drying strictly depends on some heat transfer methods, it can be easily understood that when necessary heat for evaporation is supplied to the sludge particles, water vapor is removed from the sludge material into the drying medium. As shown in Figure 3.1 (Chen et al., 2002) and Figure 3.2 (Chun and Lee, 2004), when water contents of sludges increase, their drying rates also increase.

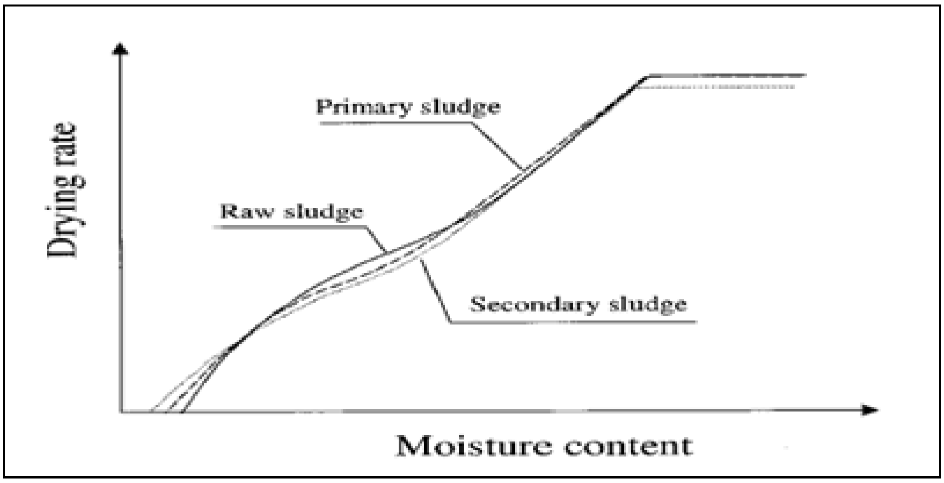

Figure 3.1 Typical drying rate curves for different types of sludges (Chen et al., 2002)

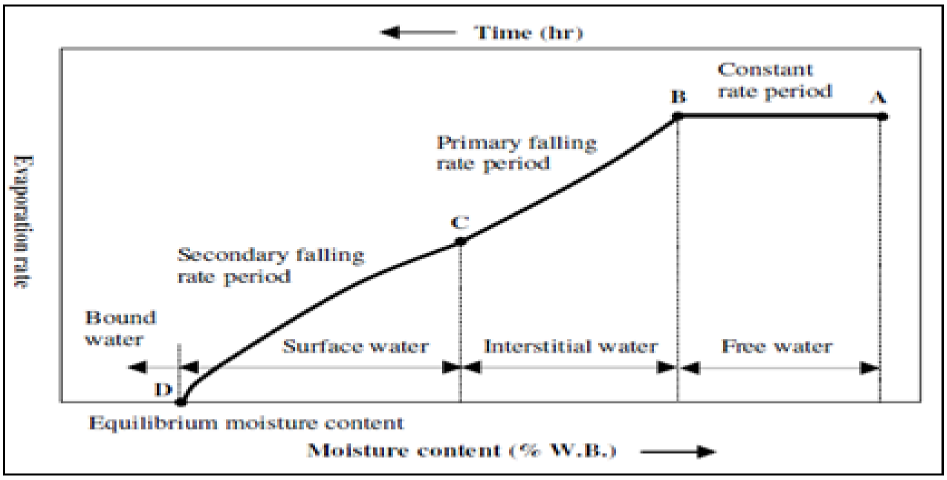

Figure 3.2 Drying curve for sewage sludge (Chun and Lee, 2004)

As explained in Section 2.4 and shown in Figure 2.1, water fractions in sludge are existed in four categories: free water, interstitial water, surface water, and bound water (Vesilind, 1994; Vaxelaire and Cezac, 2004). To remove the free water fraction, sludge thickening units like gravity thickeners, belt thickeners or centrifuges have been used. It is possible to increase the DS content of sludges upto 10% by thickening process. Mechanical dewatering units including centrifuges, belt presses, filter presses, etc. can be used to remove the interstitial water and surface water fractions from the sludges. It can be achievable 20-30% DS using dewatering process depending on the used equipment. However, the remaining water content is not possible to remove either by thickening and dewatering processes. It can be removed from the sludge as in cell and chemically bonded water fraction by using the thermal drying process. Using thermal drying process, more than 90%DS content can be obtained. Figure 3.3 gives the weight loss of 1- tone sewage sludge throughtout typical sludge treatment route.

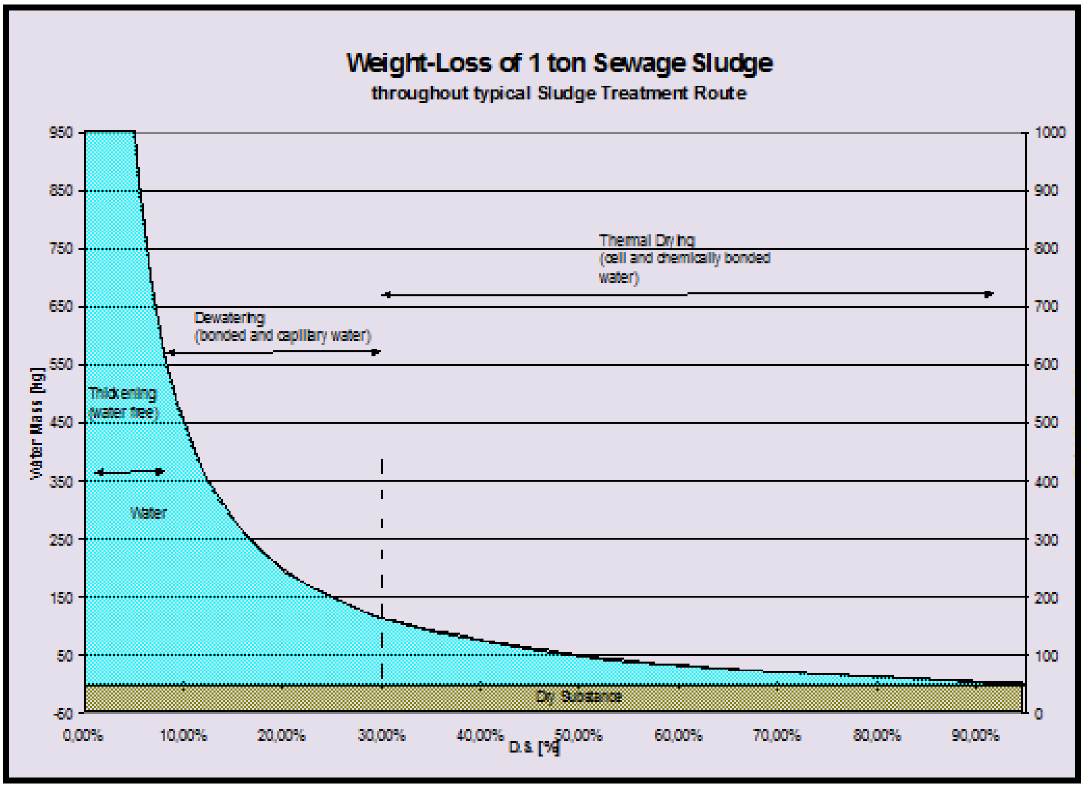

Figure 3.3 The weight loss of 1- tone sewage sludge throughtout typical sludge treatment route(www.andritz.com, Durko presentation at NSS2005).

3.3 Types of Dryer

Depending on the heat transfer methods, dryer types can be categorized into four types:

- Direct drying systems (convective dryers)
- Indirect drying systems (conduct dryers)
- Combined systems (mixed convective-contact dryers)
- Infrared dryers (with the use of infrared radiation or high frequency currents).

3.3.1 Direct Dryer

Direct dryer design depends on the convective heat transfer method, in which there is not any heating transfer medium, hot gas or air coming from any source of heat, contact directly particles of wet solids. The relation between hot medium and wet material causes an increase in solid temperature and so the water in the material evaporates (WEF-RBC-BTS, 2004; Flaga.A, nd).

Among the direct dryer types, rotary-drum dryers, flash dryers, belt dryers, and centri-dryer types are well known in the practice.

3.3.1.1 Rotary Drum Dryer

The rotating drum transports the cake mixture (normally 50-65% DS) through the drum, rolling the product and exposing the external surface of the material to the hot gases. *This transportation and drying action produces a granular product which is then separated from the exhaust gases by means of a cyclone followed by mechanical classification of the product. Oversized and undersized products can be recycled as part of the backmixing material. A closed-loop system and a slightly negative operating pressure reduce the risk of odour release in this dryer system* (Lowe, 1995). The schematic view of a rotary-drum dryer and a full scale- rotary drum dryer are given in Figures 3.4 and 3.5, respectively.

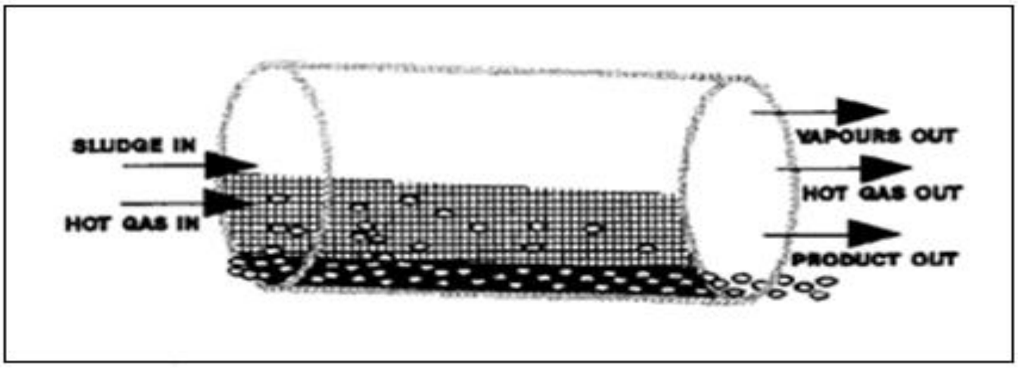

Figure 3.4 Rotary Drum Dryer (Lowe, 1995)

Figure 3.5 Convective Thermal Dryer by Siemens Water (http://www.water.siemens.com/SiteCollectionDocuments/Product_Lines/Dewatering_Systems/Brochures/EPS-SLUDGEDRY-USA-BR-1008.pdf)

Technical Features of Convective Thermal "triple pass" drum dryer (CTD) by Siemens Technology: The wet product is dried by an air stream, heated by a heat generator. The process is performed inside an enclosed rotating drum consisting of three coaxial cylinders. The capacity ranges from 1000 to 10000 kg/h of evaporated water. (http://www.water.siemens.com/SiteCollectionDocuments/Product_Lines/Dewatering_Systems/Brochures/EPS-SLUDGEDRY-USA-BR-1008.pdf)

Figure 3.6 also shows a rotary-drum dryer which is explained in Chen et al. (2002). *The inlet temperatures up to 1000 ^oC can be used without the risk of ignition with a water evaporation rate ranging from at least 800 kg/h to as much as 50000 kg/h. Recycling part of the vent gas may be used to improve the thermal efficiency of the dryer* (Chen et al, 2002).

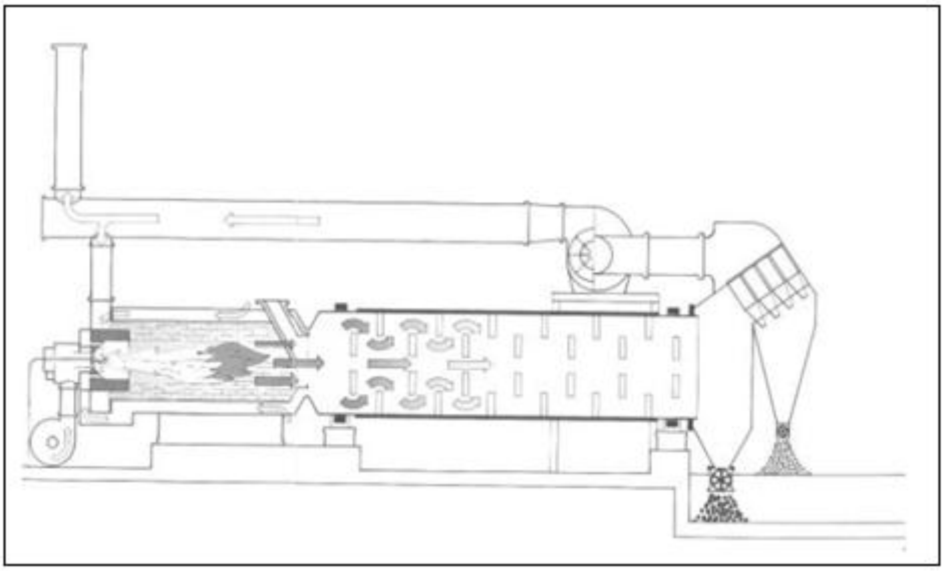

Figure 3.6 Rotary Drum Dryer

3.3.1.2 Flash Dryer

The flash drying system for sludges that require disintegration is the cage mill system. The feed sludge material is agitated in the hot gas stream by the cage mill, thereby increasing turbulence and retention time. *The circular motion of the rotor assists the partially dried sludge to move up the dryer here additional drying occurs. A mixer may be used for wet feed where a portion of the already dried sludge is diverted back into the mixer. In flash drying, heat recovery is helpful in improving the energy efficiency. Depending on the application, this is normally accompanied either by using vent gas recirculation (Figure 3.7), by employing a deodorizing preheater as a heat exchanger (Figure 3.8), or tying the flash drying system directly with a steam generating boiler that can incinerate both the dried sludge and any odorous drying gases (Figure3.9). The maximum water evaporation rate is approximately 0.1 kg water/m*^{3} *air flow at the vent* (Chen et al., 2002).

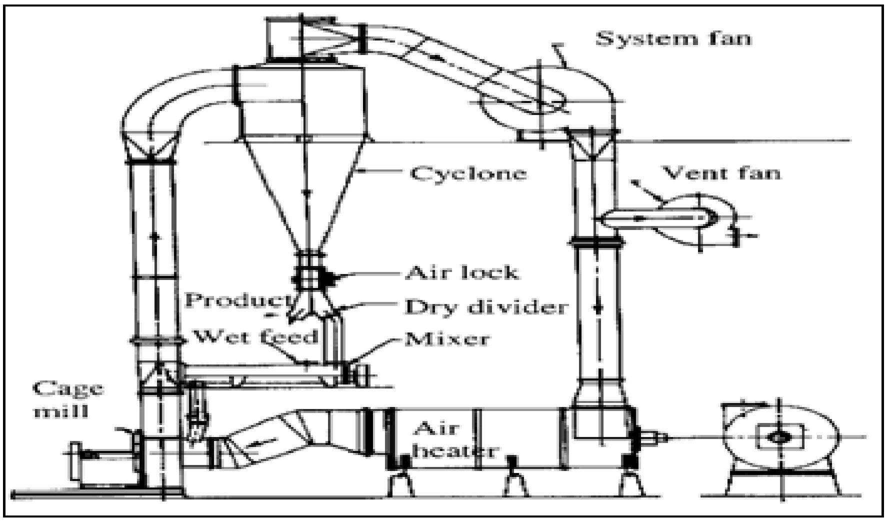

Figure 3.7 Cage-mill flash drying system with recirculation (Chen et al., 2002)

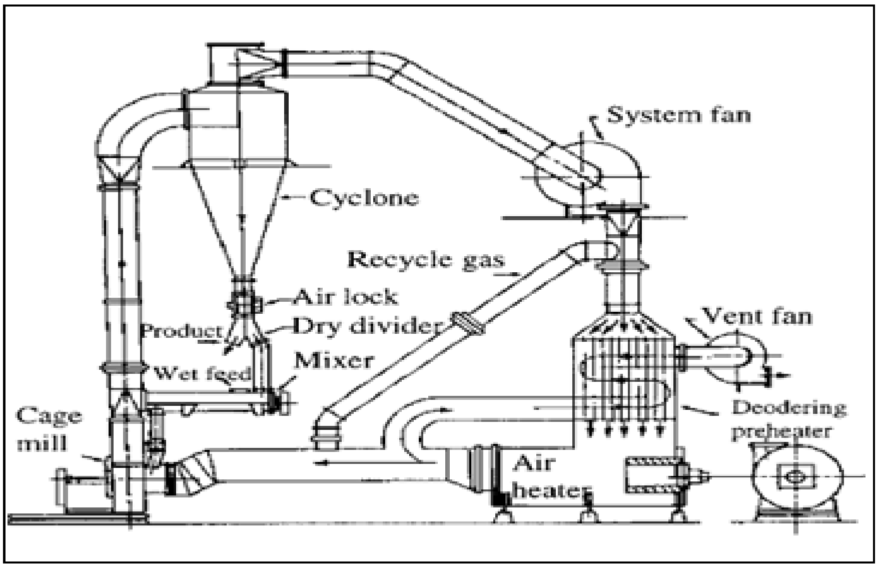

Figure 3.8 Cage-mill flash drying system with deodorizing preheater (Chen et al., 2002)

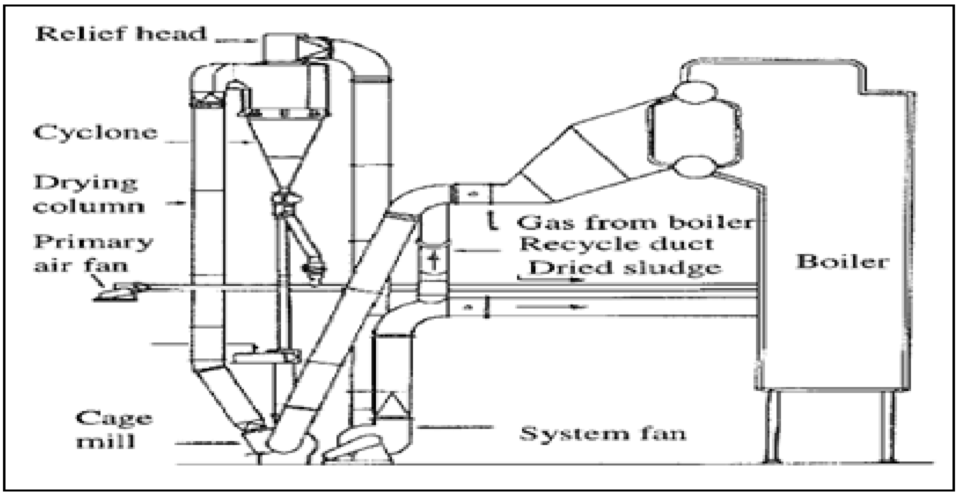

Figure 3.9 Cage-mill flash drying system with accompanying fired boiler (Chen et al., 2002)

Lowe (1995) has reported that the flash dryer relied upon the pulverization of the sludge cake within a high-speed rotating cage in the presence of hot gases. In this system the dried disintegrated sludge product leaves the dryer unit with the water vapour and is separated in a cyclone. The gases and water are then vented to the atmosphere through a scrubber or a peat bed. Some of the water-air is recycled back to the mixing chamber to recover a part of the waste heat and to maintain a low oxygen atmosphere throughout the system shown in Figure 3.10 (Lowe, 1995).

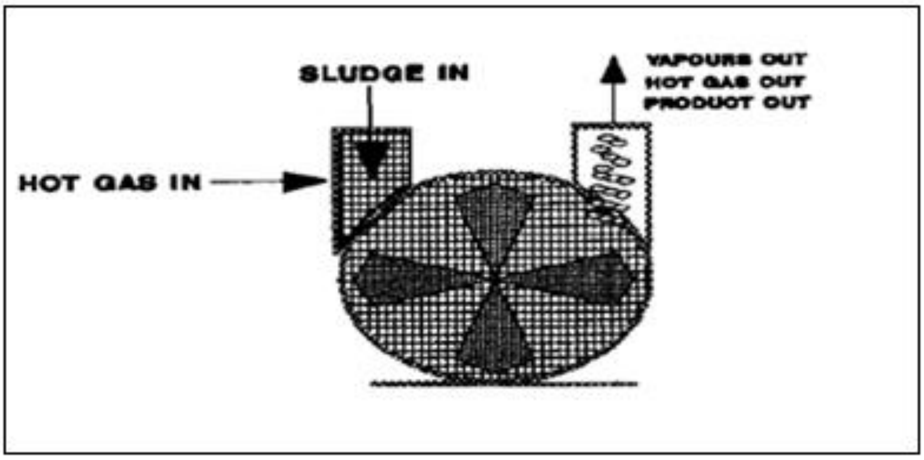

Figure 3.10 Flash Dryer (Lowe, 1995)

3.3.1.3 Belt Dryer

Belt dryer with open, semi-open and closed-loop systems is also a common type of direct dryers. For this dryer type, the dewatered sludge is fed onto a perforated, horizontal, stainless-steel belt material which then moves slowly through an enclosed housing through which hot gases are passed (Lowe, 1995). The schematic view of a belt dryer is given in Figure 3.11.

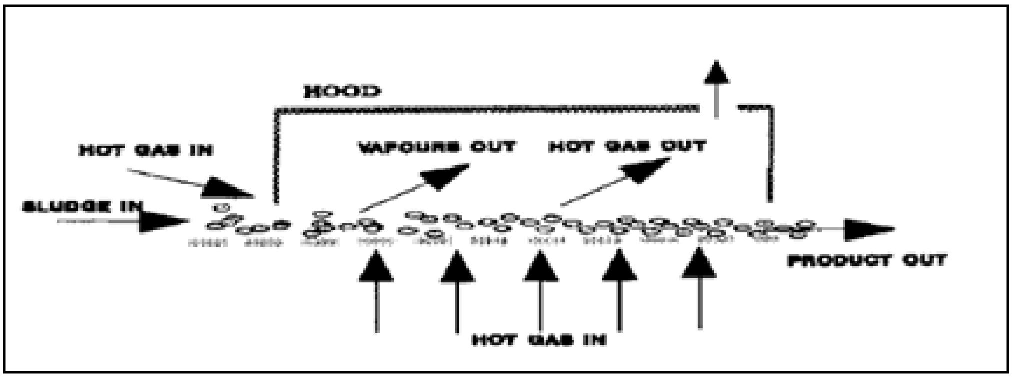

Figure 3.11 Belt Dryer (Lowe, 1995)

A closed-loop belt dryer system with the heating air dried and recirculated is given in Figure 3.12 while another system that was designed for sludge drying using infrared (IR) heating is shown in Figure 3.13. In this IR heating system, air supplied from a plenum passes across the face of the infrared heaters and is directed downward toward the sludge material in a belt passageway. *A lower plenum is provided below the upper run of the belt. It is maintained in a vacuum to draw air through the sludge. About 10–30% of the air is exhausted from the upper plenum to release moisture from the apparatus with the same portion of air made up by drawing air from the entrance and exit of the belt passageway* (Minnie, 1993). Figure 3.14 shows a moving belt sludge dryer with the belt made of cellular pockets. *The sludge-filled pockets are supported on a heated pan. Heated air is supplied from both the top and bottom surfaces of the pocket. Heat transfer is achieved by convection and conduction. The sludge may undergo multi-runs before it is dried and rejected from the pockets (Bein, 1994).* A belt dryer with stacked heating chambers claiming to have a better thermal efficiency (shown in Figure 3.15) has been patented (Nugent, 1997; Chen et al., 2002).

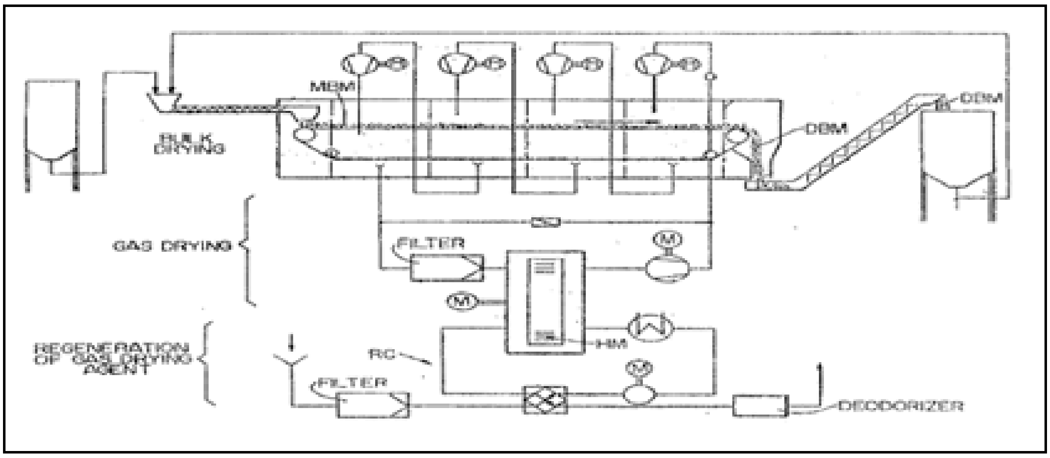

Figure 3.12 Moving belt dryer with vapor removal and heating gas recirculation system, DBM—dried biomass, HM—hygroscopic material, M—motor, MBM—moist biomass (Rutz, 1995; Chen et al., 2002)

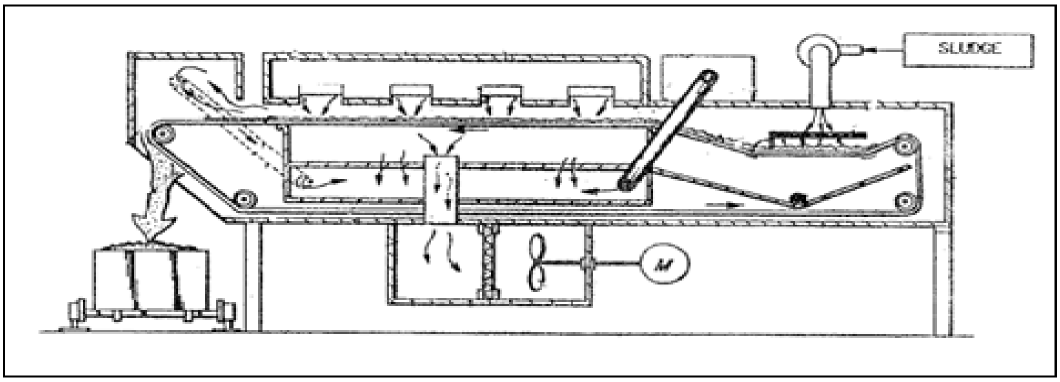

Figure 3.13 Closed loop belt dryer system with IR heating (Bein, 1994; Chen et al., 2002)

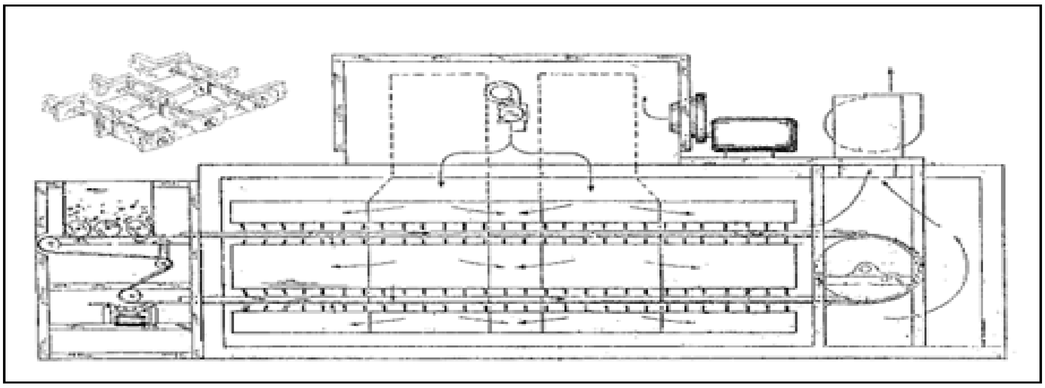

Figure 3.14 Moving belt sludge dryer with direct and indirect heating (Bein, 1994; Chen et al., 2002)

Another belt dryer example is shown in Figure 3.15 which was designed as a multi-pass moving belt drying with IR heating (Nugent, 1997). This dryer system has been manufactured by Euroby Drying Technology Ltd and an image from the dryer unit is given in Figure 3.16. The belt dryer was developed to dry different types of sludges in a simple, energy efficient, and dust free way to increase the DS contents from 20-25% to 65- 95%. The mechanically dewatered sludge is formed on to the perforated belt where it is conveyed slowly through the drying zone and discharged at the end of the conveyor. The retention time can be adjusted and homogeneous drying is achieved (http://www.euroby.com/BeltDryer.pdf). Design conditions of the belt dryer is given as follows:

- Evaporation rates range between 200 to 3,000 kg/h,
- Low temperature drying is provided for safe operation,
- Full or partial drying occurs in one step,
- Flexible heating with direct or indirect options is also possible,
- High quality granulated final product is obtained,
- Uncomplicated operation with rapid start up and shut down,
- Variably adjustable retention time
- Mobile or fixed units (http://www.euroby.com/BeltDryer.pdf).

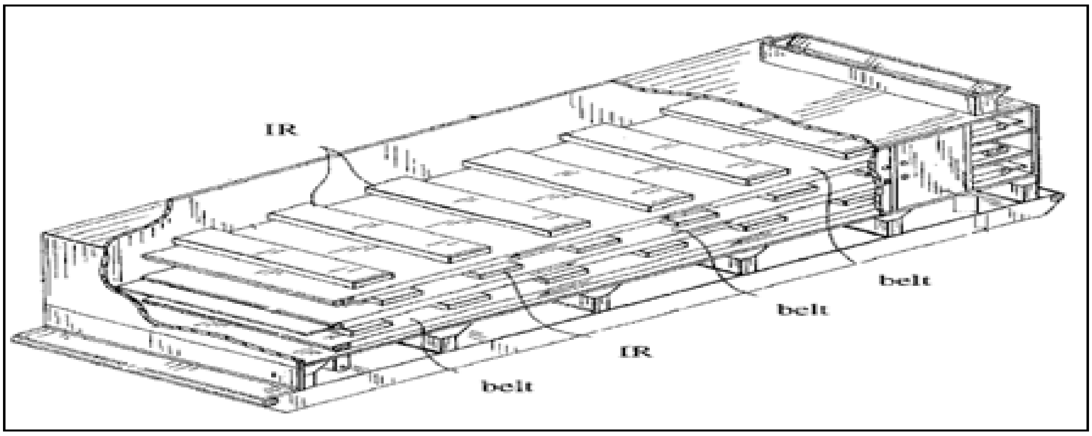

Figure 3.15 Multi-pass moving belt drying with IR heating (Nugent, 1997; Chen et al., 2002)

Figure 3.16 Belt dryer by Euroby Drying Technology Inc.

3.3.1.4 Spray Dryer

Spray dryer is known as another type of direct dryers. In this system, dewatering and drying processes have been done in a single machine. Some technical features for spray dryers are given below:

- Water evaporation capacity range from 500 to 2,000 kg/h,
- DS content of the final product is between 65 and 90 % DS,
- No back-mixing of dried product, simple plant design based upon proven Centrifuge technology with minimal peripheral equipment
- Short start-up and shut-down time
- Thermal stage can be fuelled by oil, natural gas, bio-gas or waste heat
- Requires relatively small footprint,
- Low manning level and automatic operation (http://www.euroby.com)

A patented system called as Centridry® combines the centrifuge dewatering unit with a thermally efficient flash drying stage in one unit. A conventional centrifuge dewatering equipment has been modified with an additional thermal jacket into which the dewatered cake is discharged. Figure 3.17 shows the dryer unit. In this system, hot gas dries and pneumatically transports the sludge material to the cyclone where the dried product is separated from the vapour stream and discharged to the product outloading stage. The product free vapour is returned to the hot gas generator for re-heating with excess vapour. The final product can be pelletised and is suitable for agriculture or thermal utilisation (http://www.euroby.com/Centridry.pdf).

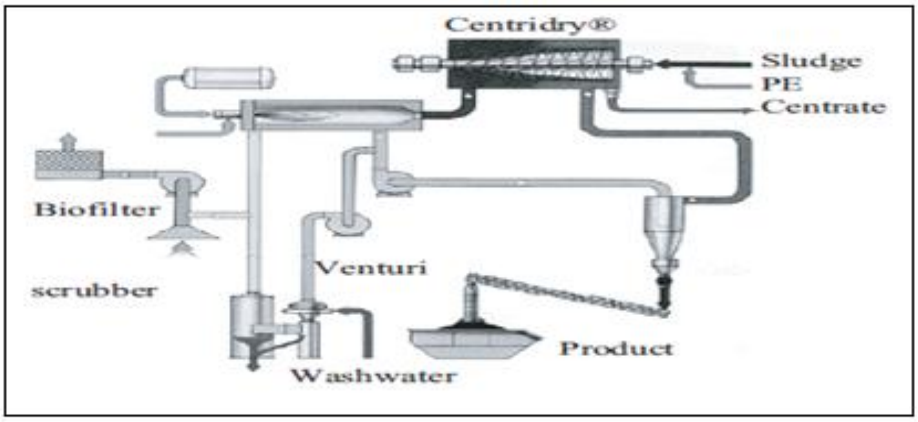

Figure 3.17 Centridryer (Chen et al. 2002, (http://www.euroby.com/Centridry.pdf)

3.3.2 Indirect Dryers

Indirect thermal dryers have the solid metal walls, which separate the sludge material from the heat transfer medium (steam, hot water, or oil). Thermal energy is transferred from the heat transfer medium into the metal wall and then from the metal wall into the sludge’s solids. The heat transfer method in this dryer system is conduction. The solids particles have never come in direct contact with the heating medium and the solids temperature is elevated by the contact between solids and hot metal surfaces (WEF-RBC-BTS, 2004). The drying rate in the indirect dryer systems may be lower than that in the direct dryers due to the direct systems can operate at much higher temperatures (Chen et al., 2002).

Most common indirect dryer types are the tray dryers, paddle dryers, and disc or thin-film dryers. These systems have also two common types as single and two stage systems.

Since indirect dryers produce less gas, most of their designs are done as a closedloop system with either heat recovery and/or odor removal units. As mentioned above the dryers depend on the heat being transferred from a heated surface. Therefore, the handling of the interfacial behavior of the sludge material and the heated surface is an important issue regarding the dewatered sludge fed to the dryer has low DS content around 25% DS Mechanical agitation is important in the designing step since there is no air flow provided to disperse or disintegrate the sludge cake. To prevent the fouling on the heating surface due to the sticky behavior of sludge with the solid content 55-70%, the mechanical mixing is very important. Depending on the requirement of the final water contentof the dried sludge, single or two-stage indirect drying systems can be employed (Chen et al., 2002).

3.3.2.1 Thin Film Dryer

To improve the dried sludge’s burning properties in an incinerator, a single-stage thin film evaporator can be applied to obtain a final solid content up to 65%. In this technology, sludge in a horizontal agitated thin film evaporator is usually used. Its drying rate lies between 20 and 160 kg/m^2.h (Gru¨ ter et al., 1990). The schematic view of a thin-film dryer is given in Figure 3.18 .

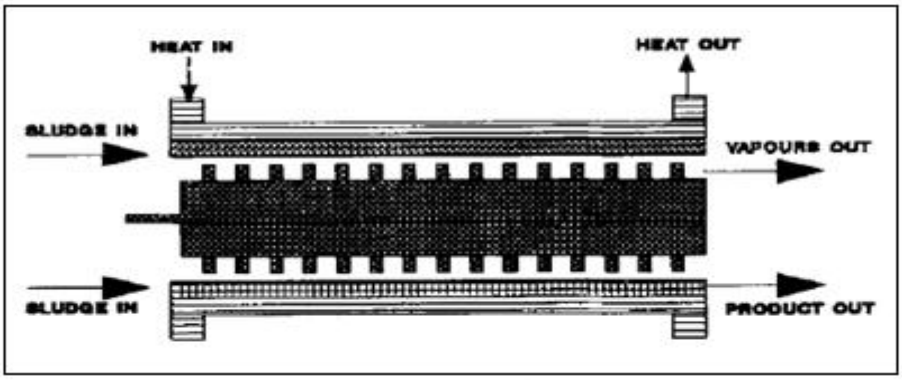

Figure 3.18 Thin-Film Dryer (Lowe, 1995)

When higher final solid content is reuired, a rotary paddle or disc dryers can be used either alone or as the second stage following a thin film evaporator (Chen et al., 2002).

3.3.2.2 Rotatable-disc Dryer

Figure 3.19 shows the rotatable-disc indirect dryer consisting of a stator with scrapers and a rotor with agitators and driving units. The heat transfer surface can be self-cleaned with the gentle friction forces created from the rotor motion. The nearly consecutive chambers ensure almost a plug flow of the sludge through the dryer, which is an important issue in sludge sterilization (Utvik, 1991). The single-stage, indirect, closed-loop systems are normally built around contact/disc dryers. Sludge cake can bedried upto 85%DS and, is pelletized followed by cooling before storage. A backmixing system returns dried sludge to a paddle backmixing system where it is mixed with the sludge cake before entering the dryer. Steam is used as the indirect heat carrier and the exit vapours are passed through a heat-recovery system, followed by deodorization before release to atmosphere (Lowe,1995). Figures 3.20-3.23 show different types of rotatable-disc dryer systems.

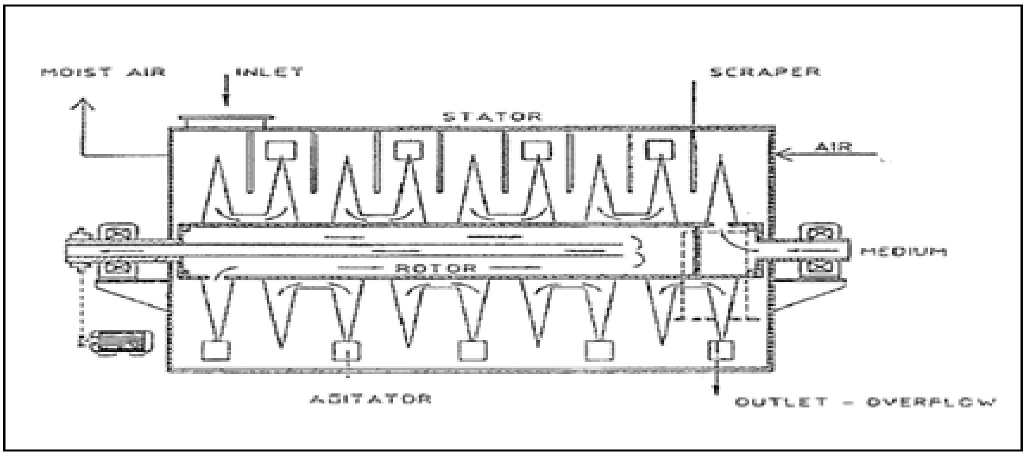

Figure 3.19 Design principles of rotadisc (Chen et al., 2002)

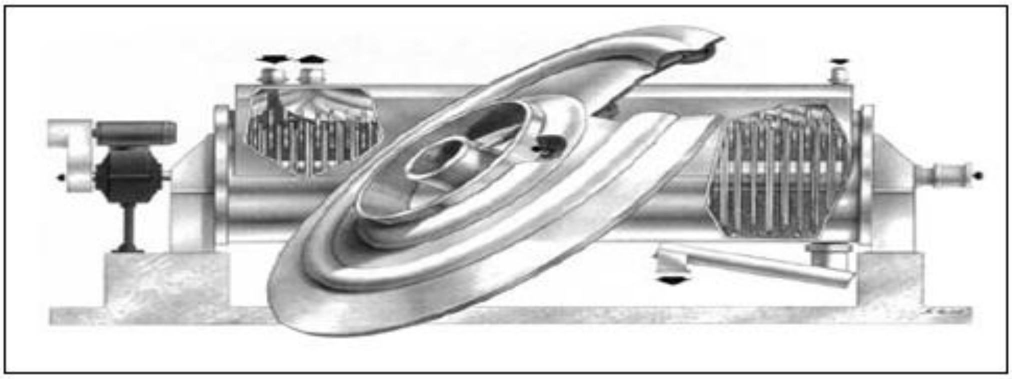

Figure 3.20 Rotaplate indirect dryer (Chen et al., 2002

Figure 3.21 Kneading and self-cleaning disc dryer—twin shafts (Chen et al., 2002).

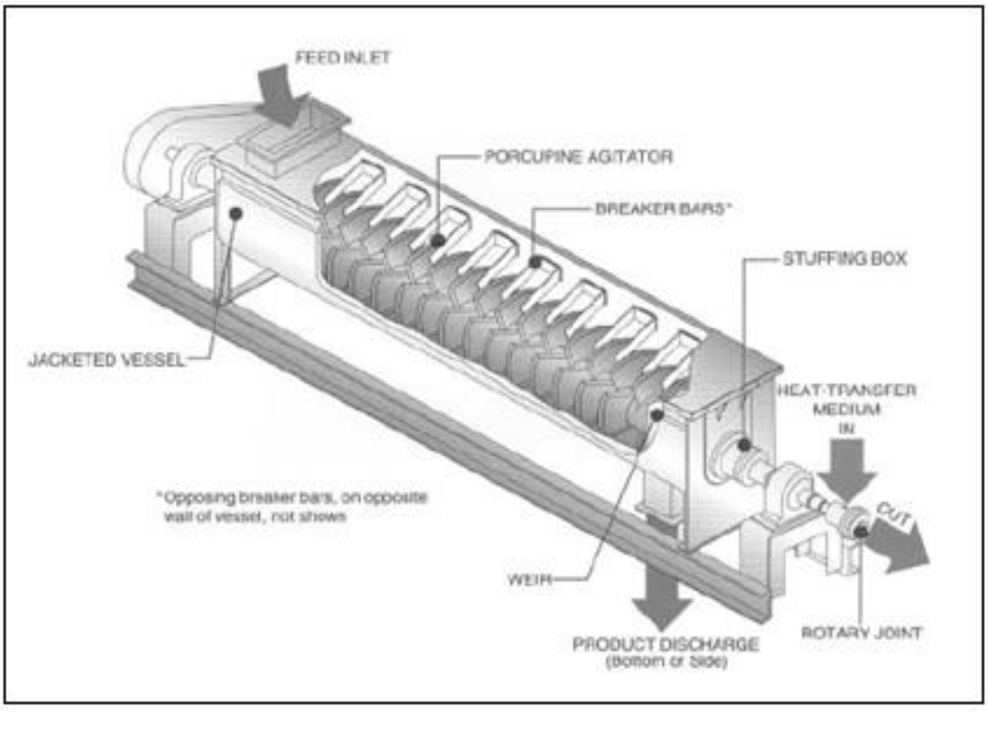

Figure 3.22 The Porcupine processor (http://www.bethcorp.com/Prod-Porcupine.html; Chen et al., 2002)

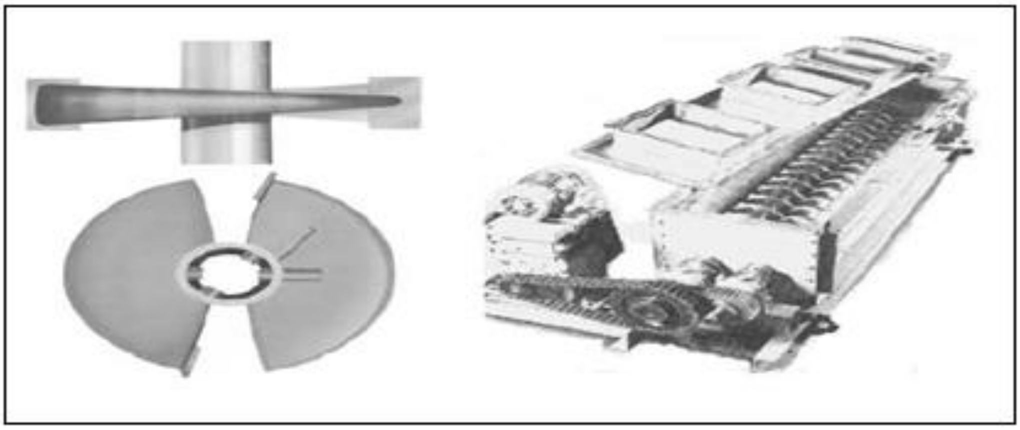

Figure 3.23 K-S Nara paddle and paddle dryer (http://www.komline.com/docs/paddle_dryer_processor.html; Chen et al., 2002)

3.3.2.3 Tray Dryers

Vertical multistage tray dryers can be given as another example of indirect systems shown in Figure 3.24 . The sludge is fed via the inlet at the upper part of the dryer and moved by the rotating arms from one heated tray to another in a zig-zag path until it exits the bottom as a dried and pelletized product with up to 95% DS. The dryer trays are hollow and heated by steam or thermal oil (Girovich, 1990; 1991). The sludge can be uniformly spread on the heated surface with its layer thickness controlled properly.

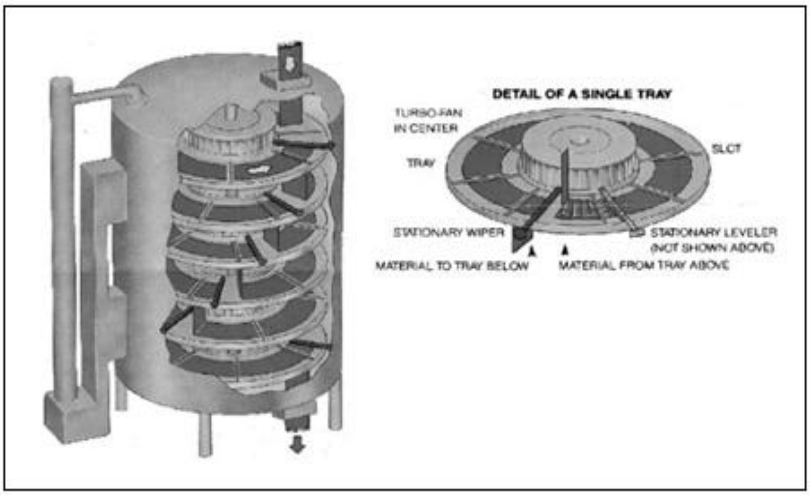

Figure 3.24 Vertical multi-tray dryer (http://www.wyssmont.com/product_detail.php?section=Dryers&id=1; Chen et al., 2002)

3.3.2.4 Paddle Dryers

Paddle dryers are as also indirect drying systems. These dryersare designed to solve the sticky phase problems without recirculation of the dry product (Arlabosse et al., 2005).

In order to explain paddle dryer's operational conditions, the K-S Paddle Dryer can be exemplified.The K-S Paddle Dryer is indirectly heated with steam or thermal fluid (hot oil) and provides for high energy efficiencies and low off-gas volumes. Heat transfer mediums can be heat up to 750 °F (app. 400 °C). Evaporation rates per square feet of heat transfer surface are maximized through self-cleaning paddles and the mixing effect. Movement of the sludge material between the slanting surfaces of the revolving wedge-shaped paddles lead to shearing forces cleaning the paddle surfaces and maximize conductivity. Counter rotating shafts move the sludge away from the walls. *The wedge-shaped paddles, and the intermeshing of the dual agitators, create a localized mixing effect around the paddle. This allows more individual particles in the bed to be exposed directly to the heat transfer surface, thereby increasing the heat transfer rate, allowing the use of smaller equipment. Dual counter rotating shafts with intermeshing wedge-shaped paddles produce intimate mixing and optimize heat transfer* (http://www.komline.com/downloads/brochures/PDCbrochure080707.pdf).

An other paddle dryer example is the Naratherm® paddle dryer. *It consists of a 4.08 m long horizontal jacketed trough, through which pass two 22 rpm rotating shafts. On each shaft, hollow wedge-shaped paddles are welded. To ensure a good plugflow, the paddles of both shafts intermesh. The sludge is fed into one end of the trough and flows by gravity and mixing to the opposite end of the trough, where the dry material is discharged. All metallic surfaces in contact with the sludge (the jacket, the hollow shafts and paddles) are heated with a saturated vapor at a pressure close to 6 bar. This 32* m^2 *contact surface area is self cleaned according to friction forces induced by rotors motion* (Arlabosseet al., 2005). Figures 3.25 and 3.26 show some paddle dryer systems.

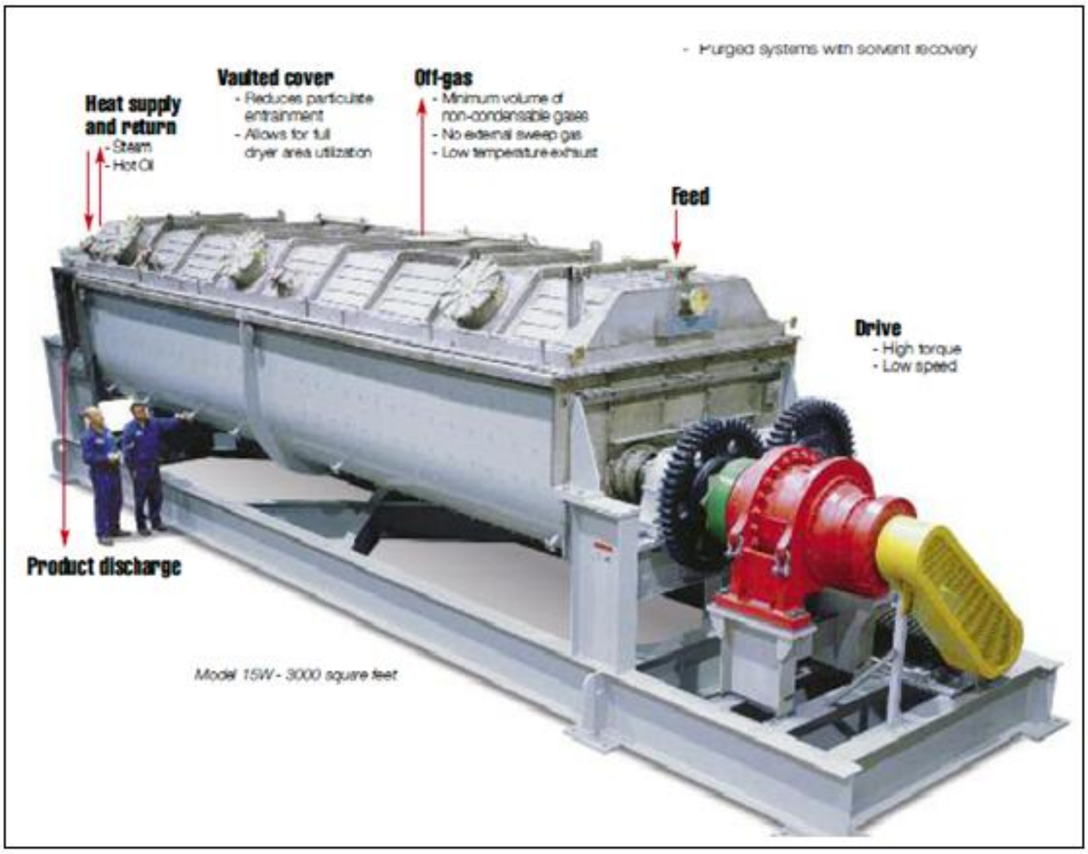

Figure 3.25 Model 15W - 3000 square feet (http://www.komline.com/downloads/brochures/PDCbrochure080707.pdf)

Figure 3.26 Model 8W - 390 square feet of heat transfer area (http://www.komline.com/downloads/brochures/PDCbrochure080707.pdf)

3.3.3 Combined Dryer Systems

Direct and indirect drying systems are combined in one system because of their advantages of both systems into a single stage. For instance, INNODRY® 2E uses two stages for drying, taking the first from indirect drying (thin film evaporator) and the second from direct drying technology (belt dryer) shown in Figure 3.27 (http://www.degremont-technologies.com/IMG/pdf/INNODRY_2E_EU_Innoplana.pdf)

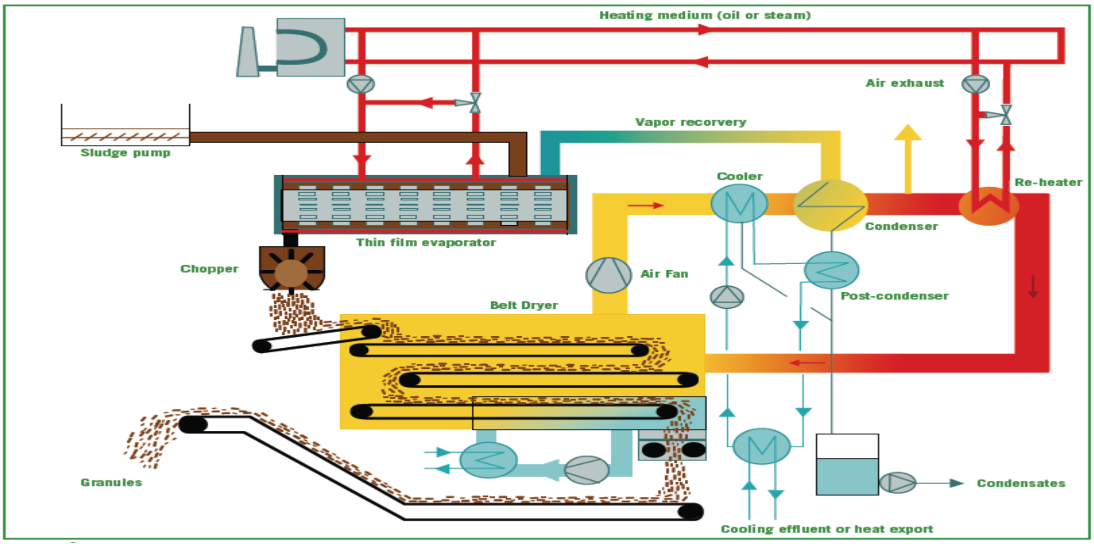

Figure 3.27 Combined system example: INNODRY®2E PROCESS (By Degremont technology)

Some technical features of INNODRY 2E technology can be summarized as follows:

- Capacity of the dryers ranges from 500 kg up to 6 t water evaporation per hour/unit
- DS content of the inlet sludge is about 18-35% DS
- Dried sludge has dry solids content between 65 and 90%
- Energy need is about 675 to 725 kWh per ton water evaporated
- Fully hygienized product has obtained according to USEPA Rule 503 Class A (http://www.degremont-technologies.com/dgtech.php?article403).

Another example is the fluidized bed dryers shown in Figure 3.28. The wet or dewatered sludge cakes are fed into fluidized bed system. *The heat for water evaporation is supplied mostly from the hot surfaces of thermal oil tubes. The heated* *air of about 85^{o}C provides some heat and mainly ensures that the sludge granules stay in a fluidized state to enhance the heat transfer between the sludge and the hot tube surface. Sludge can be dried to 5% moisture content in such a dryer* (Fouhy and Moore, 1994; Chen et al., 2002). Figures 3.28 and 3.29 show some fluidized bed dryer systems.

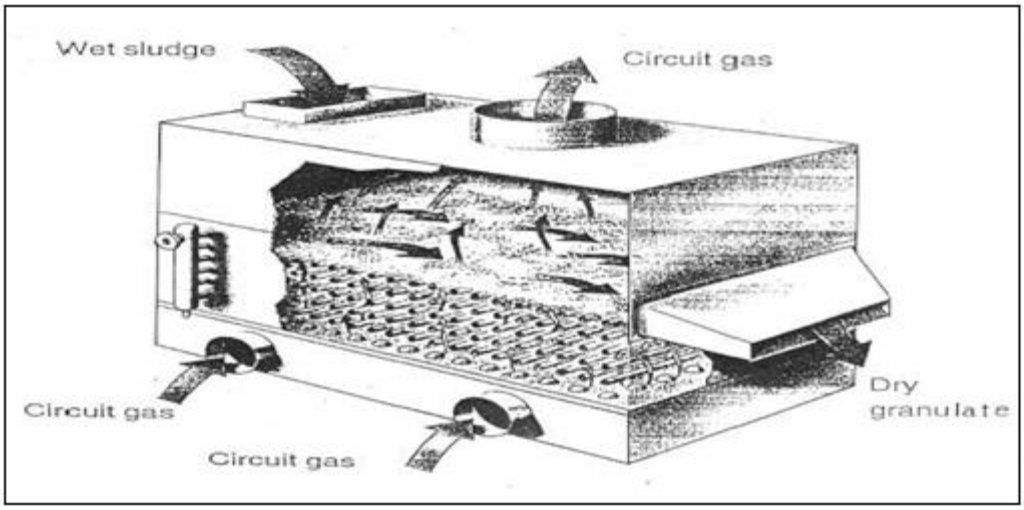

Figure 3.28 Fluidized bed dryer with heating tubes (Chen et al., 2002)

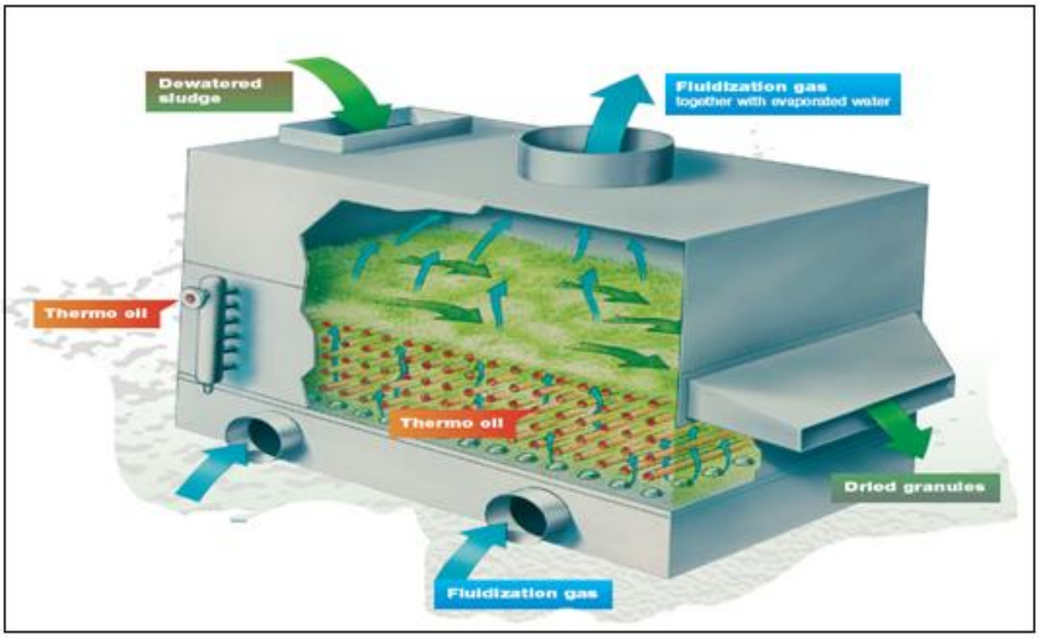

Figure 3.29 Fluid Bed Dryer System (By Andritz Technology, http://www.andritz.com/ep-thermal-brochure-fds-e.pdf)

Some teachnical properties of fluid bed dryer by AndritzTechnology are given below:

- *the physical properties of the fluid bed result in a virtually dustfree final product*
- *low drying (product) temperature*
- *indirect heat supply via heat exchanger in the fluidized bed*
- *various heat sources may be used, e.g. thermo oil, steam, waste gas, etc.*
- *Product is treated in an inert atmosphere only (<3% O_2), ensuring a high safety standard for the entire drying system*
- *Good environmental compatibility is ensured due to closed gas-tight construction; low off-gas quantity from drying process, and low odour emissions*
  (http://www.andritz.com/ep-thermal-brochure-fds-e.pdf)

In another system, wet sludge is fed into one of the cells around the superheater and suspended by the superheated steam blownthrough the perforated base plate by the impeller shown in Figure 3.30. The partially dried sludge moves successively through each cell before it is discharged (Chen et al., 2002).

Sludge drying systems can also be used with the sludge incineration systems as shown in Figure 3.31. *This is a concept of combining sludge drying with sludge incineration. The drying is achieved by mixing heated sand with wet sludge in a rotary kiln. The dried sludge is burned in a fluidized bed with sand. The flue gas heats the sand on top of the burner (Isheim, 1981). This combination is supposed to have higher energy efficiency. In fact, the integrated fluidized bed dryer/incinerator is currently a popular choice in Japan because of its compactness and high energy efficiency with no bad odors generated. In this industrialized dryer/incinerator, the dewatered sewage sludge is distributed over a hot fluidized sand bed at about 800^{o}C and subsequently reduced to micro-size particles as a result of rapid evaporation and combustion* (Hasatani, 2001).

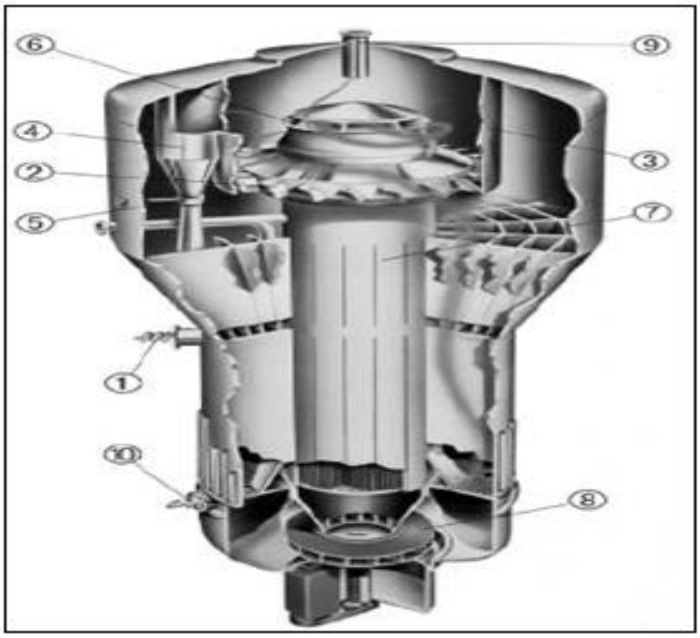

Figure 3.30 Fluidized bed dryer with superheated steam heating, 1—screw conveyor, 2—stationary blade, 3—cylinder, 4—side cyclone, 5—ejector, 6—stationary vanes, 7—superheater, 8—impeller, 9—top outlet, 10—screw conveyor (Chen et al., 2002)

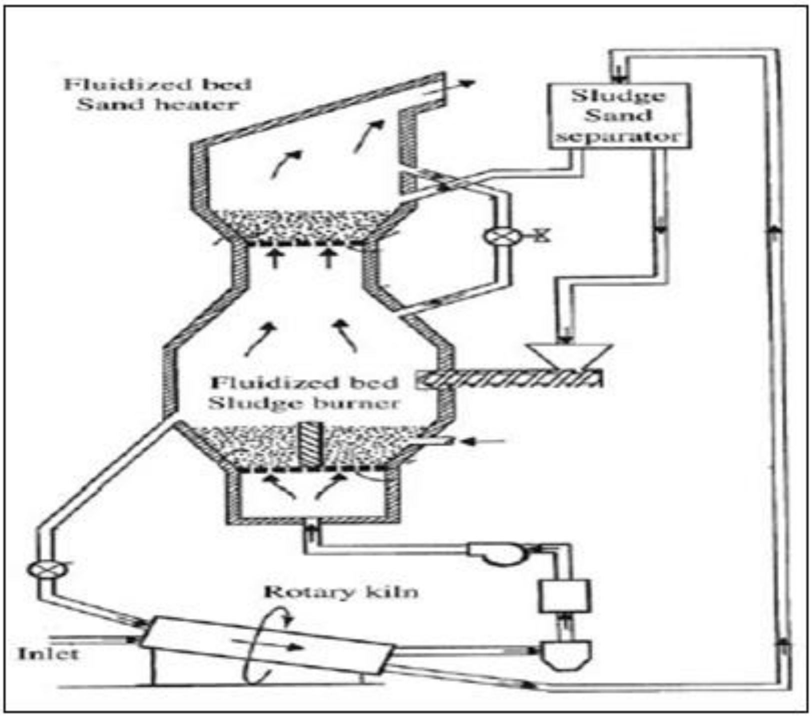

Figure 3.31 Rotary kiln dryer using sands heated in a fluidized bed burner (Chen et al., 2002)

3.3.4 Solar Drying

A simple and cost-efficient way to dry sludge and facilitate its disposal is possible with solar drying application. Although solar drying seems often as a first natural choice, the drying of sludge using solar energy requires a huge amount of land and may bring about an odor problem. However, there can be also solar sewage sludge drying greenhouses as closed system in practice. A solar sludge drying system is given in Figure 3.32.

Solar drying systems have lower investment and operation costs compared to the other drying systems. These systems use free and inexhaustible energy and also produce dried sludge which has the high degree of dryness. In addition, natural hygienization (without adding any other substances) occur during the process (http://www.richel.fr/richelportal/easysite/go/02o-00000u-003/english/our-specialist-areas/solar-sewage-sludge-drying-greenhouses).

Figure 3.32 Solar sludge drying- Outside and Inside of the Greenhouse

3.4 Advantages and Disadvantages of Sludge Drying Systems

Although there are many advantages of sludge drying process in terms of prevention of the environmental pollution, it has also some disadvantages in practical applications. The advantages and disadvantages are summarized in Table 3.1.

Table 3.1 Advantages and disadvantages of sludge drying (WEF-RBC-BTS, 2004)

Advantages	**Disadvantages**
Heat-dried material meets the requirements of the US EPA Part 503 for vector and pathogen control and the product is typically classified as Class A with respect to pathogen density levels.	Safety concerns of thermal drying include the explosive potential of the dust and the potential for product overheating and fires.
Thermal drying reduces the volume and weight of sludge produced in the plant. This results in reduced transportation costs.	This process require a high capital and operational costs.
Odors arising from the process can be contained and controlled.	Air emissions are produced at any thermal drying facility. Air permitting and air pollution control will be required.
Dried material can be used as a fertilizer, fertilizer supplement, or soil conditioner. The material can be also be used as a fuel so it has a marketable value also.	Marketability of the dried material is sensitive to regional conditions. An evaluation of the market for the dried product should be conducted to determine optimum uses and value of the product.
The heat-dried product is easily handled, conveyed and stored. The material can be delivered to consumers in bulk, bags, or other containers.	Drying of certain types of solids (undigested primary) can result in a more odorous product that can negatively affect its marketability.
Thermal drying is a well-proven existing technology. The technology can be applied at both wastewater treatment plant with a high capacity and also small industrial plant.	

CHAPTER FOUR

MATERIALS AND METHODS

4.1 Introduction

This chapter gives the information on the materials and methods used in this study. In research, removal of sludge water content by drying process was investigated in details.

For sludge drying experiments, the effects of drying time and temperature were evaluated. In order to determine the effects of time and temperature during drying process, Box Wilson statistical experimental method was used.

4.2 Materials

4.2.1 Sludge Samples

Dewatered sludge cake samples used in this study was taken from IZSU Çiğli Municipal Wastewater Treatment Plant located in Izmir, Turkey. In this plant with a 7 m^3/sec wastewater treatment capacity, advanced biological treatment processes treating carboneous material, phosphorus, and nitrogen have been applied. Approximately 600 tones sludge have been daily produced. Sludges have been dewatered using a dewatering system including 7 centrifuge decanters, which have 120 m^3/h dewatering and also 150 m^3/h thickening capacity (www.izsu.gov.tr).

At the begining of each experimental application, sludge cake characteristics were determined. pH, temperature, total solid content and volatile solids content of the sludge cakes were analyzed according to Standard Methods (APHA, 2005).

4.3 Experimental Approach for Drying Procedure

Drying experiments were done using an oven, which can be operated at different temperatures ranging between 50 °C to 250 °C. Raw sludge cake samples were first placed into pyrex pots or an aluminium foil as much as a thin film plate. Then, they were dried at different temperatures at the ambient pressure conditions for different drying times. The drying times and temperatures were applied depending on the experimental statistical analysis namely –Box Wilson-, which is explained in subsection 4.4. After drying studies, the dried products were subjected to the further analysis to determine the drying potential of sludge cake samples.

4.4 Methods Used in the Experimental Studies

4.4.1 Analytical Methods

In the course of the carrying out the experimental studies, dry solids content (DS), water content (WC), volatile solid content (VS), temperature, pH, calorific value parameters were analyzed. In addition, thermal gravimetric analyze (TGA) was realized both on the sludge cake and also thermally dried sludge samples at different drying time and temperatures.

Most of the measurements in this study were triplicated. All analyses were regularly done according to Standard Methods (APHA, 2005) except for TGA anaylsis given in subsequent subsection (4.4.1.3).

4.4.1.1 Temperature, pH Measurements

Temperature and pH parameters were measured by WTW model 340i multi analyzer shown in Figure 4.1 .

Figure 4.1 WTW model 340i multi analyzer used in experimental studies

4.4.1.2 Dry Solids Content (DS), Water Content (WC), Volatile solid content (VS) Analysis and TGA Analyze

In the measurement of dry solid and water contents of sludge samples, an oven - Nüve FN 400 model- was used. Figure 4.2 shows the oven used in experimental studies. The temperature of the oven was kept as 105 ± 3 ^{o}C. In order to determine the dry solid contents of sludge cake and dried sludge samples, a method which depends on the gravimetric measurement was used as detailed in Standard Methods (APHA, 2005).

The volatile solids content of sludges were determined using a muffleoven –Nuve brand MF 120 model- at 550 ^{o}C temperature as detailed in Standard Methods (APHA, 2005). Nuve MF 120 muffle oven is shown in Figure 4. 3.

Sludge water distribution was also measured by a drying test based on a thermo-gravimetric method (TGA) as described by Kopp and Dichtl (2000). The result of TGA analyses were achieved by calculating the water removals from the material for each half an hour in the first two hours and the analyse was gone on in the fourth hours and then 24 hours. The water distribution could then be derived from the curve of the drying time vs. the water content of the sample.

Figure 4.2 FN 400 Nüve drying oven

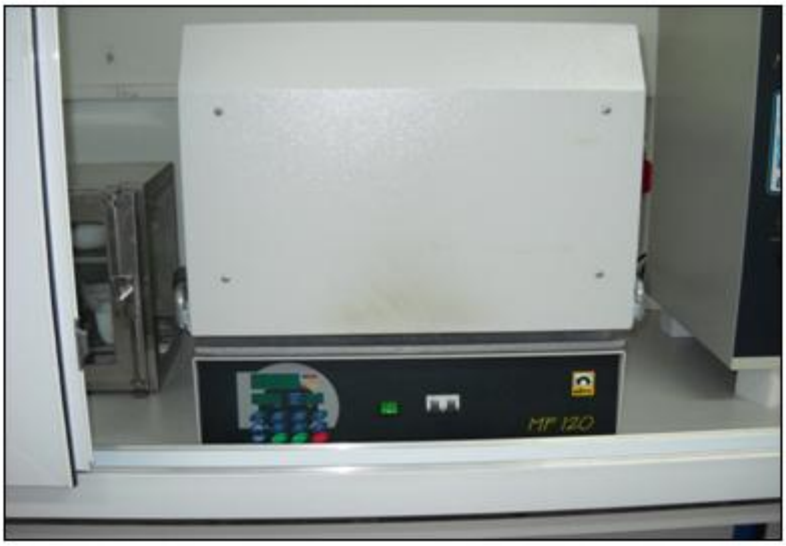

Figure 4.3 MF120 Nuve Muffle Oven

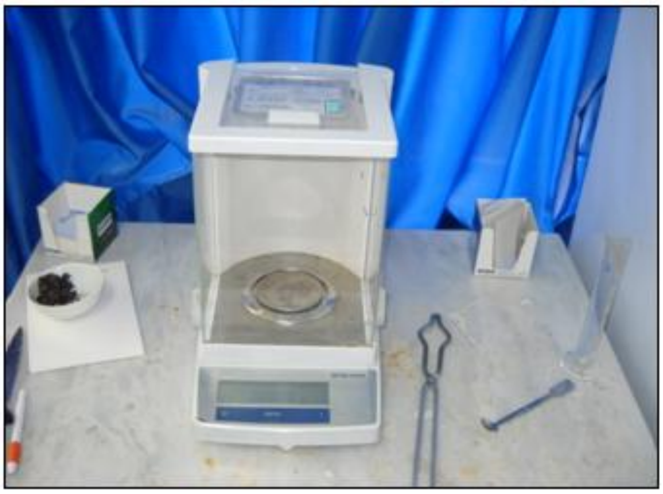

Figure 4.4 Sensitive Tare used in experimental studies.

4.4.1.3 Calorific Value Analysis

In order to evaluate calorific value of the processed sludge cakes, some samples were first choosen. Dried samples were grinded and kept for further analysis at a calorimeter IKA brand C200 model shown in Figure 4.5.

Figure 4.5 Calorimeter IKA C200

Before starting the analyse, less amount of sample (approximately 0.5 g) was weihgted and placed in the calorimeter’s container and a yarn, which is fasten to wire of the device, was placed into the grinded sample. After closing the lid of the stainless container, oxygen gas was exposed during 45seconds as shown in Figure 4.6.

Figure 4.6 Stainless container, in which oxygen gas was exposed.

After then, the container was placed into the analyzer as given in Figure 4.7 and the weihgten value was written on the screen. Nearly 2 liters of water was filled trought the black hole and the analysis was started.

Figure 4.7 Calorimeter IKA C200

Achieved and calculated data for high heating value in dry base were used to calculate the high heating value in original base, low heating value in original base and low heating value in dry base. All calculated data were evaluated in the statictical programme (statistica7) in order to examine the correlation among the time, temperature effects on dryness degree of sludges and their calorific (heating) values. The results will be given in Chapter 5.

The calorimeter IKA C200 gave only high heating value in dry base as a result. So low heating value in original base, high heating value in original base and low heating values in dry base were calculated with the help of the formula given below.

- *For the low heating value in original base:*

$$LHW= ((100-(A+ B)/100)* X)-(6* A) \quad \text{(Eq.1)}$$

$$X= ((C+6*D)*100)/(100-(D+E)$$

A: Moisture content in original base
B: Ash content in original base
C: Low heating value in dry base
D: Hygroscopic moisture content
E: Ash content in dry base

- *For the low heating value in dry base:*

$$LHW= F-5,85*(9*((100-(D+E))/100)*5+D) \quad \text{(Eq.2)}$$

F: High heating value in dry base

- *For the high heating value in original base:*

$$HHW= G+5,85*(9*((100-(A+B)/100)*5+A) \quad \text{(Eq.3)}$$

G: Low heating value in original base

4.5 Statistical Methods Used

First of all, time and temperature were selected as two important parameters affecting the water removal from the sludge. In order to find out what extend these two parameters effect the efficiency of the dry solid content and volatile solid content, and also calorific value of sludge, Box Wilson statistical design method was used. According to the Box Wilson design, minimum and maximum points of the parameters must be choosed and a table must be arranged with the help of the coded form given below.

Table 4.2 Coded form

Trial Number	**X_1**	**X_2**
1	-1	-1
2	-1	+1
3	+1	-1
4	+1	+1
5	-k	0
6	+k	0
7	0	-k
8	0	+k
9	0	0
10	0	0
11	0	0

n = variable number

0 = center point

+1 = max. point

-1 = min. point

$$\mp k = centerpo\,\mathrm{int} \mp \left(\frac{\max - \min}{2\sqrt{n}} \right)$$

$$\text{Center point} = \left(\frac{\max + \min}{2} \right)$$

X_1 : time

X_2 : temperature

Then by using the method, k values and center points were calculated. Finally depend on the points which were given trough the method, the experimental studies were carried out. The results were utilized by using non-lineer estimation in the computer program Statistica (version 7) for the determining of the response function. Using this programme, the predicted and residual values“b”coefficient values, and also regression value (R^2) were obtained. In the software programme, the estimated function was written as follows:

$$y=b_o+(b_1*X_1)+(b_2*X_2)+(b_{12}*X_1*X_2)+(b_{11}*X_1^2)+(b_{22}*X_2^2) \qquad \text{(Eq.4)}$$

The experimental studies were done as two series. In the first experimental study, the drying time range of 10-120 minutes and the temperature range of 50-180 ^oC were selected as operational conditions. The drying time range of 10-180 minutes and the temperature range of 80-250 ^oC were used for the second experimental study. Experimental results and their evaluations are discussed in the following chapter.

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Introduction

In order to determine thermal drying effects on sludge cake, the results and evaluations of the experimental studies are given in this chapter. To examine the drying time and the temperature effects on sludge drying process, two experimental series were carried out. Experimental studies were designed by using the Box Wilson experimental statistical method for the obtained data to be evaluated and done as two series. In the first experimental study, the drying time range of 10-120 minutes and the temperature range of 50-180 ^{o}C were selected as the operational conditions while the time range of 10-180 minutes and the temperature range of 80-250 ^{o}C were used for the second experimental series. This chapter presents the experimental results obtained from the both series.

5.2 Raw Sludge Cake Properties

At the begining of each experimental series, sludge cake characteristics were analyzed regarding the pH, temperature, total solids content and volatile solids content parameters. The sludge cake characteristics are summarized in Table 5.1. Total solids and the volatile solids contentof sludge cake was found about 23.8% and 47%, respectively. The sludge cake taken for the second experimental study has 21.7% of total solids and 57.7% the volatile solids content. The picture of the sludge cake sample taken from Cigli MWWTP is given in Figure 5.1.

Table 5.1 Sludge cake properties

	pH	***Temperature, °C***	***Calorific value, cal/gDS***	***DS, %***	***VS, %***
I.Experimental study (10-120min.; 50-180 °C)	6.28	25	2900	23.76	47.09
				23.91	47.26
				23.85	46.66
II. Experimental study (10-180min.; 80-250 °C)	6.32	25	3100	21.53	55.71
				21.20	58.06
				22.43	59.24

Figure 5.1 Sludge cake sample after centrifuge decantor dewatering unit

Drying experiments were done in an oven as explained in Chapter 4. Sludge cake samples were first placed into pyrex pots or an aluminium foil as much as a thin film plate. Then, they were dried at different temperatures at the ambient pressure conditions for different drying times depending on the experimental statistical analysis method. After drying studies, the dried products were subjected to the further analysis, which their results will be elaborated in this chapter. Some pictures of dried products taken after drying experiments are given in Figures 5.2- 5.7. By looking at only the figures we can easily keep an eye on the shrinkage and fracture on the sludge film.

Figure 5.2 Dried sludge product after 95 minutes of drying time at 105 ^oC.

Figure 5.3 Dried sludge product after 95 minutes of drying time at 165 ^oC.

Figure 5.4 Dried sludge product after 35 minutes of drying time at 165 ^oC.

Figure 5.5 Dried sludge product after 155 minutes of drying time at 165 ^{o}C.

Figure 5.6 Dried sludge product after 10 minutes of drying time at 250 ^{o}C.

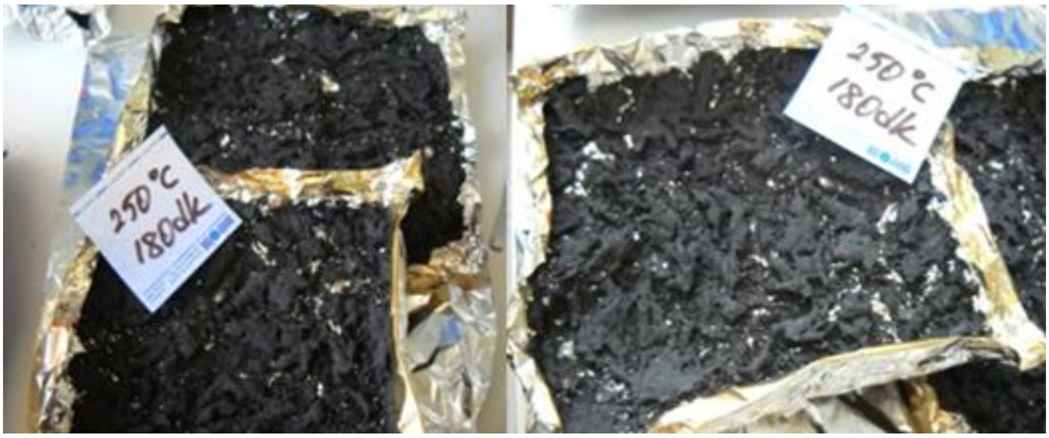

Figure 5.7 Dried sludge after 180 minutes of drying time at 250 ^{o}C.

5.3 Results of the First Experimental Study (Drying time range: 10-120 minutes and temperature range: 50-180 ^{o}C)

Two important operating parameters: drying time (X_1) and drying temperature (X_2) were chosen as independent variables. Drying time (X_1) was changed between 10 and 120 minutes while the drying temperature (X_2) was varied between 50 and 180 ^{o}C. Experimental data points used in Box–Wilson statistical design regarding the drying time and temperature ranges is given in Table 5.2. The experiments consisted of four axial (A), four factorial (F) and one centre (C) point. The centre point was repeated three times to estimate the experimental error.

Table 5.2 Experimental data points used in Box–Wilson statistical design regarding the drying time and temperature ranges

Trial number	**Time (X_1), minutes**	**Temperature (X_2), ^{o}C**
1 (A)	10	50
2 (A)	10	180
3 (A)	120	50
4 (A)	120	180
5 (F)	26	115
6 (F)	104	115
7 (F)	65	69
8 (F)	65	161
9 (C)	65	115
10 (C)	65	115
11 (C)	65	115

The performance of the drying process was described by the following response function:

$$y=b_o+(b_1*X_1)+(b_2*X_2)+(b_{12}*X_1*X_2)+(b_{11}*X_1^2)+(b_{22}*X_2^2) \qquad \text{(Eq.4)}$$

where; Y is the predicted response function (percent DS, VS or calorific value), b_0 is the offset term. The coefficients of the response functions were determined by using the experimental data and the Statistica 7.0 softwate program for regression analysis. The results are given in the following subsections.

5.3.1 Dry Solid Content Results of Sludge

Experiments regarding the DS contents of raw and dried sludge materials were done according to the experimental data points determined by using Box–Wilson statistical design as shown in Table 5.2. The DS results are given in Table 5.3.

The graphical depiction of DS results is given in Figure 5.8 for raw sludge cake and dried sludge samples at different temperatures (50 and 180 ^{o}C) for 10 and 120 minutes of drying time. As can be seen from this figure, the higher drying temperatures and the drying times lead to higher DS contents. When the minimum temperature with the maximum retention time were used, a little amount increases in DS content was obtained.

Table 5.3 DS results of sludge cake and dried sludge materials

Time (min.)	Temperature (^{o}C)	Sludge cake	DS (%)
No heating time	25	Raw sludge cake	23.85
			23.76
			23.91
10	50	Dried cake	24.90
			25.26
			24.63
10	180	Dried cake	26.48
			27.56
			28.21
120	50	Dried cake	27.04
			27.59
			27.24
120	180	Dried cake	84.80
			89.46
			92.19
26	115	Dried cake	24.42
			25.47
			24.21
104	115	Dried cake	44.76
			47.52
			52.06
65	69	Dried cake	25.50
			26.46
			25.01
65	161	Dried cake	57.73
			52.99
			53.58
65	115	Dried cake	28.42
			30.20
			29.58

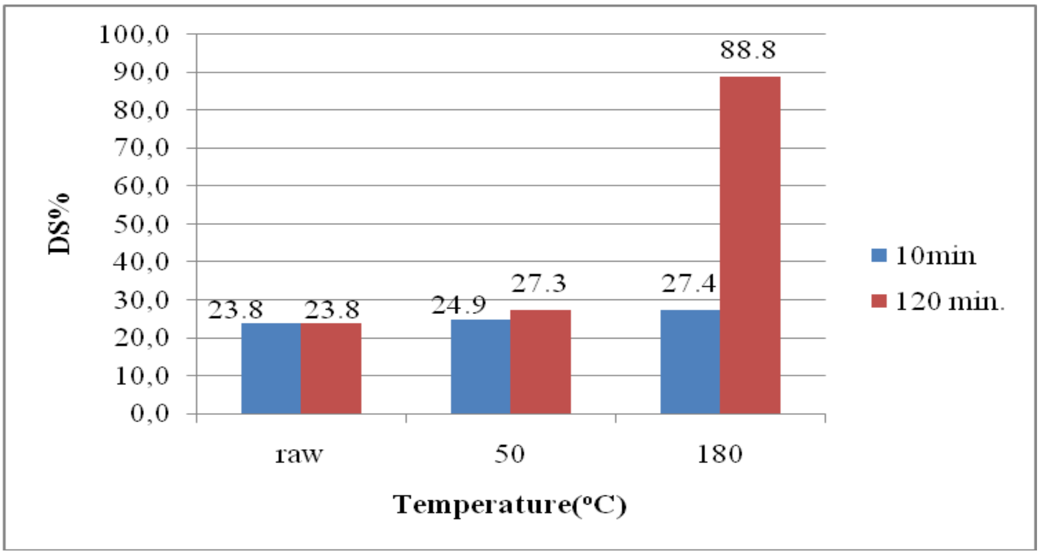

Figure 5.8 DS results for raw sludge cake and dried sludge samples at different temperatures for 10 and 120 minutes of drying time.

Figure 5.9 shows DS results at 115 °C for different drying times, while Figure 5.10 shows the results at 65 min. of drying time for different temperature applications. It is clear from the figures that the both parameters are very effective on the sludge drying process. At the same temperature application, increased DS values obtained with the increasing of drying time. Similiarly, increased in the temperatures at the same drying time application led to higher DS values of the dried products.

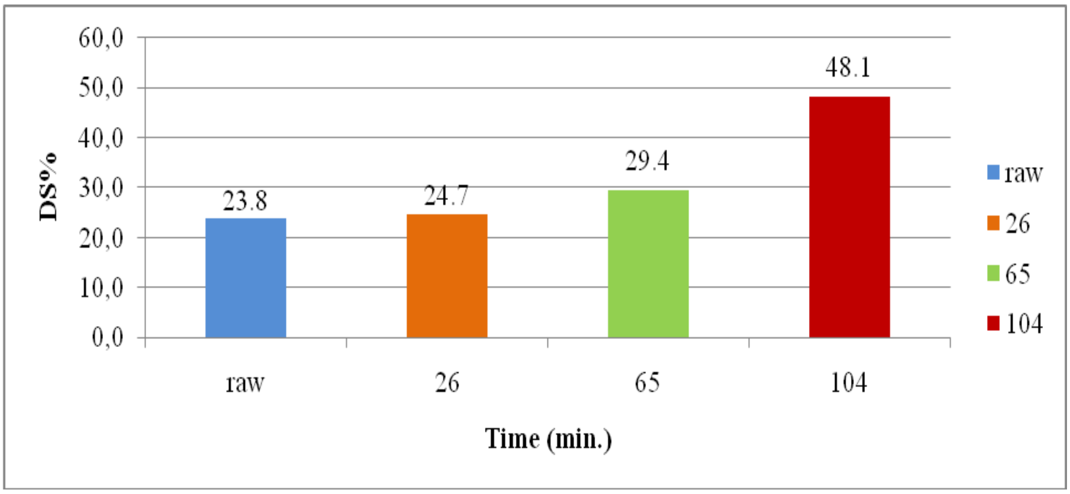

Figure 5.9 DS results for raw sludge cake and dried products at 115 ^{o}C for different drying times.

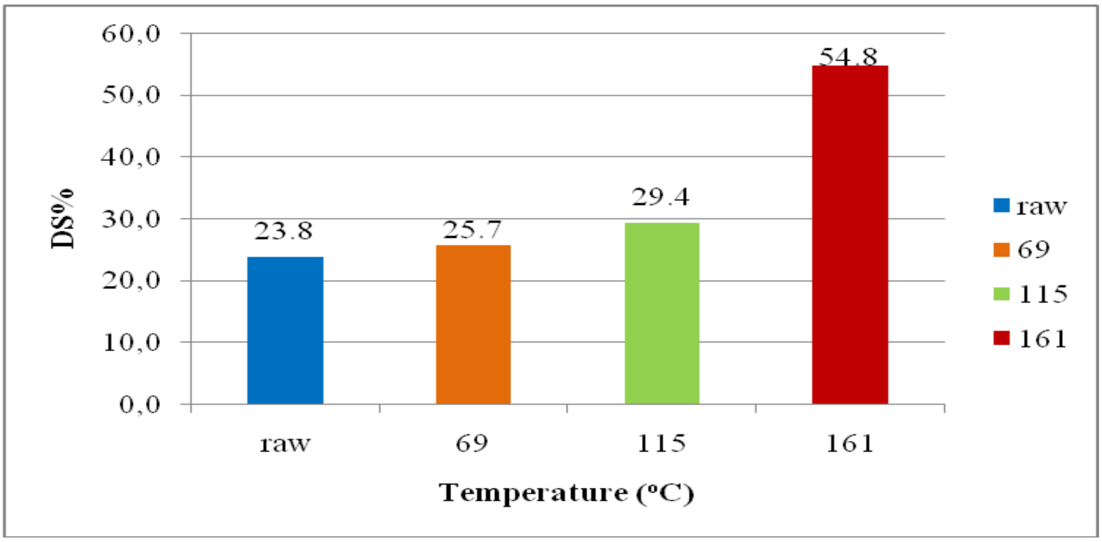

Figure 5.10 DS results for raw sludge cake and dried products at 65 min of drying time for different temperature applications.

Experimental data was used for determination of the response function coefficients for each independent variable. A Statistica 7.0 program was used for regression analysis. The estimated coefficients of the response functions are shown in Table 5.4. The response functions were used in calculating the predicted values of DS. The observed values were introduced to the statistical programme (Statistica 7) and the predicted DS results given in Table 5.5 were obtained. The regression coefficient was achieved as R^2= 0.98832. Predicted and experimental values of DS were in good agreement.

Table 5.4 Coefficients of the response functions for DS

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
45.37845	-0.25814	-0.51174	0.0042	0.000545	0.002183

Table 5.5 Predicted and residual values for dry solid content of sludge samples in the first experimental series

Time (min.)	Temperature (^oC)	Predicted Value	Residual Value
10	50	24.82213783	0.106654778
10	180	29.0334301	-1.6204704
120	50	27.31230164	-0.02077241
120	180	91.57739258	-1.74789762
26	115	21.614254	3.084436655
104	115	44.67180634	3.443846703
65	69	24.8192997	0.836553216
65	161	49.04940414	5.717559338
65	115	32.31463623	-4.14774132
65	115	32.31463623	-2.91352463
65	115	32.31463623	-2.73864412

Relationships between drying time, temperature and the dry solids content of dried sludge samples can be seen from Figure 5.11. DS results as a function of temperature at different drying times are depicted in Figure 5.12 while the results as a function of drying time for varied temperatures are plotted in Figure 5.13. The increases of drying time and temperature cause the higher dry solid content of sludge.

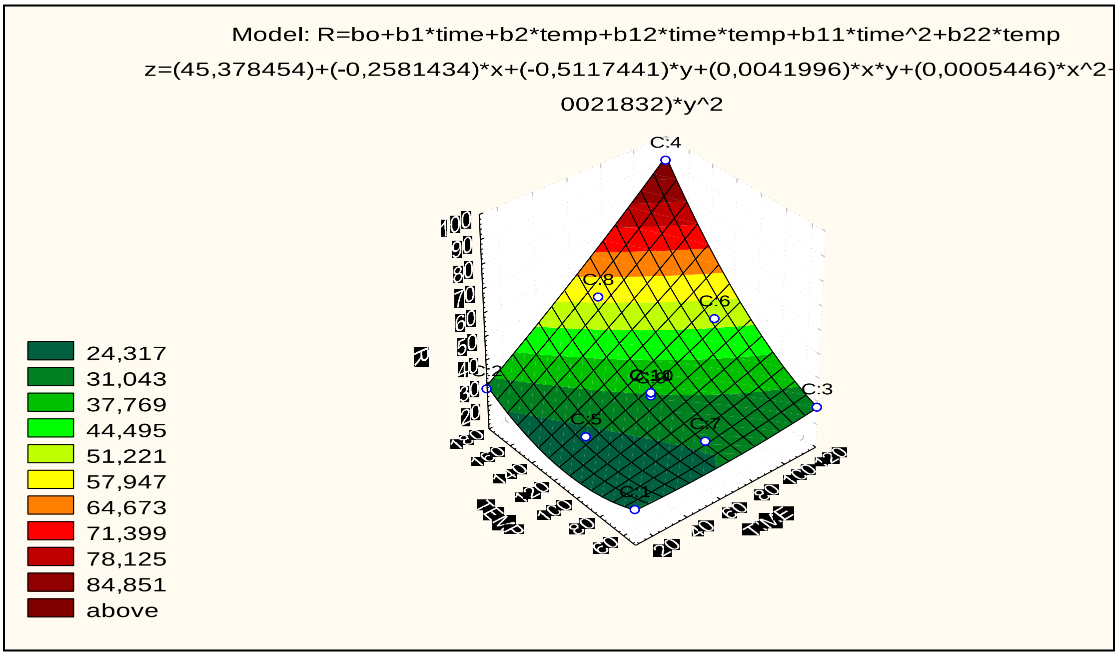

Figure 5.11 Relationships between drying time, temperature, and dry solids content of dried sludge samples.

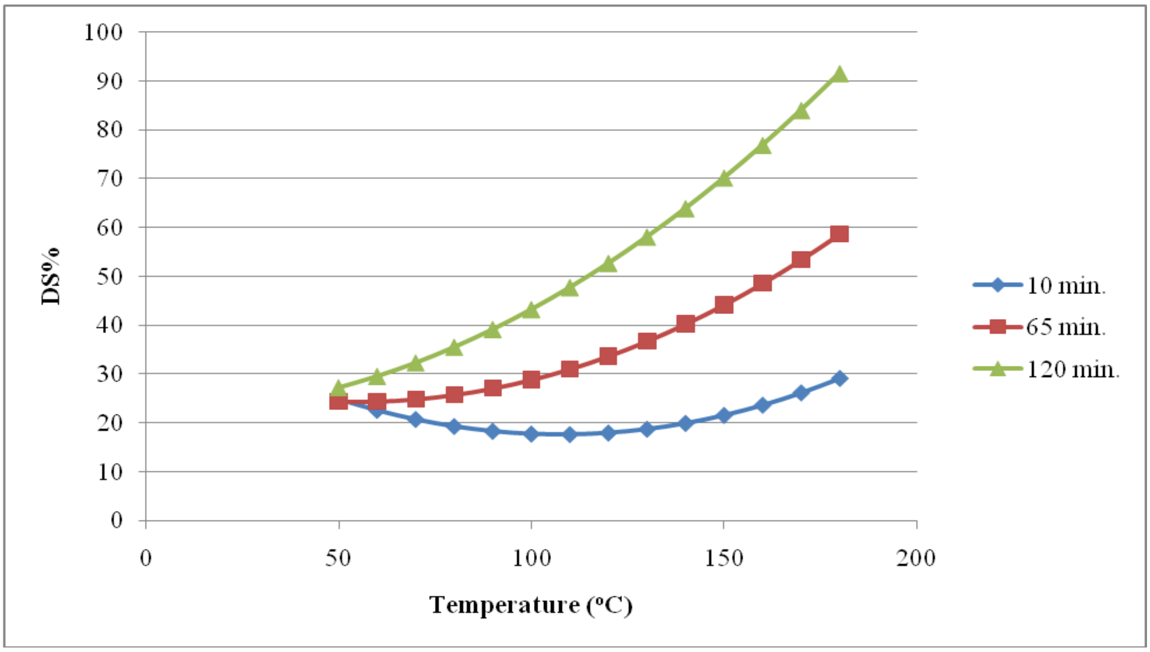

Figure 5.12 Dry solid content of sludge as a function of temperature for different drying times.

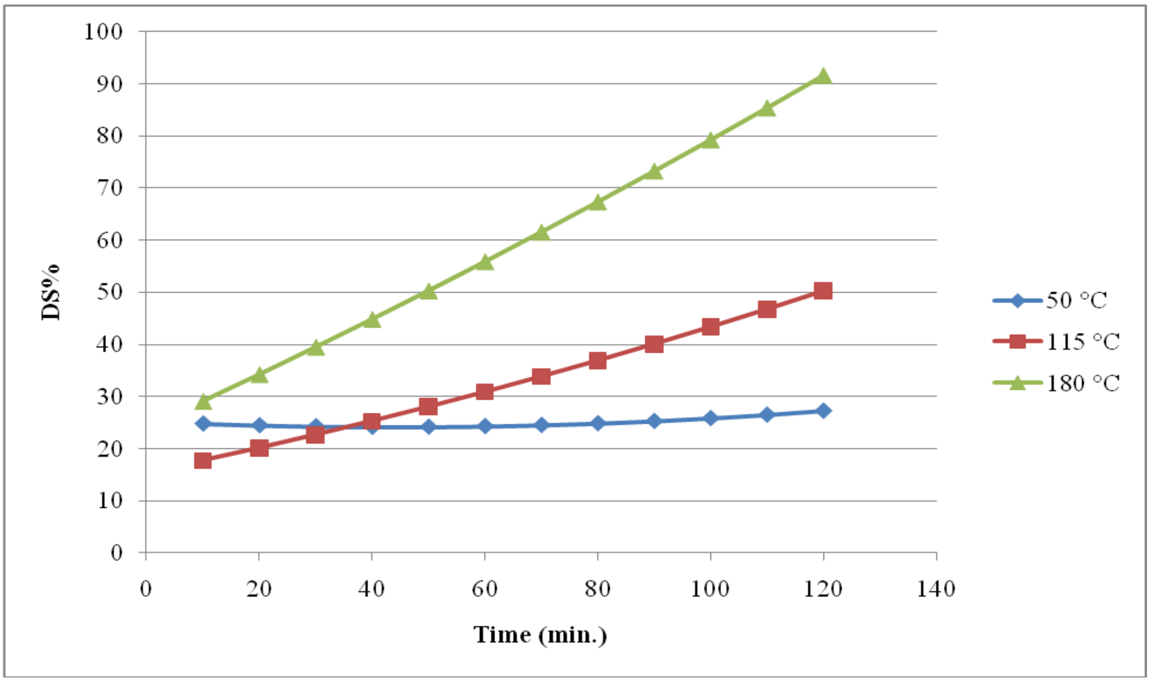

Figure 5.13 Dry solid content of sludge as a function of drying time at varied temperatures.

5.3.2 Volatile Solids Content (VS) Results

VS experiments for raw sludge cake and dried sludge materials were done according to the experimental data points given in Table 5.2. The VS results of this experimental series are presented in Table 5.6.

Table 5.6 VS results of sludge cake and dried sludges samples

Time (min.)	Temperature (^oC)	Sludge cake	VS (%)
No heating time	25	Raw sludge cake	47.09
			47.26
			46.66
10	50	Dried cake	53.76
			53.14
			48.12
10	180	Dried cake	50.23
			53.19
			47.89
120	50	Dried cake	53.54
			53.97
			47.41
120	180	Dried cake	52.05
			53.31
			52.35
26	115	Dried cake	53.03
			52.56
			52.40
104	115	Dried cake	53.27
			52.71
			53.10
65	69	Dried cake	52.90
			52.49
			53.49
65	161	Dried cake	52.62
			52.71
			51.72
65	115	Dried cake	51.50
			54.48
			45.72

VS results are also plotted in Figure 5.14 for raw sludge cake and dried sludge samples at different temperatures (50 and 180 ^oC) for 10 and 120 minutes of drying time. The elevated temperatures and drying time did not drastically change the VS values. Only a small scale changes were observed in VS values regarding the increases either in drying temperatures or the drying times.

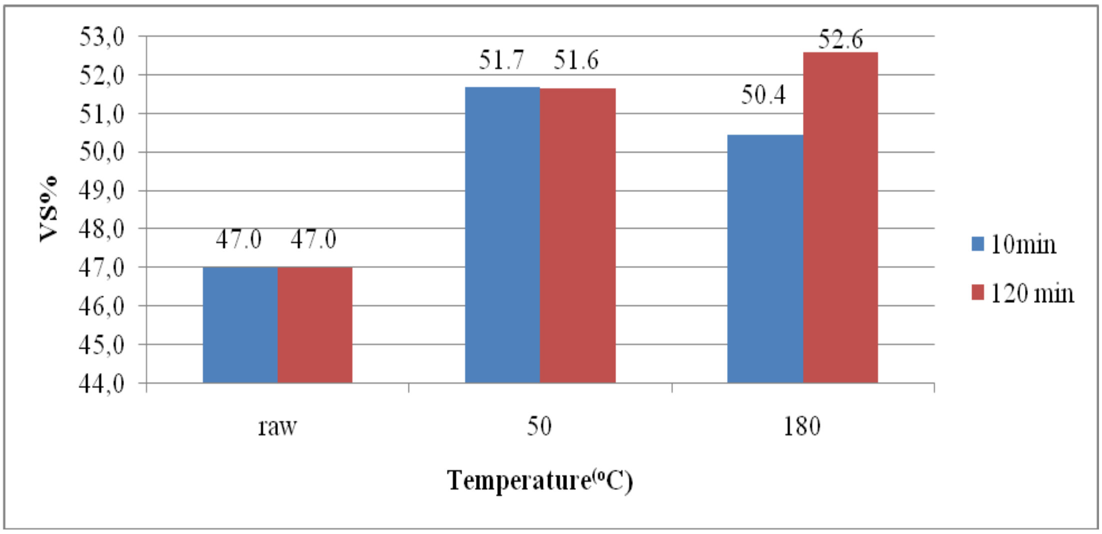

Figure 5.14 VS results for raw sludge cake and dried sludge samples at different temperatures for 10 and 120 minutes of drying time.

Figure 5.15 shows VS results at 115 ^{o}C for different drying times, while Figure 5.16 presents the results at 65 min. of drying time for different temperature applications. It can be said that the both parameters are not very effective on VS changes of the sludge during the drying process. However, some slightly increased VS values were obtained with the increasing drying time and temperature as shown in these figures.

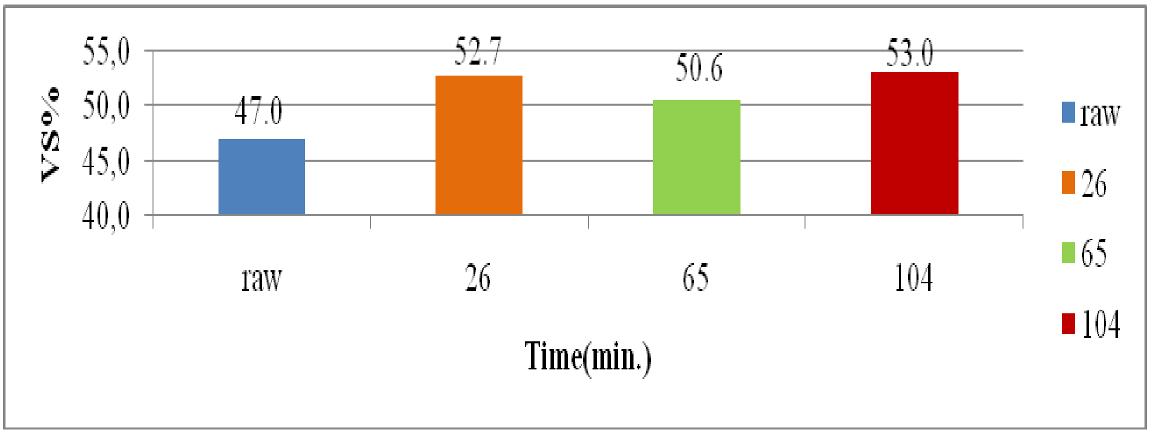

Figure 5.15 VS results for raw sludge cake and dried products at 115 ^{o}C for different drying times.

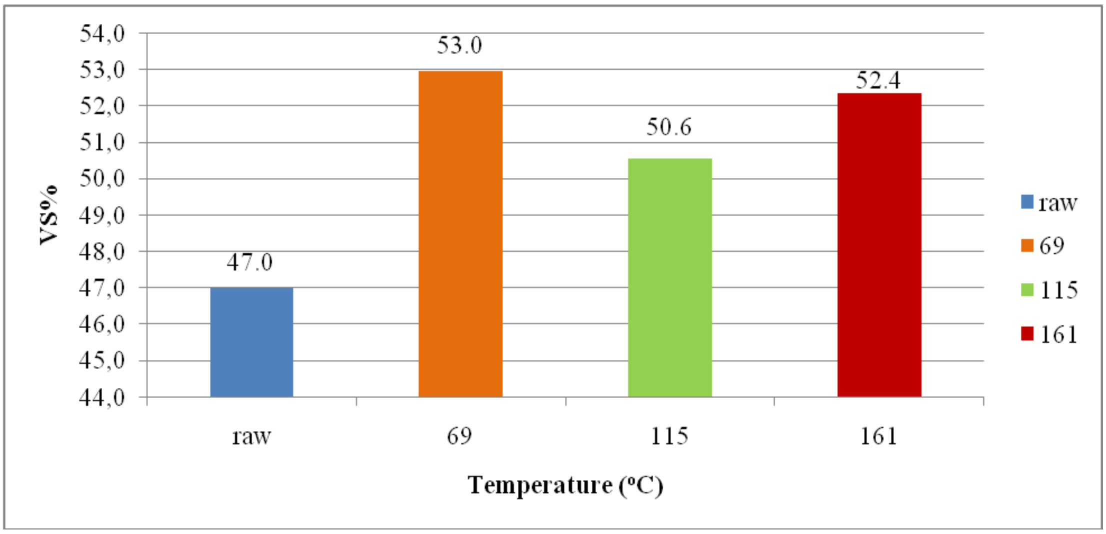

Figure 5.16 VS results for raw sludge cake and dried products at 65 min of drying time for different temperature applications

Experimental data was used for determination of the response function coefficients for each independent variable. The estimated coefficients of the response functions shown in Table 5.7 were used in calculating the predicted values of VS. The predicted DS results given in Table 5.8 were obtained. The regression coefficient was achieved as R^2= 0. 92608. Predicted and experimental values of VS were found in good agreement.

Table 5.7 Coefficients of the response functions from the statistical programme for VS

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
41.69739	0.02373	0.17191	0.00043	-0.00043	-0.00080

Table 5.8 Predicted and residual values for volatile solids content of sludge samples in the first experimental series

Time (min.)	Temperature (^oC)	Predicted Value	Residual Value
10	50	48.70189	-0.58563
10	180	47.68537	0.19997
120	50	47.58863	-0.17981
120	180	52.70897	0.60579
26	115	52.49821	0.53221
104	115	53.88460	-0.61241
65	69	51.41944	1.06983
65	161	52.87156	-1.15035
65	115	53.83848	0.29563
65	115	53.83848	0.64246
65	115	53.83848	-0.81770

Relationships between drying time, temperature and the volatile solids content of dried sludge samples can be seen from Figure 5.17. VS results as a function of drying time for varied temperatures are depicted in Figure 5.18 while the results as a function of temperature at different drying times are plotted in Figure 5.19. The model results showed that the VS values slightly decreased at the maximum temperature and drying time applications although little increases in VS were obtained with the increasing the drying time and temperature.

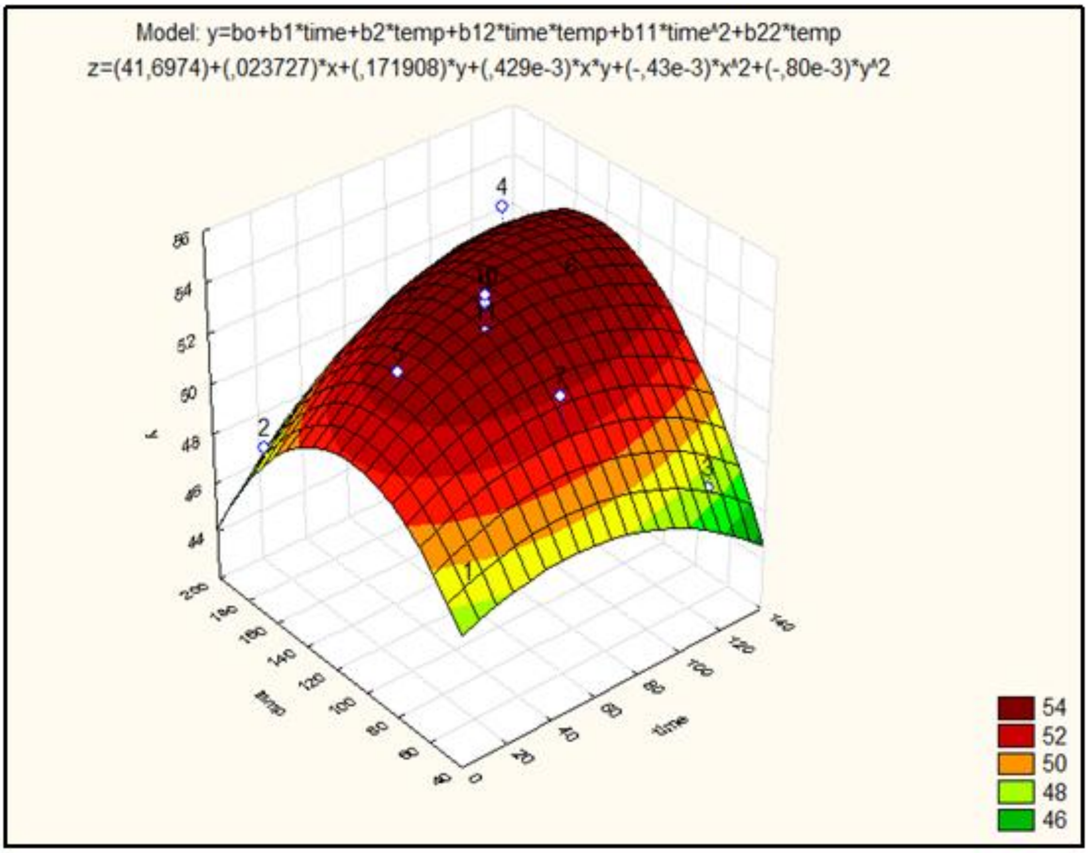

Figure 5.17 Relationships between drying time, temperature, and volatile solids content of dried sludge samples.

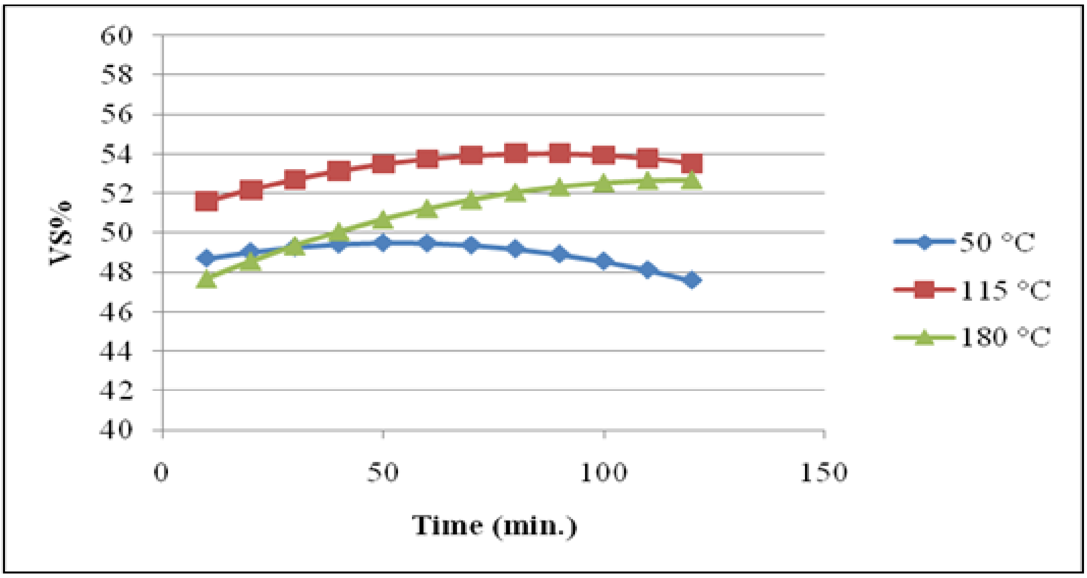

Figure 5.18 VS contents of sludge as a function drying time at different temperature applications.

The graphic below shows that the increasing temperature is not able to sharply effect to the rise of volatile solid content of dried sludge cake under different retention time.

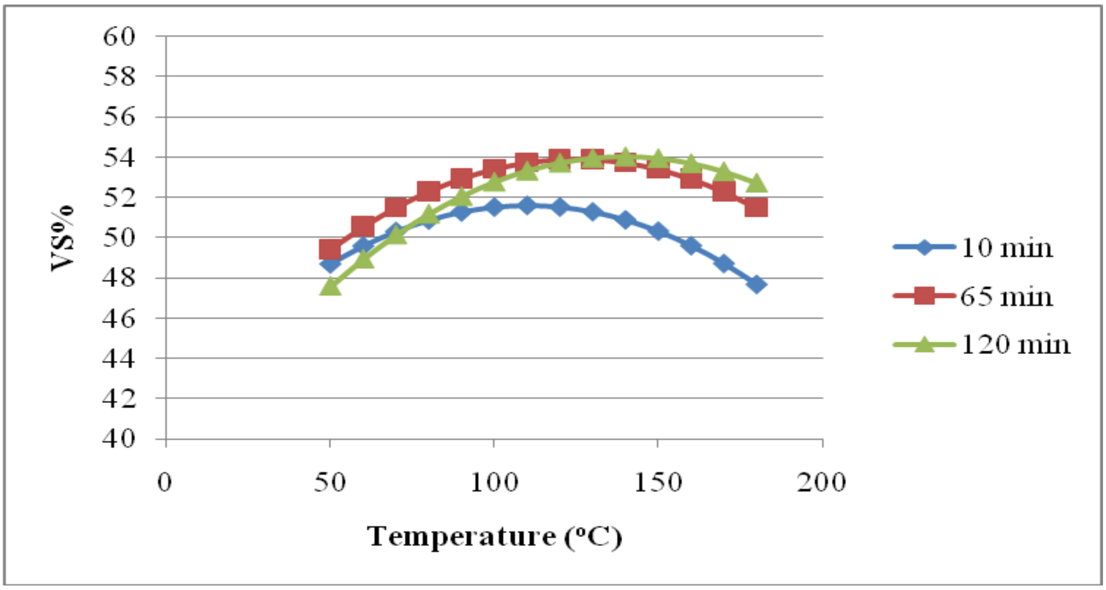

Figure 5.19 VS contents of sludge as a function of temperature for different drying times.

5.3.3 Heating (Calorific) Value Results of Dried Sludge Samples

Experimental data was used for determination of the response function coefficients for each independent variable. Low and high heating (calorific) values of the sludge samples were determined based on several original and dry base measurements. The experimental evaluations were done using the same evaluation method with Statistica 7.0 program for regression analysis as discussed in the above sections.

a) Low Heating (Calorific) Value (LHV) of Sludge in Original Base

The estimated coefficients of the response functions and the predicted values of LHV are shown in Tables 5.9 and 5.10, respectively. The regression coefficient was obtained as R^2= 0. 97840. Predicted and experimental values of LHV were in good agreement.

Table 5.9 Coefficients of the response functions for LHV of sludge in original base

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
1042.017	-12.881	-17.549	0.171	0.041	0.073

Table 5.10 Predicted and residual values for LHV of sludge in original base in the first experimental study

Time (min.)	Temperature (^oC)	Predicted Value	Residual Value
10	50	605.476	-134.854
10	180	194.629	125.104
120	50	283.166	77.455
120	180	2992.752	-57.838
26	115	434.825	-50.940
104	115	423.298	-16.855
65	69	308.076	-9.957
65	161	1142.381	144.560
65	115	1237.206	193.276
65	115	605.476	-134.476
65	115	605.476	-135.476

Relationships between drying time, temperature and LHV of dried sludge samples can be seen from Figure 5.20. LHV results of dried sludge samples as a function of temperature and drying time are shown in Figures 5.21 and 5.22, respectively. The model results showed that the LHV values in original base drastically increased with the increasing time and temperature.

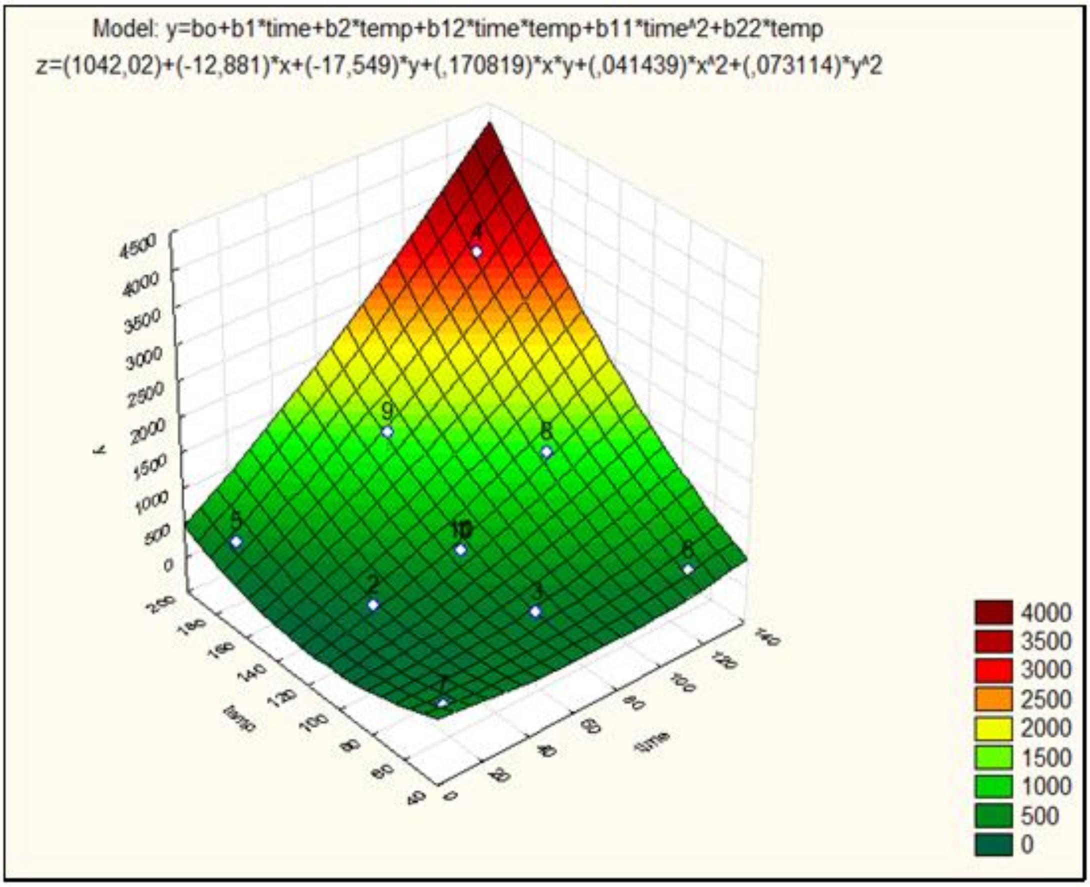

Figure 5.20 Relationships between drying time, temperature, and LHV of dried sludge samples in original base.

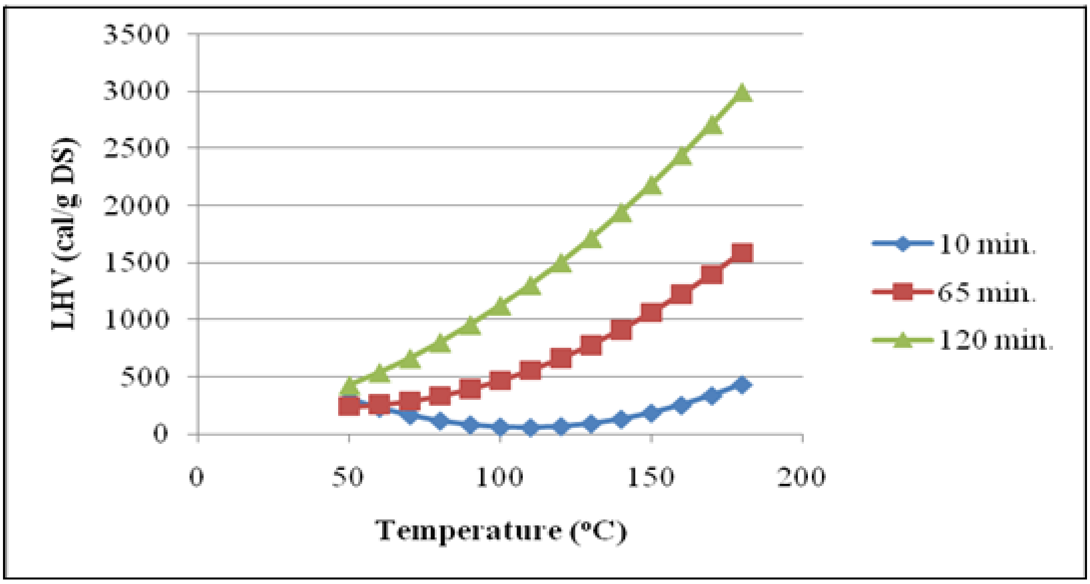

Figure 5.21 LHV of sludge in original base as a function of the temperature applied

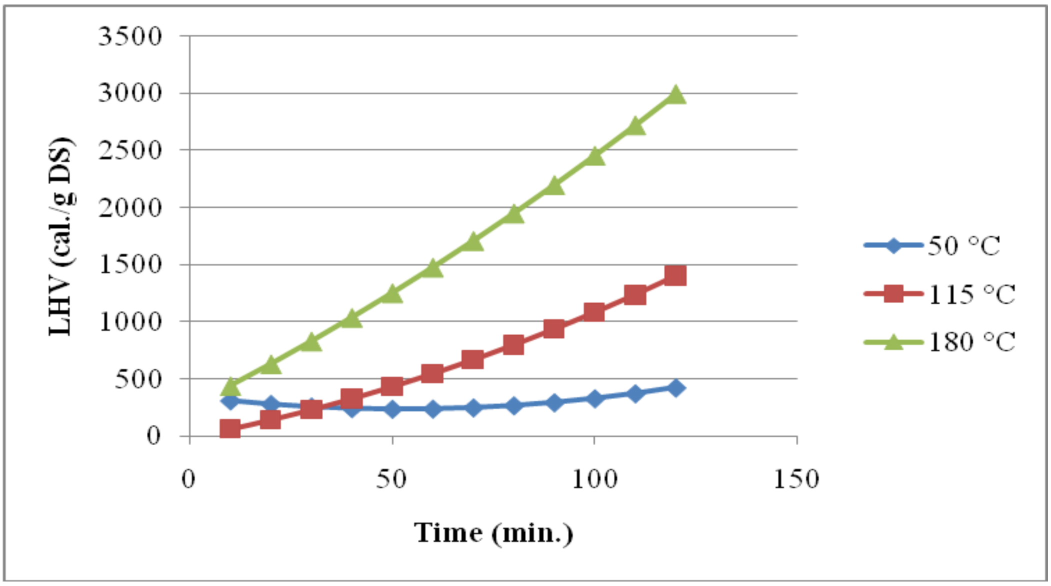

Figure 5.22 LHV of sludge in original base as a function of the drying time applied.

b) LHV of Sludge in Dry Base

When observed and calculated values, and operational conditions (time and temperature) were introduced, the statistical programme (Statistica 7) gives the predicted and residual value, regression coefficient, and also "b" coefficients. The estimated coefficients of the response functions and the predicted values of LHV are shown in Tables 5.11 and 5.12, respectively. The regression coefficient was obtained as R^2= 0. 74848. Predicted and experimental values of LHV were in good agreement.

Table 5.11 Coefficients of the response functions for LHV of sludge in dry base

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
2915.241	-0.879	1.926	-0.003	0.013	-0.011

Table 5.12 Predicted and residual values for low calorific value of sludge in dry base in the first experimental study

Time (min.)	Temperature (^oC)	Predicted Value	Residual Value
10	50	2970.919	-26.2186
10	180	2969.389	41.7001
120	50	2983.496	47.3335
120	180	2935.953	6.2229
26	115	2892.987	-4.6743
104	115	3056.434	-8.5657
65	69	2975.229	-19.4630
65	161	3013.413	10.9642
65	115	2911.763	5.5394
65	115	2970.919	-26.9192
65	115	2970.919	-25.9192

Relationships between drying time, temperature and LHV of dried sludge samples in dry base are shown in Figure 5.23. LHV results of dried sludge samples as a function of temperature and drying time are shown in Figures 5.24 and 5.25, respectively. The model results showed that the LHV values in dry base drastically increased with the increasing time. However, increased temperature values led to the decreases in LHV values in dry base.

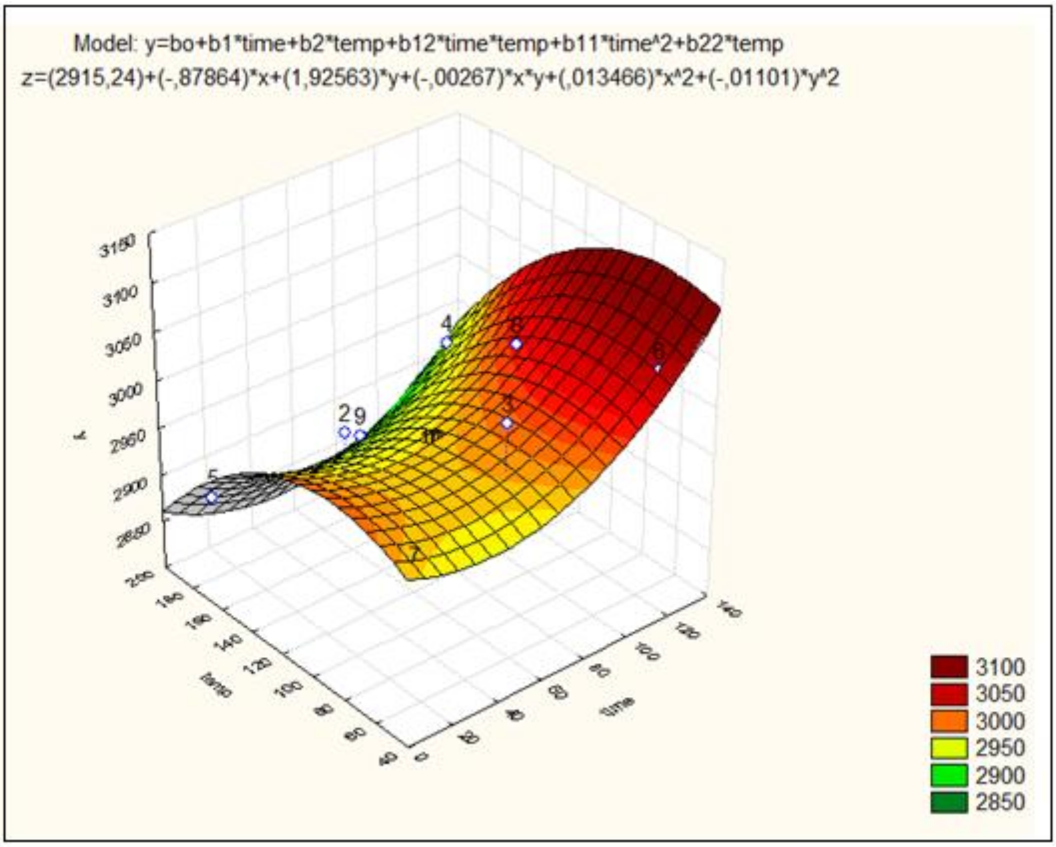

Figure 5.23 Relationships between retention time, temperature, and LHV of sludge in dry base.

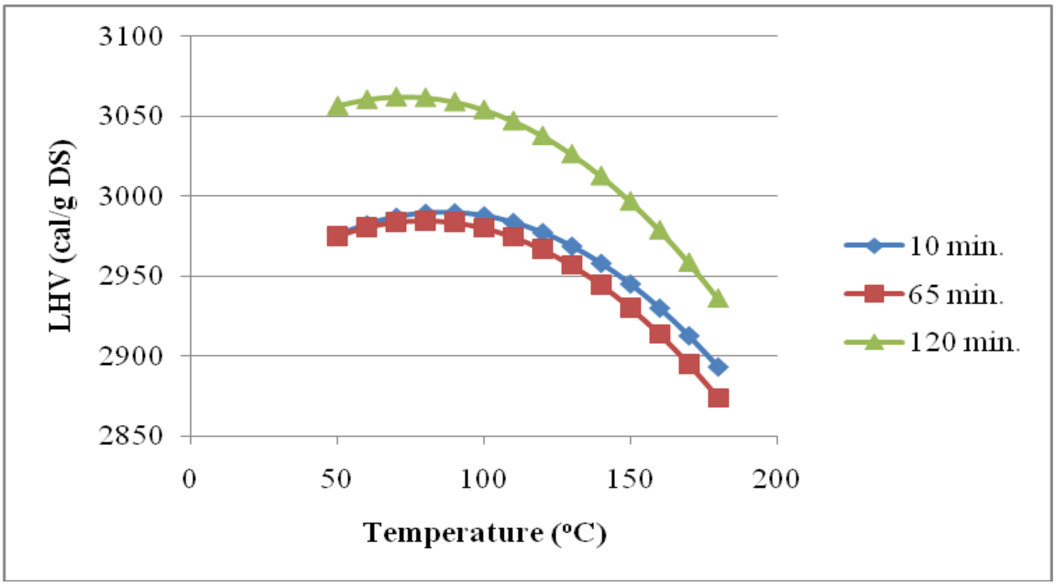

Figure 5.24 The effect of temperature on LHV of sludge in dry base

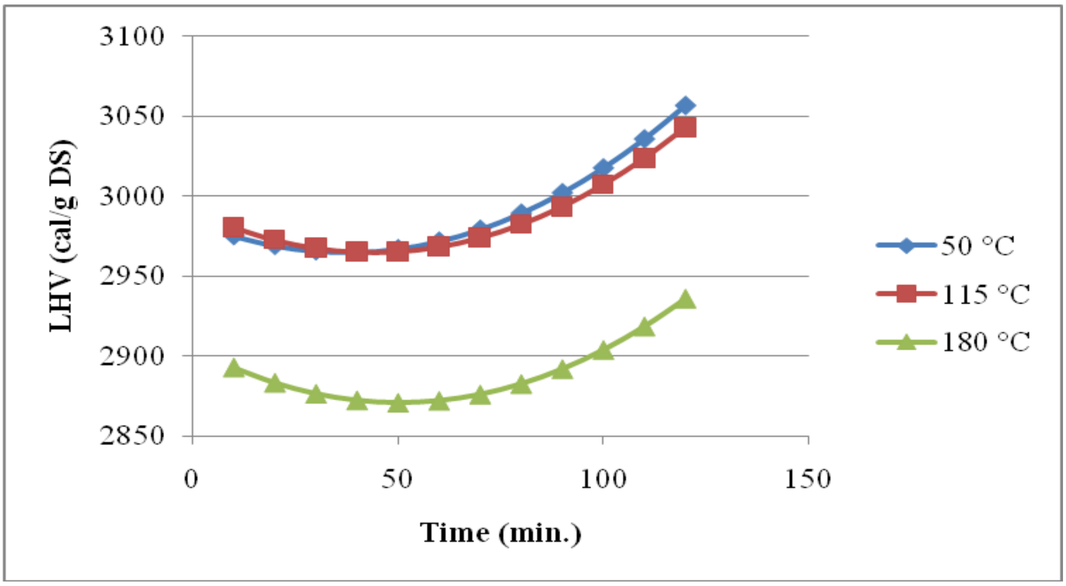

Figure 5.25 The effect of retention time on LHV of sludge in dry base

c) High Heating (Calorific) Value (HHV) of Sludge in Original Base

The estimated coefficients of the response functions and the predicted values of HHV in original base are shown in Tables 5.13 and 5.14, respectively. The regression coefficient was obtained as R^2= 0. 97831. Predicted and experimental values of HHV results were in good agreement.

Table 5.13 Coefficients of the response functions for HHV of sludge in original base

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
1416.332	-11.369	-15.149	0.149	0.037	0.063

Table 5.14 Predicted and residual values for high calorific value of sludge in original base in the first experimental study

Time (min.)	Temperature (^{o}C)	Predicted Value	Residual Value
10	50	1041.755	-118.635
10	180	683.076	109.674
120	50	759.130	69.394
120	180	3127.909	-50.262
26	115	888.563	-44.151
104	115	884.898	-15.327
65	69	781.006	-9.216
65	161	1513.860	126.909
65	115	1590.869	168.125
65	115	1041.755	-117.755
65	115	1041.755	-118.755

Relationships between drying time, temperature and HHV of dried sludge samples in original base are shown in Figure 5.26. HHV results of dried sludge samples as a function of temperature and drying time are shown in Figures 5.27 and 5.28, respectively. The model results showed that the HHV values in original base drastically increased with the increasing time and temperature.

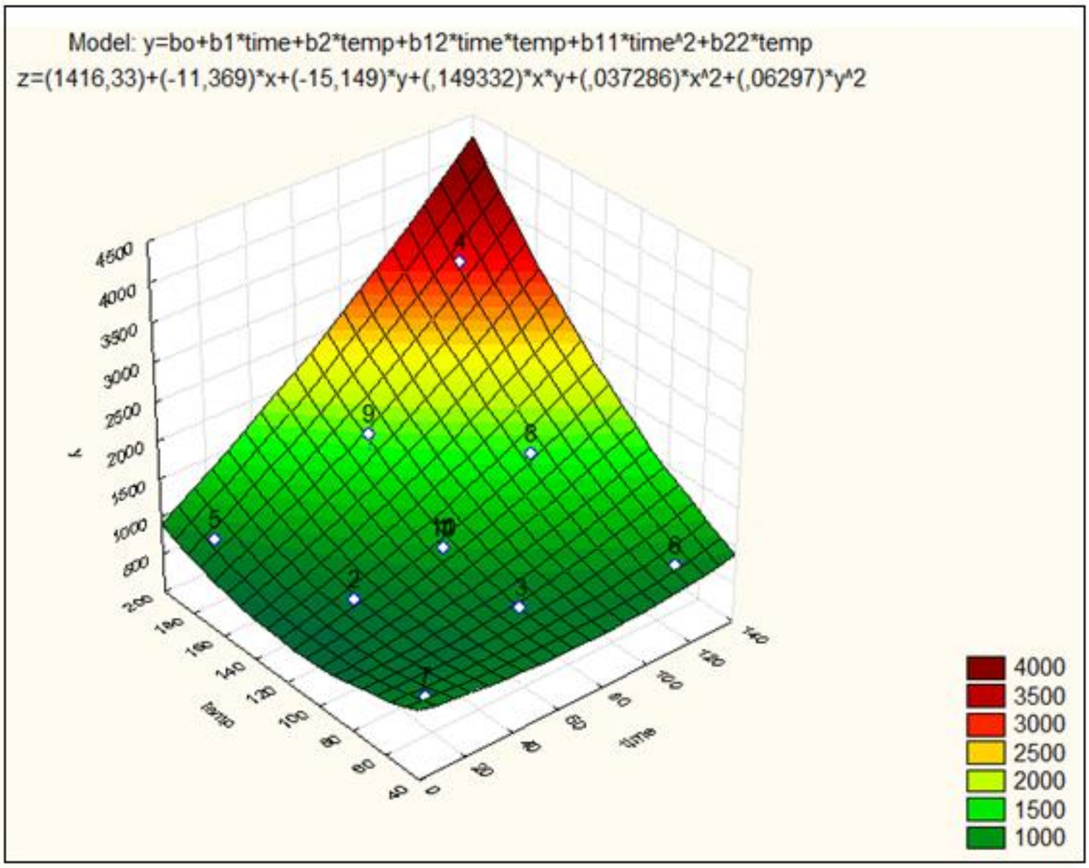

Figure 5.26 Relationships between retention time, temperature, and HHV of sludge in original base.

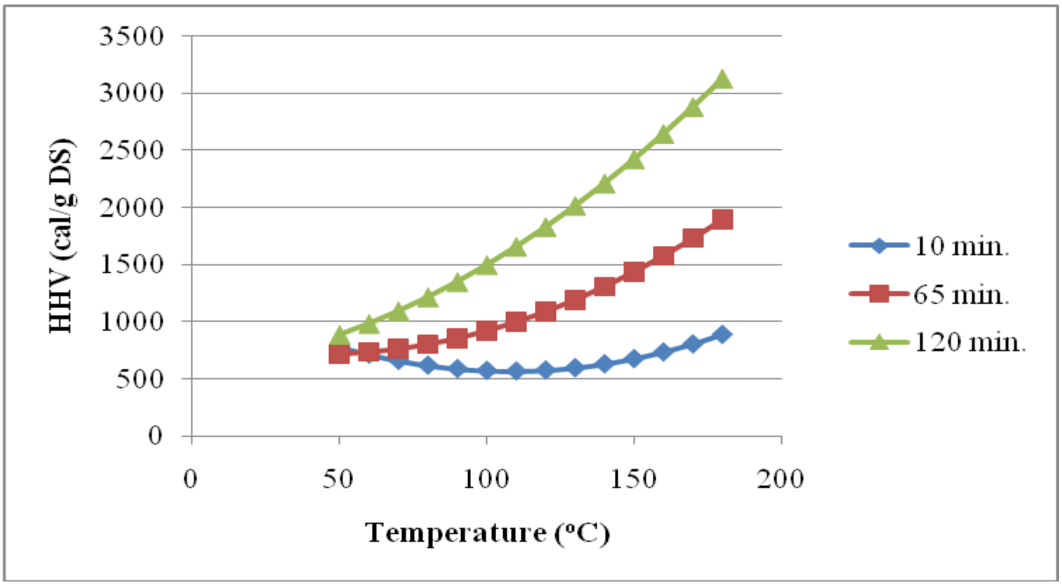

Figure 5.27 The effect of temperature on HHV of sludge in original base after drying process

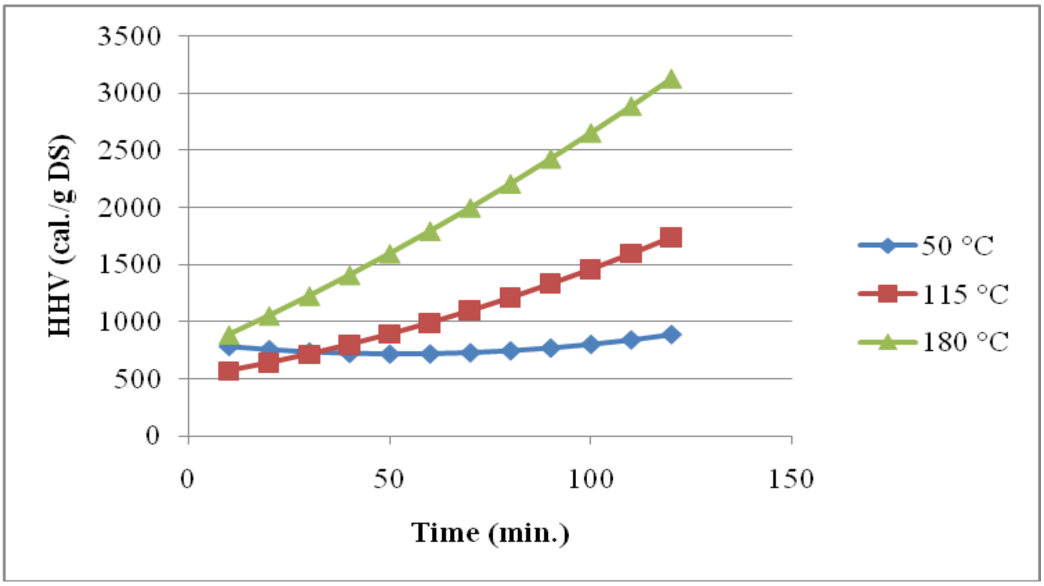

Figure 5.28 The effect of drying time on HHV of sludge in original base after drying process

d) *High Calorific Value of Sludge in Dry Base*

The estimated coefficients of the response functions and the predicted values of HHV in original base are shown in Tables 5.15 and 5.16, respectively. The regression coefficient was obtained as R^2= 0. 76339. Predicted and experimental values of HHV results were in good agreement.

Table 5.15 Coefficients of the response functions for HHV of sludge in dry base

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
3055.383	-0.9266	2.049253	-0.00274	0.013726	-0.01157

Table 5.16 Predicted and residual values for high calorific value of sludge in dry base in the first experimental study

Time (min.)	Temperature (^oC)	Predicted Value	Residual Value
10	50	3115.345	-24.3450
10	180	3115.047	41.3681
120	50	3127.186	46.0574
120	180	3076.738	7.2615
26	115	3036.586	-4.5864
104	115	3198.958	-7.8127
65	69	3119.661	-19.6605
65	161	3157.397	7.9509
65	115	3054.543	3.4566
65	115	3115.345	-24.3450
65	115	3115.345	-25.3450

Relationships between drying time, temperature and HHV of dried sludge samples in dry base are shown in Figure 5.29. HHV results of dried sludge samples as a function of temperature and drying time are shown in Figures 5.30 and 5.31, respectively. The model results showed that the HHV values in dry base drastically increased with the increasing time. However, it was not the case for temperature.

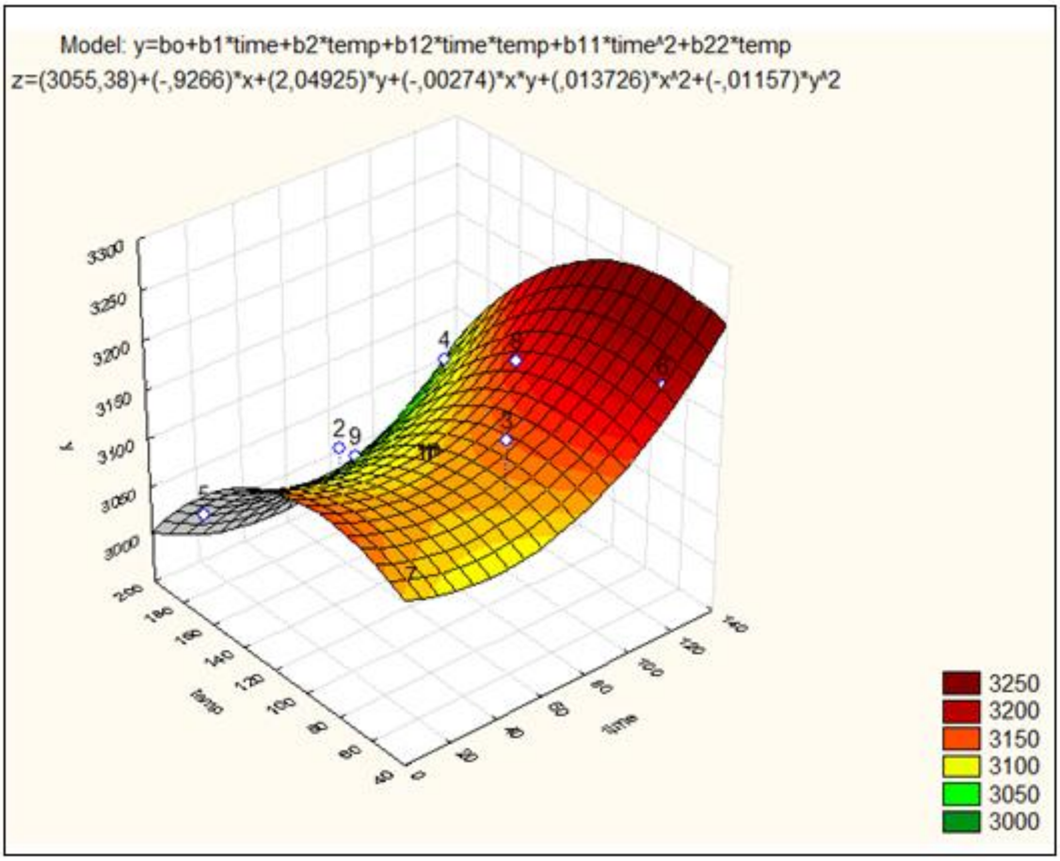

Figure 5.29 Relationships between drying time, temperature, and high calorific value of sludge in dry base.

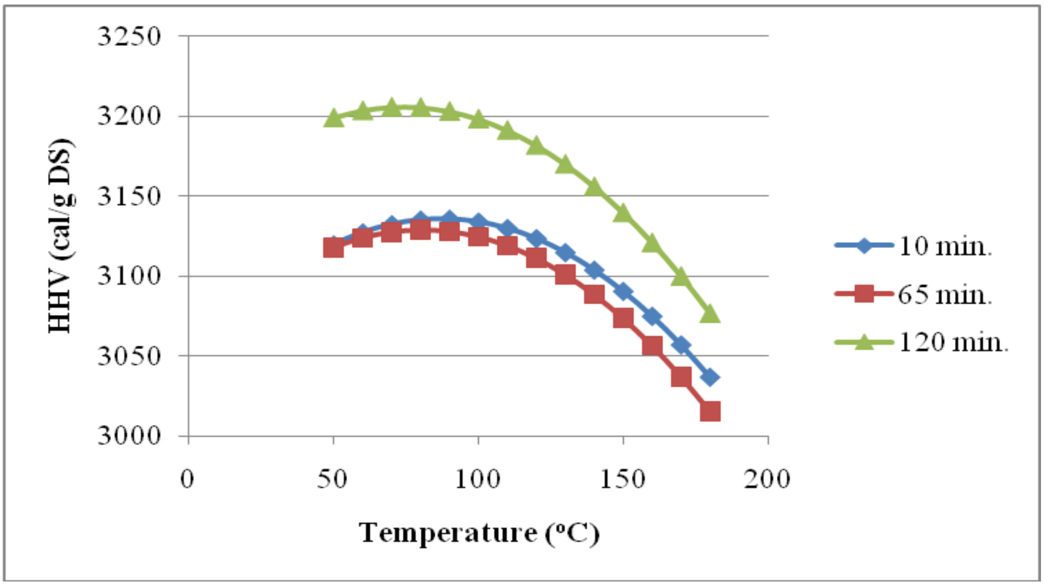

Figure 5.30 The effect of temperature on HHV of sludge in dry base.

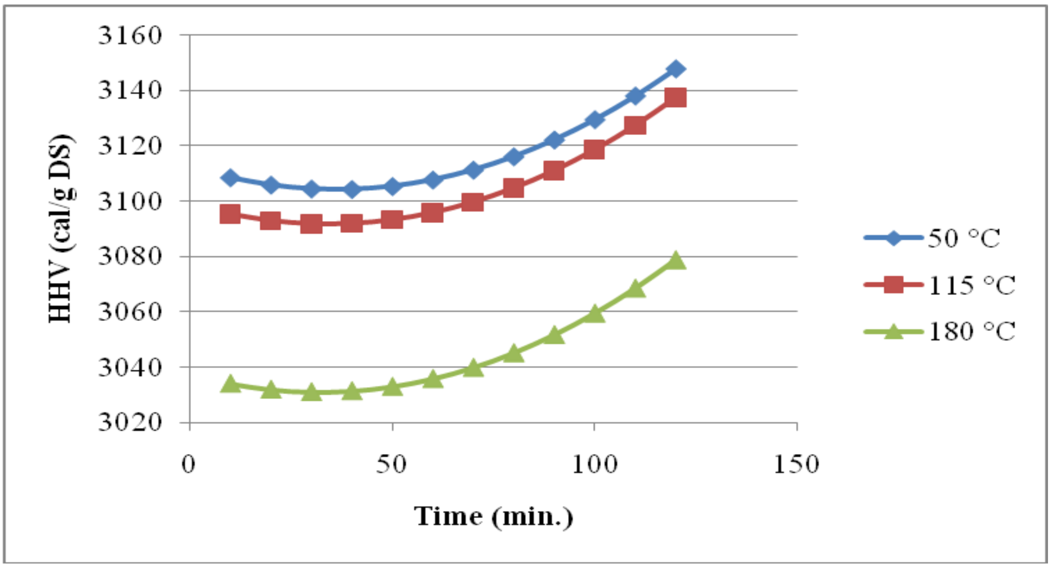

Figure 5.31 The effect of drying time on HHV of sludge in dry base.

5.3.4 TGA Analysis Results

The results of TGA for the sludge cakes are given in Figures 32 and 34 for different dying time and temperature conditions. It is clear from the figures that depending on the drying time increasing, water content and weight of the sample also decreased. At the same drying time, the increases in the temperature cause drastically increased in the DS content of sludge which means led to the lower water contents and weight.

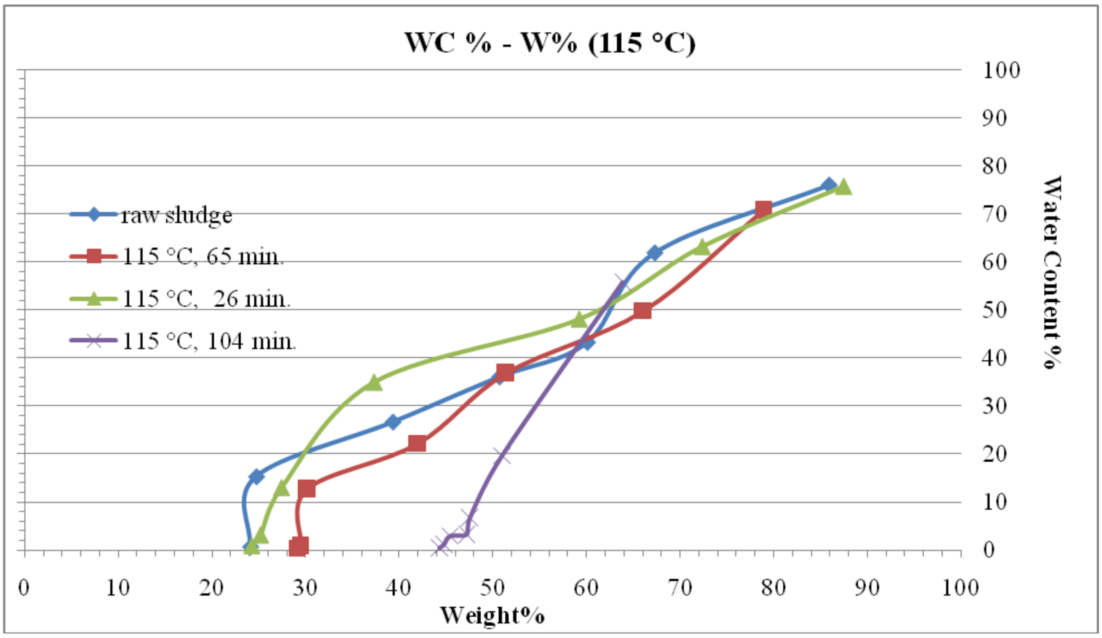

Figure 5.32 The decreases in the water content of sludge at the same drying temperature (115 ^{o}C)

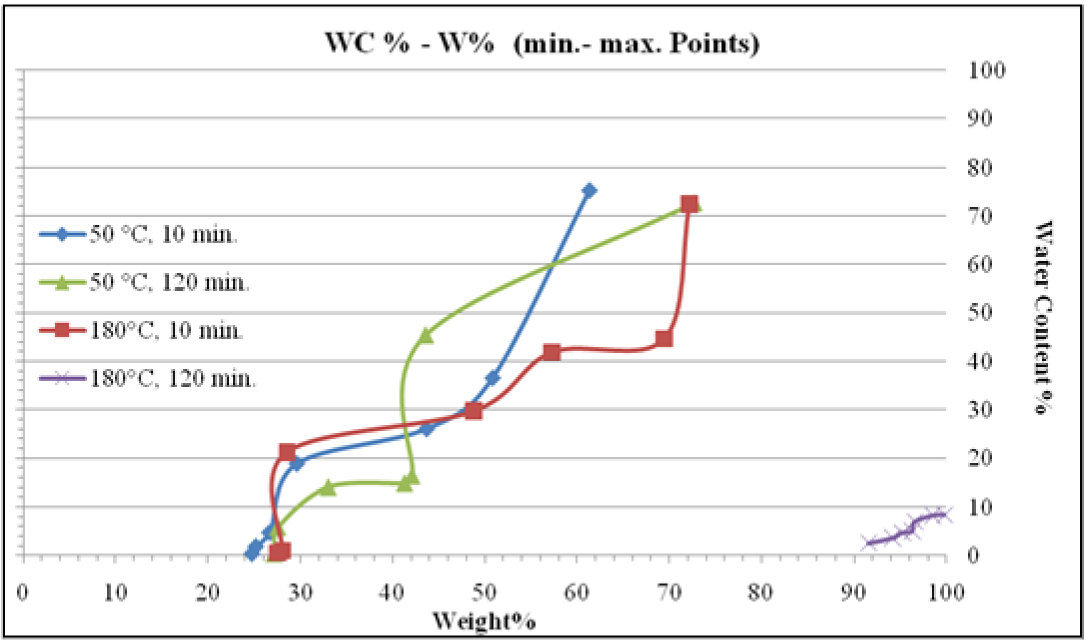

Figure 5.33 The decreases in the water content of sludge at different drying times and temperatures

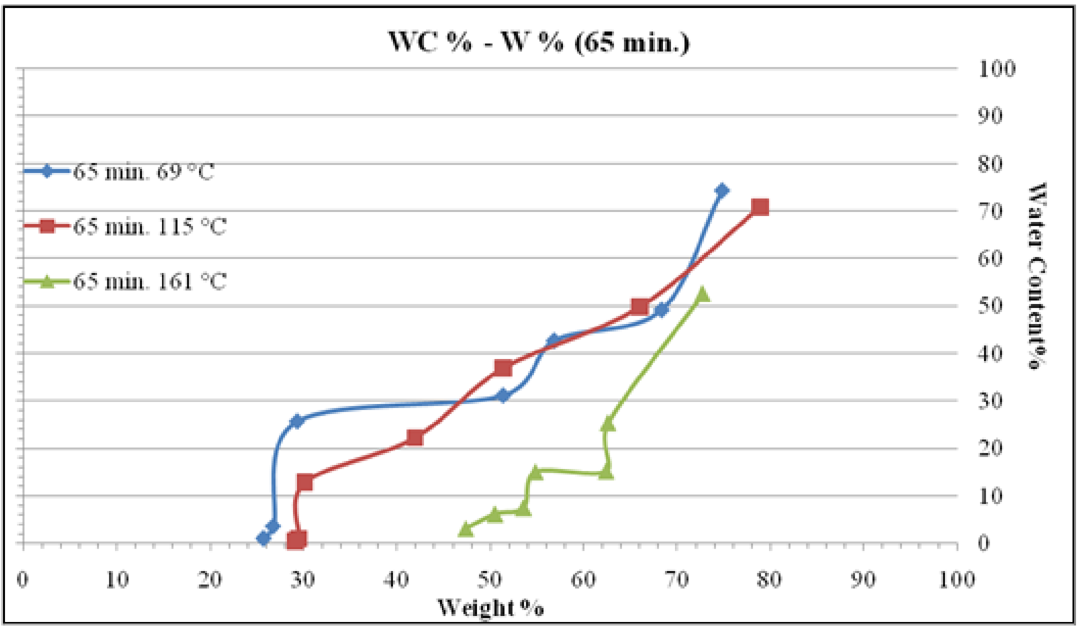

Figure 5.34 The decreases in the water content of sludge at the same drying time (65min).

5.4 Results of the Second Experimental Study (Drying time range: 10-180 minutes and temperature range: 80-250 ^{o}C)

Two important operating parameters: drying time (X_1) and drying temperature (X_2) were chosen as independent variables as in the first experimental series. Drying time (X_1) was changed between 10 and 180 minutes while the drying temperature (X_2) was varied between 80 and 250 ^{o}C. Experimental data points used in Box–Wilson statistical design regarding the drying time and temperature ranges is given in Table 5.17.

Table 5.17 Experimental data points used in Box–Wilson statistical design regarding the drying time and temperature ranges

Trial number	**Time (X_1) (min.)**	**Temperature (X_2) (^{o}C)**
1	10	80
2	10	250
3	180	80
4	180	250
5	35	165
6	155	165
7	95	105
8	95	225
9	95	165
10	95	165
11	95	165

5.4.1 Dry Solid Content of Sludge Results

Experiments regarding the DS contents of raw and dried sludge materials were done according to the experimental data points determined by using Box–Wilson statistical design as shown in Table 5.17. The DS results are given in Table 5.18.

Table 5.18 DS results of sludge cake and dried sludge materials

Time (min.)	**Temperature (^oC)**	**Sludge cake**	**DS (%)**
No heating time	25	Raw sludge cake	22.43
			21.53
			21.20
10	80	Dried cake	22.40
			22.44
			22.38
10	250	Dried cake	27.98
			46.21
			28.99
180	80	Dried cake	36.69
			34.40
			33.92
180	250	Dried cake	100
			99.8
			99.6
35	165	Dried cake	29.44
			29.70
			31.62
155	165	Dried cake	98.96
			99.09
			99.07
95	105	Dried cake	30.19
			31.01
			32.56
95	225	Dried cake	99.15
			99.08
			99.21
95	165	Dried cake	58.76
			56.77
			55.36

The graphical depiction of DS results is given in Figure 5.35 for raw sludge cake and dried sludge samples at different temperatures (80 and 250 ^{o}C) for 10 and 180 minutes of drying time. As can be seen from this figure, the higher drying temperatures and the drying times lead to higher DS contents. When the minimum temperature with the maximum retention time were used, a little amount increases in DS content was obtained.

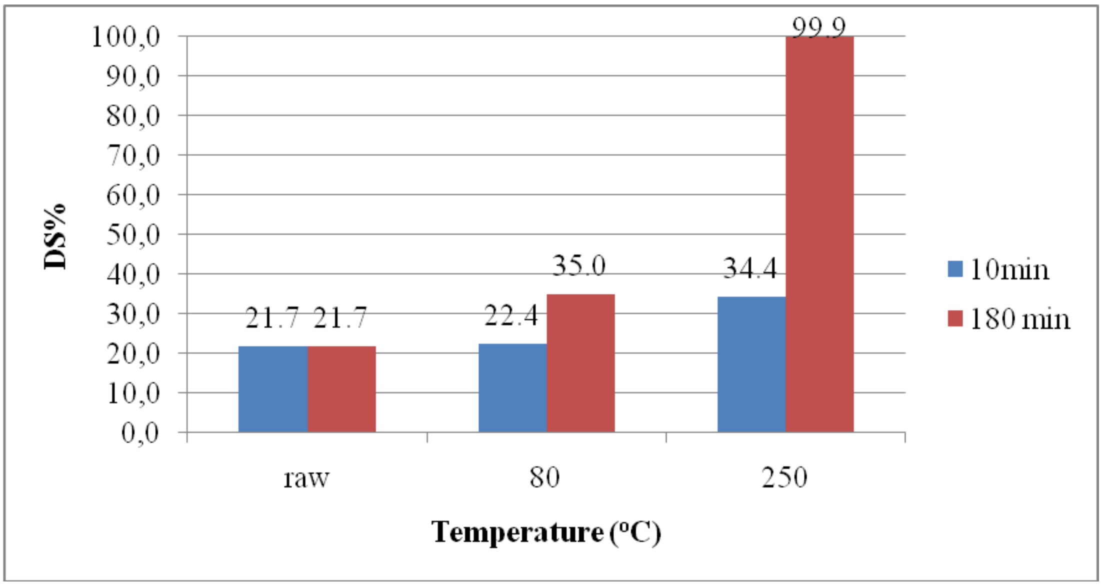

Figure 5.35 DS results for raw sludge cake and dried sludge samples at different temperatures for 10 and 180 minutes of drying time.

Figure 5.36 shows DS results at 165 ^{o}C for different drying times, while Figure 5.37 shows the results at 95 min. of drying time for different temperature applications. It is clear from the figures that the both parameters are very effective on the sludge drying process as concluded in first experimental series. At the same temperature application, increased DS values obtained with the increasing of drying time. Similiarly, increased in the temperatures at the same drying time application led to higher DS values of the dried products.

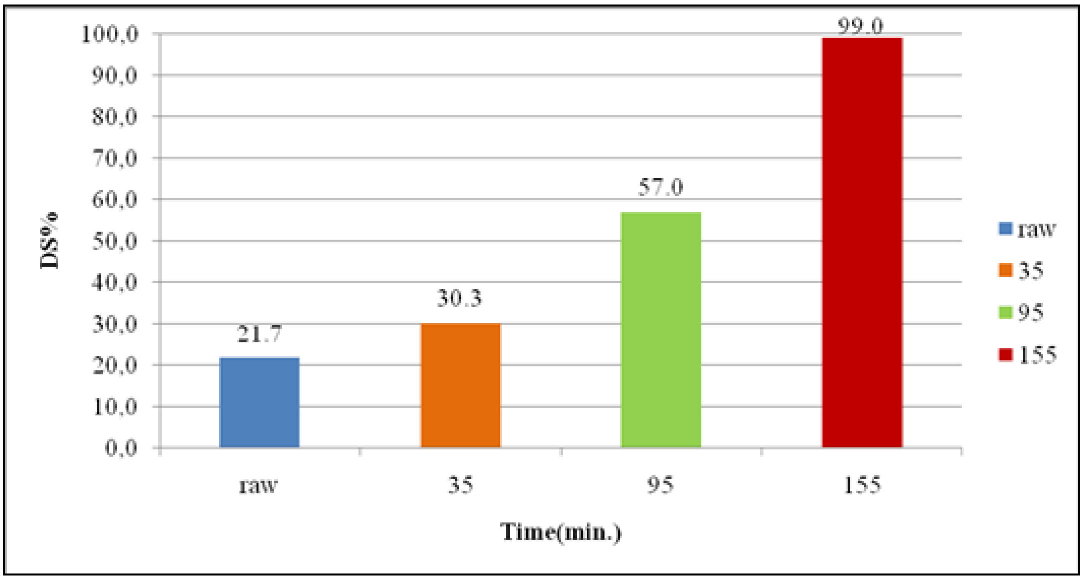

Figure 5.36 DS results for raw sludge cake and dried products at 165 °C for different drying times.

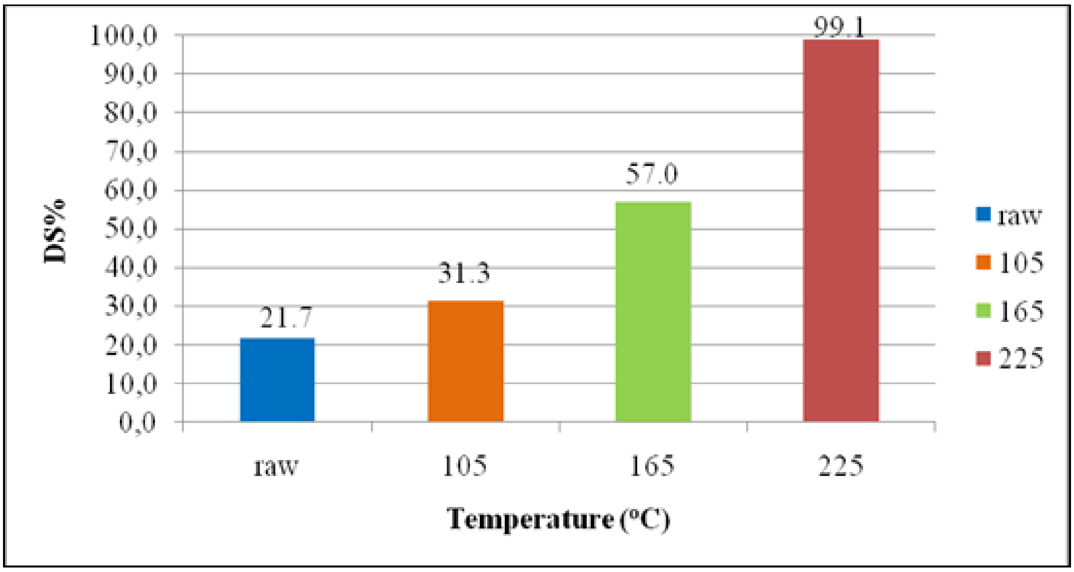

Figure 5.37 DS results for raw sludge cake and dried products at 95 min of drying time for different temperature applications

Experimental data was used for determination of the response function coefficients for each independent variable as in the first experimental series. A Statistica 7.0 program was used for regression analysis. The estimated coefficients of the response functions are shown in Table 5.19. The response functions were used in calculating the predicted values of DS. The observed values were introduced to the statistical programme (Statistica 7) and the predicted DS results given in Table 5.20

were obtained. The regression coefficient was achieved as R^2= 0. 85061. Predicted and experimental values of DS were in good agreement; but, not as much as in the first experimental study.

Table 5.19 Coefficients of the response functions for DS

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
-29.8757	0.2708	0.5748	0.0020	-0.0016	-0.0015

Table 5.20 Predicted and residual values for dry solid content of sludge samples in the second experimental study

Time (min.)	Temperature (°C)	Predicted Value	Residual Value
10	50	10.8973	11.5396
10	180	29.7225	-0.7311
120	50	33.8748	0.0410
120	180	111.7298	-12.2298
26	115	44.3417	-14.9047
104	115	81.3951	17.6748
65	69	46.1870	-15.9985
65	161	80.3094	18.7686
65	115	68.5337	-2.2086
65	115	68.5337	-2.5921
65	115	68.5337	0.6408

Relationships between drying time, temperature and the dry solids content of dried sludge samples can be seen from Figure 5.38. DS results as a function of temperature at different drying times are depicted in Figure 5.39 while the results as a function of drying time for varied temperatures are plotted in Figure 5.40. The increases of drying time and temperature cause the higher dry solid content of sludge.

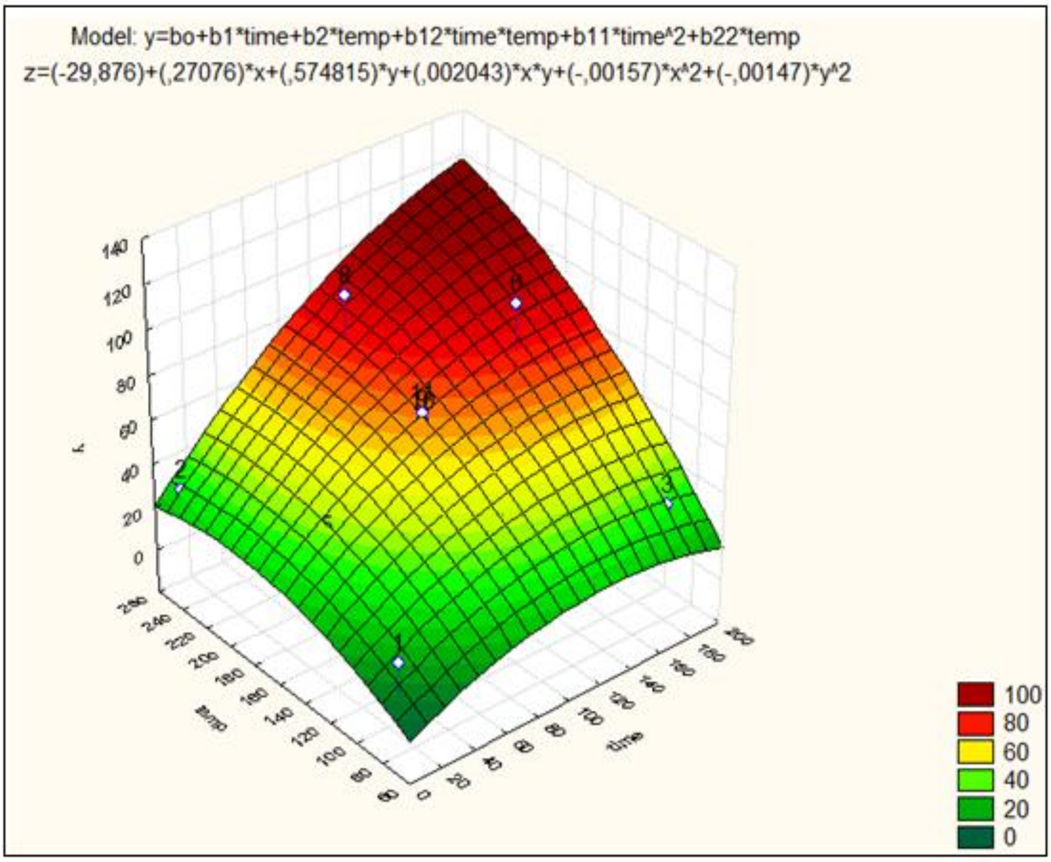

Figure 5.38 Relationships between drying time, temperature, and DS of dried sludge

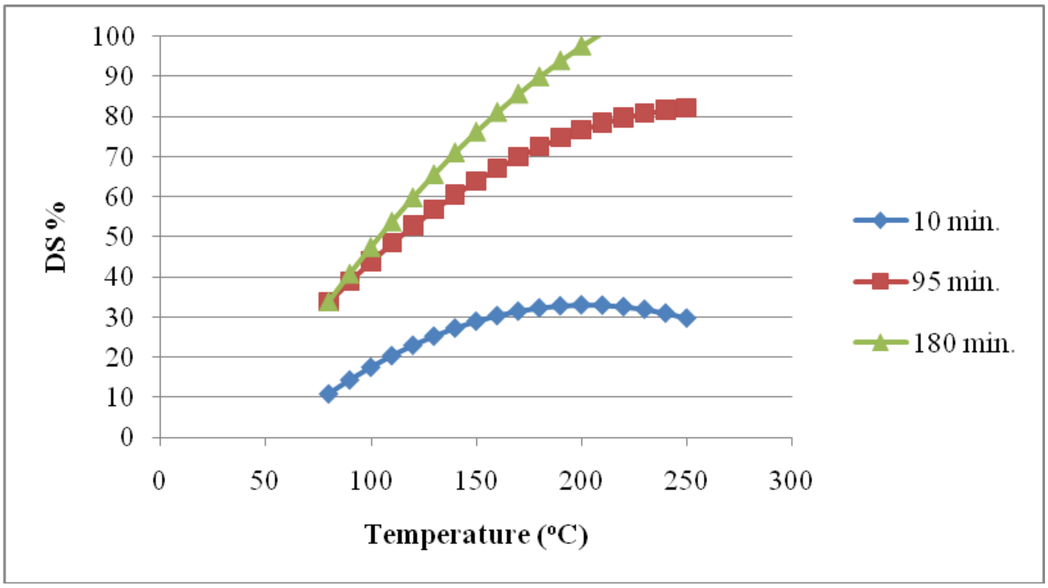

Figure 5.39 DS as a function of drying temperature for different drying times.

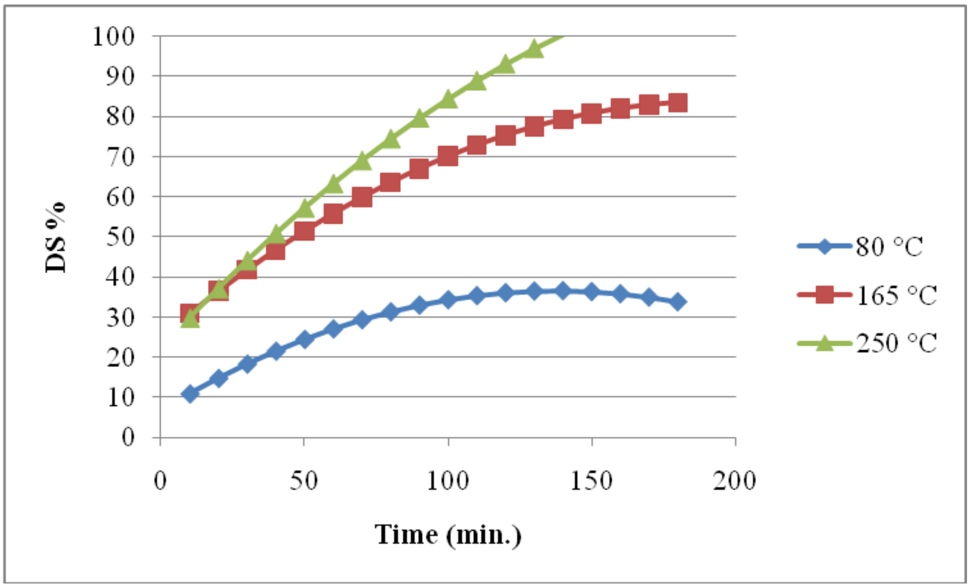

Figure 5.40 DS as a function of drying time for different drying temperatures

5.4.2 Volatile Solid Content (VS) Results

VS experiments for raw sludge cake and dried sludge materials were done according to the experimental data points given in Table 5.18. The VS results of this experimental series are presented in Table 5.19.

Table 5.19 VS results of sludge cake and dried sludges samples

Time (min.)	Temperature (^oC)	Sludge cake	VS (%)
No heating time	25	Raw sludge cake	55.71
			58.06
			59.24
10	80	Dried cake	59.17
			60.70
			59.32
10	250	Dried cake	57.25
			55.10
			59.78
180	80	Dried cake	59.90
			61.27
			61.06
180	250	Dried cake	33.04
			32.32
			43.56
35	165	Dried cake	59.79
			60.13
			60.31
155	165	Dried cake	62.06
			52.26
			55.94
95	105	Dried cake	59.87
			57.88
			60.46
95	225	Dried cake	54.38
			54.74
			54.83
95	165	Dried cake	56.65
			53.41
			55.91

VS results are also plotted in Figure 5.41 for raw sludge cake and dried sludge samples at different temperatures (80 and 250 ^{o}C) for 10 and 180 minutes of drying time. The elevated temperatures and drying time did not drastically change the VS values except for the highest drying time and temperature application, which VS decreased up to 36.3%. The heating values for this application should also be checked to make conclusion on this result.

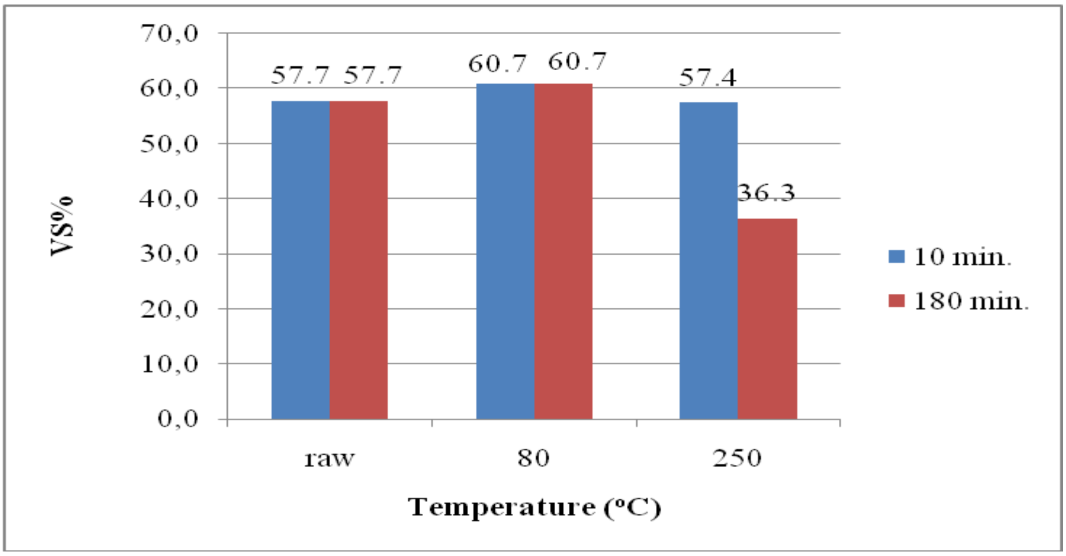

Figure 5.41 VS results as a function of drying temperature.

Figure 5.42 shows VS results at 165 ^{o}C for different drying times, while Figure 5.43 presents the results at 95 min. of drying time for different temperature applications. It can be said that the VS values decreased depending on the increases in drying temperature and time values.

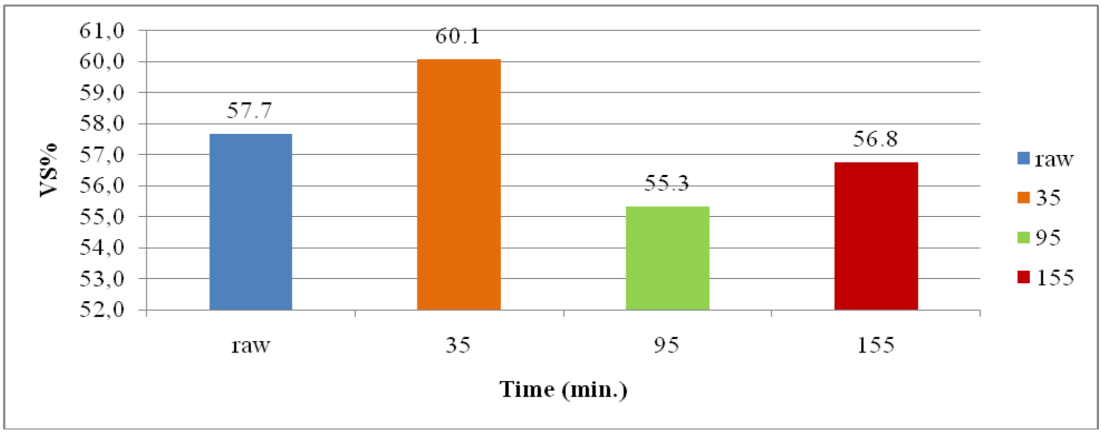

Figure 5.42 VS results for raw sludge cake and dried products at 165 ^{o}C for different drying times.

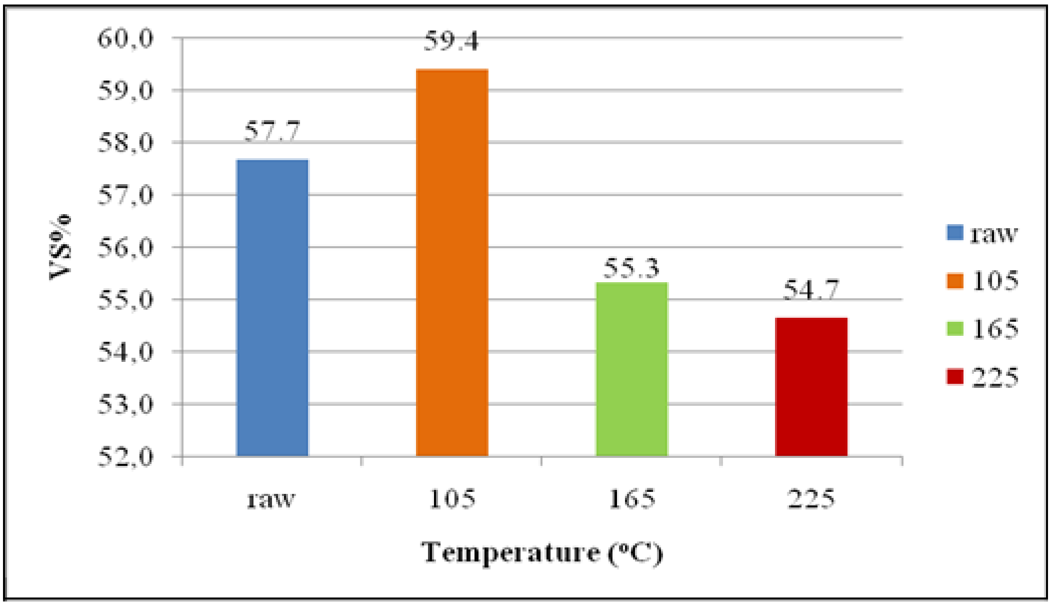

Figure 5.43 VS results for raw sludge cake and dried products at 95 min of drying time for different temperature applications

Experimental data was used for determination of the response function coefficients for each independent variable. The estimated coefficients of the response functions shown in Table 5.20 were used in calculating the predicted values of VS. The predicted DS results given in Table 5.21 were obtained. The regression coefficient was achieved as R^2= 0. 933918. Predicted and experimental values of VS were found in good agreement.

Table 5.20 Coefficients of the response functions from the statistical programme for VS

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
50.38836	0.07802	0.13711	-0.00076	-0.00002	-0.00041

Table 5.21 Predicted and residual values for VS contents of sludge samples in the second experimental study

Time	Temperature	Predicted Value	Residual Value
10	80	58.8962	0.8326
10	250	57.8744	-0.4980
180	80	60.9742	-0.2284
180	250	37.8672	-1.5590
35	165	60.1221	-0.0453
155	165	53.7941	2.9610
95	105	59.8265	-0.4271
95	225	51.3105	3.3429
95	165	57.0465	-1.7214
95	165	57.0465	-1.5194
95	165	57.0465	-1.1379

Relationships between drying time, temperature and the volatile solids content of dried sludge samples can be seen from Figure 5.44. VS results as a function of drying time for varied temperatures are depicted in Figure 5.45 while the results as a function of temperature at different drying times are plotted in Figure 5.46. The model results showed that the VS values decreased at the maximum temperature and drying time applications.

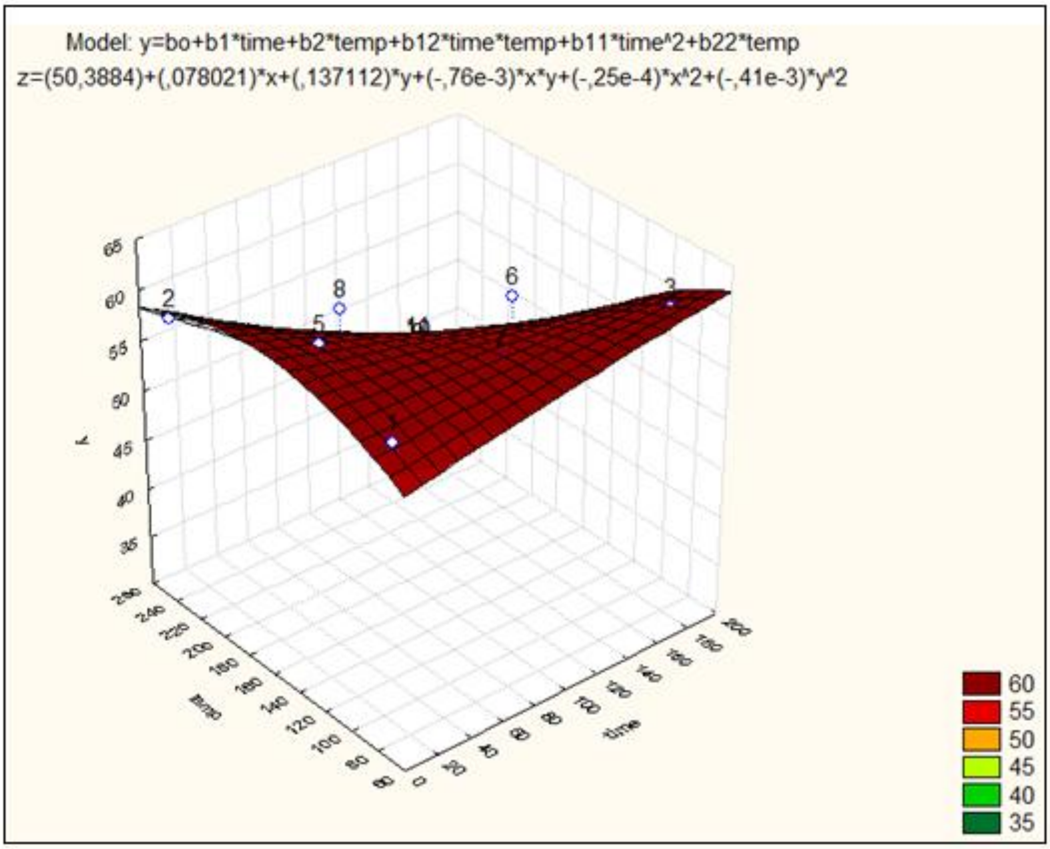

Figure 5.44 Relationships between drying time, temperature, and volatile solids content in dried sludge samples.

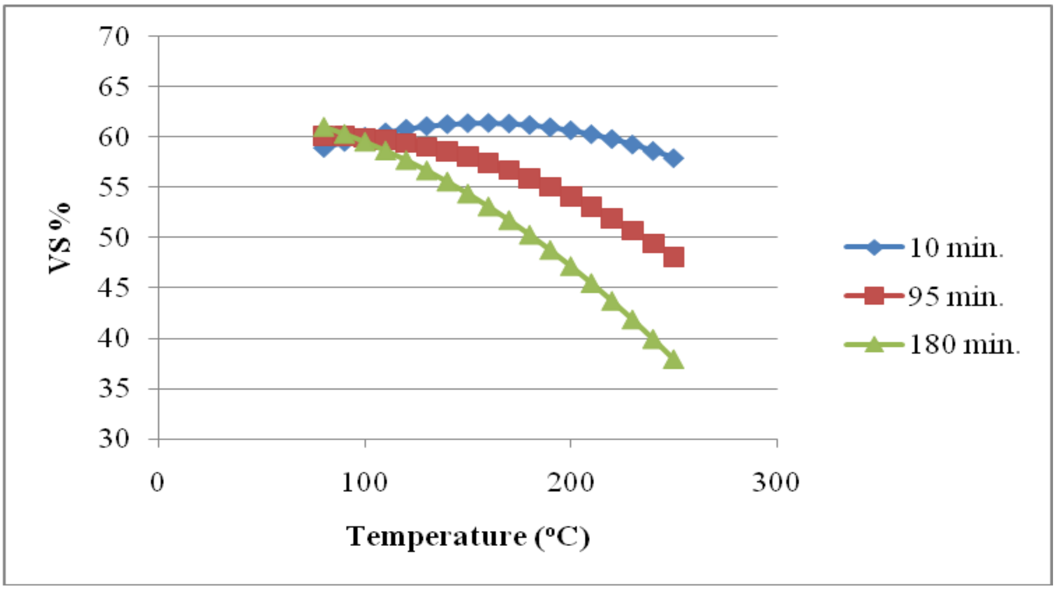

Figure 5.45 VS contents of sludge as a function drying temperature

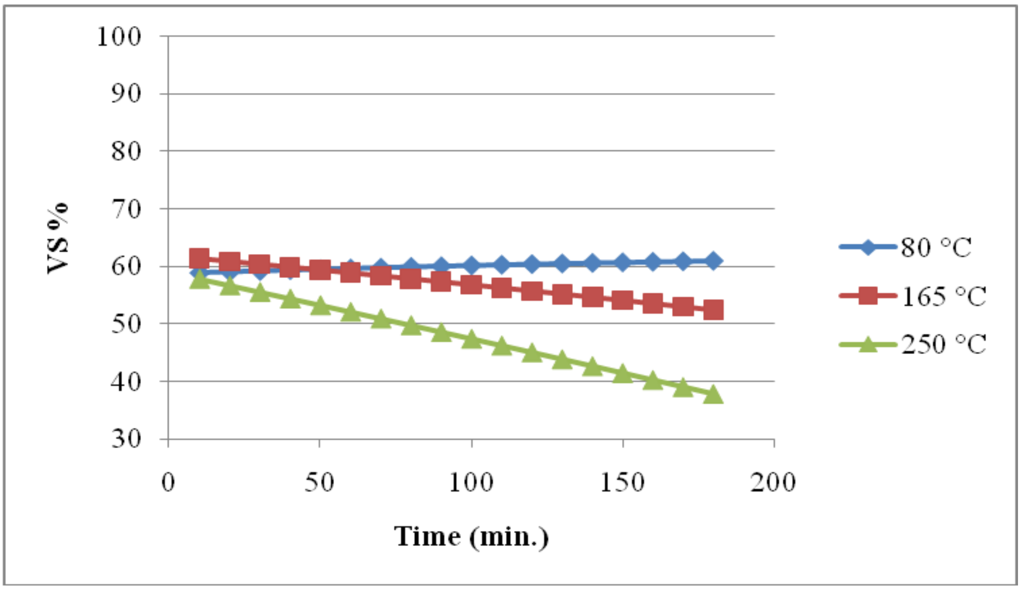

Figure 5.46 VS contents of sludge as a function drying time at different temperature applications

5.4.3 Heating (Calorific) Value Results of Dried Sludge Samples

Experimental data was used for determination of the response function coefficients for each independent variable. Low and high heating (calorific) values of the sludge samples were determined based on several original and dry base measurements. The experimental evaluations were done using the same evaluation method with Statistica 7.0 program for regression analysis as discussed in the above sections.

a) Low Heating (Calorific) Value (LHV) of Sludge in Original Base

The estimated coefficients of the response functions and the predicted values of LHV are shown in Tables 5.21 and 5.22, respectively. The regression coefficient was obtained as R^2= 0. 79747. Predicted and experimental values of LHV were in good agreement.

Table 5.21 Coefficients of the response functions for LHV of sludge in original base

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
-2241.2929	15.6846	27.9038	0.0366	-0.0639	-0.0614

Table 5.22 Predicted and residual values for LHV of sludge in original base in the second experimental study

Time (min.)	Temperature (^oC)	Predicted Value	Residual Value
180	80	876.075	-45.841
10	80	-222.537	490.136
35	165	1371.765	-749.583
95	165	2176.093	-10.003
180	250	3291.297	-494.979
10	250	1136.221	40.999
95	225	2620.890	645.997
155	165	2520.126	769.019
95	105	1288.897	-626.560
95	165	2176.093	-10.093
95	165	2176.093	-9.093

Relationships between drying time, temperature and LHV of dried sludge samples in original base are shown in Figure 5.47. LHV results of dried sludge samples as a function of temperature and drying time are shown in Figures 5.48 and 5.49, respectively. The model results showed that the LHV values in original base drastically increased with the increasing time. However, increased temperature values led to the decreases in LHV values in original base.

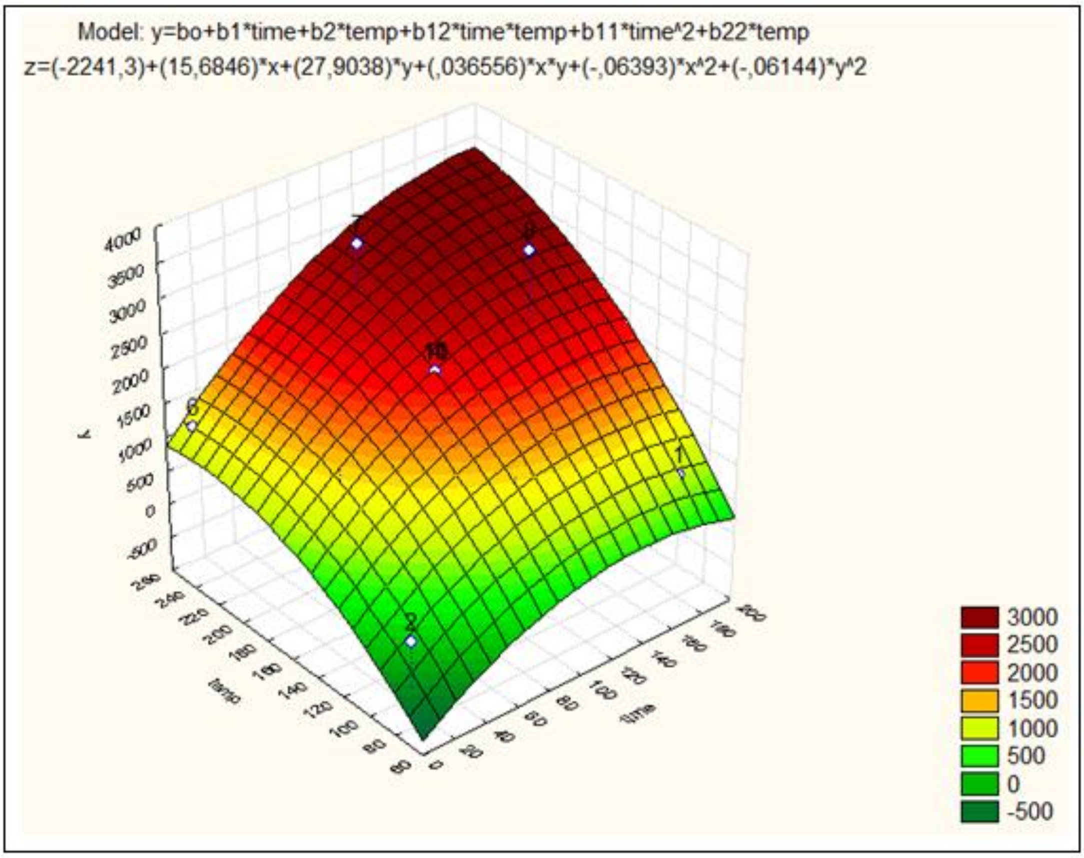

Figure 5.47 Relationships between drying time, temperature and LHV of sludge in original base

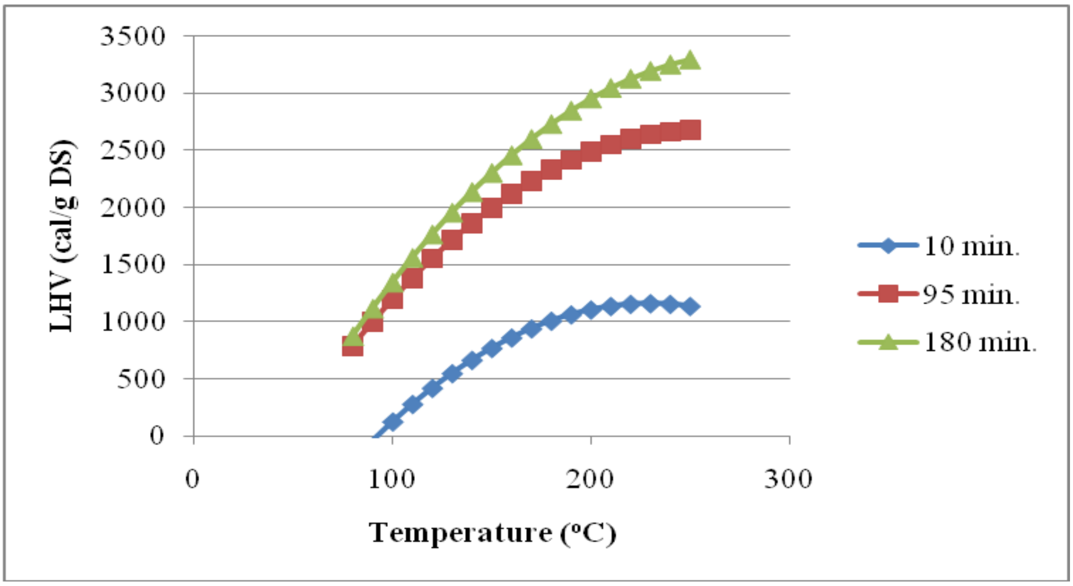

Figure 5.48 LHV of sludge in original base as a function of the temperature applied

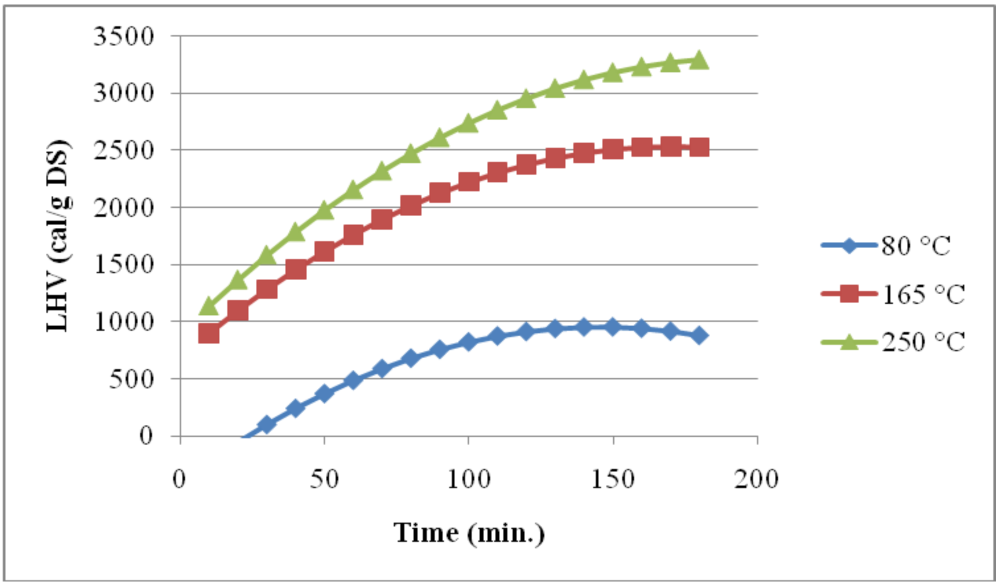

Figure 5.49 LHV of sludge in original base as a function of the drying time applied.

b) LHV of Sludge in Dry Base

When observed and calculated values, and operational conditions (time and temperature) were introduced, the statistical programme (Statistica 7) gives the predicted and residual value, regression coefficient, and also “b” coefficients. .The estimated coefficients of the response functions and the predicted values of LHV are shown in Tables 5.23 and 5.24, respectively. The regression coefficient was obtained as R^2= 0. 85969. Predicted and experimental values of LHV were in good agreement.

Table 5.23 Coefficients of the response functions for LHV of sludge in dry base

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
2812.9008	4.5290	5.8203	-0.0161	-0.0143	-0.0165

Table 5.24 Predicted and residual values for low calorific value of sludge in dry base in the second experimental study

Time	Temperature	Predictd Value	Residual Value
180	80	3292.189	6.188
10	80	3203.831	63.008
35	165	3371.793	-106.389
95	165	3372.648	26.067
180	250	2863.491	-50.106
10	250	3239.470	6.715
95	225	3243.830	53.855
155	165	3270.280	54.602
95	105	3382.557	-105.643
95	165	3372.648	25.352
95	165	3372.648	26.352

Relationships between drying time, temperature and LHV of dried sludge samples in dry base are shown in Figure 5.50. LHV results of dried sludge samples as a function of temperature and drying time are shown in Figures 5.51 and 5.52, respectively. The model results showed that the LHV values in dry base slightly increased with the increasing time and temperature. However, maximum temperature and time application led to the decreases in LHV values in dry base. In this experimental study, highest heating values were obtained when comparing to the first study.

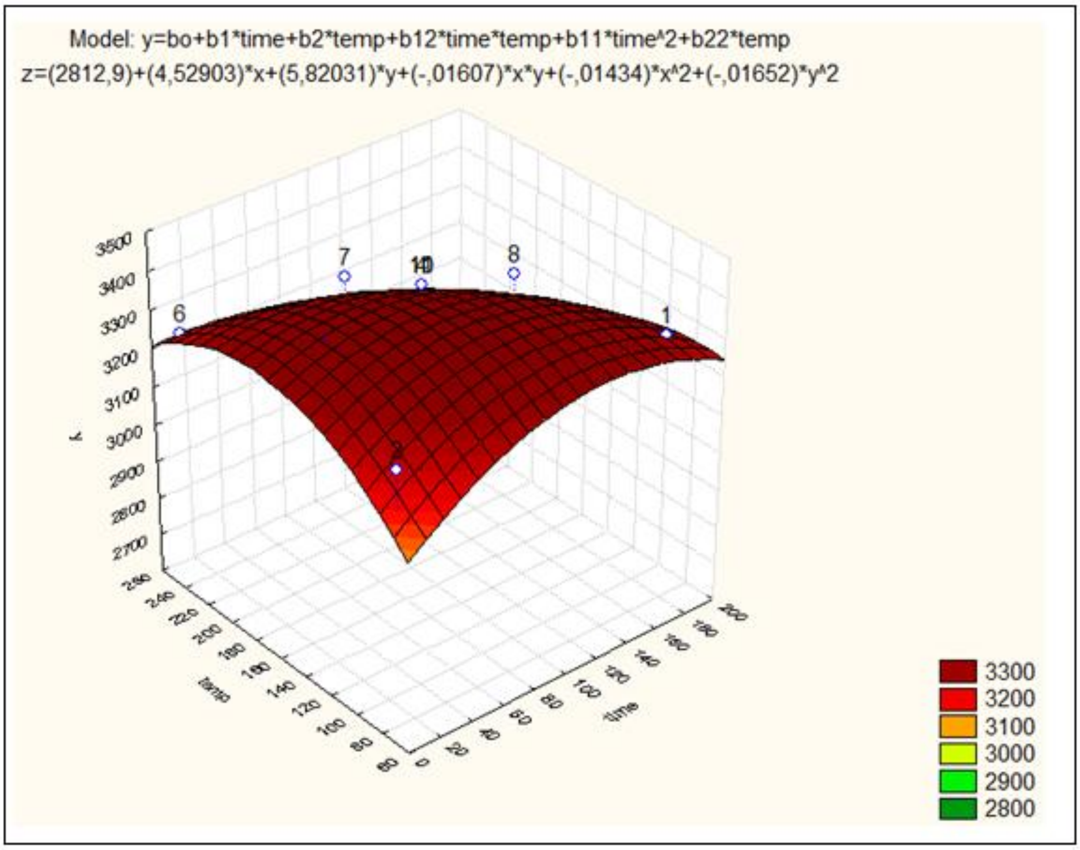

Figure 5.50 Relationships between drying time, temperature, and LHV of sludge in dry base.

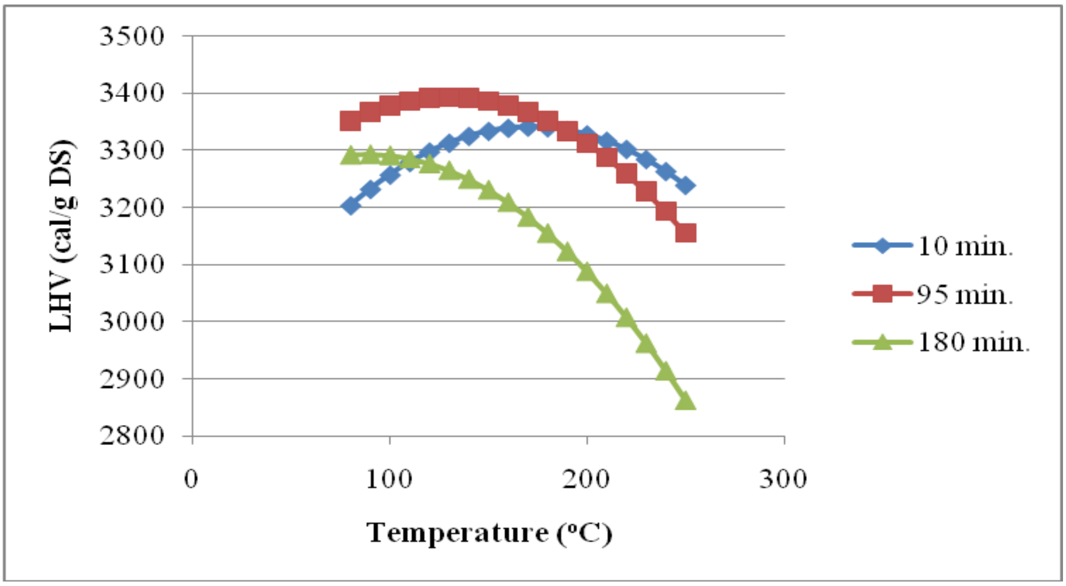

Figure 5.51 The effect of temperature on LHV of sludge in dry base

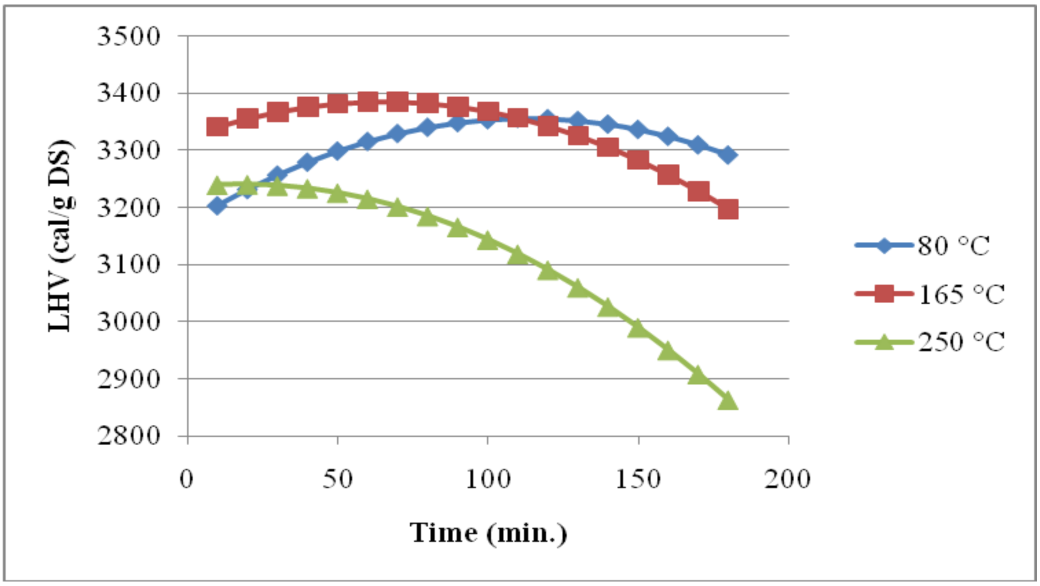

Figure 5.52 The effect of drying time on LHV of sludge in dry base

c) High Heating (Calorific) Value (HHV) of Sludge in Original Base

The estimated coefficients of the response functions and the predicted values of HHV in original base are shown in Tables 5.25 and 5.26, respectively. The regression coefficient was obtained as R^2= 0. 78532. Predicted and experimental values of HHV results were in good agreement.

Table 5.25 Coefficients of the response functions for HHV of sludge in original base

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
-1564.5173	14.4154	26.1070	0.0293	-0.0575	-0.0584

Table 5.26 Predicted and residual values for high calorific value of sludge in original base in the second experimental study

Time (min.)	Temperature (^oC)	Predicted Value	Residual Value
180	80	1303.994	-43.738
10	80	312.370	445.582
35	165	1757.566	-684.724
95	165	2464.126	-8.214
180	250	3365.082	-449.807
10	250	1526.158	39.513
95	225	2831.933	583.743
155	165	2756.583	701.682
95	105	1676.095	-566.786
95	165	2464.126	-8.126
95	165	2464.126	-9.126

Relationships between drying time, temperature and HHV of dried sludge samples in original base are shown in Figure 5.53. HHV results of dried sludge samples as a function of temperature and drying time are shown in Figures 5.54 and 5.55, respectively. The model results showed that the HHV values in original base drastically increased with the increasing time and temperature.

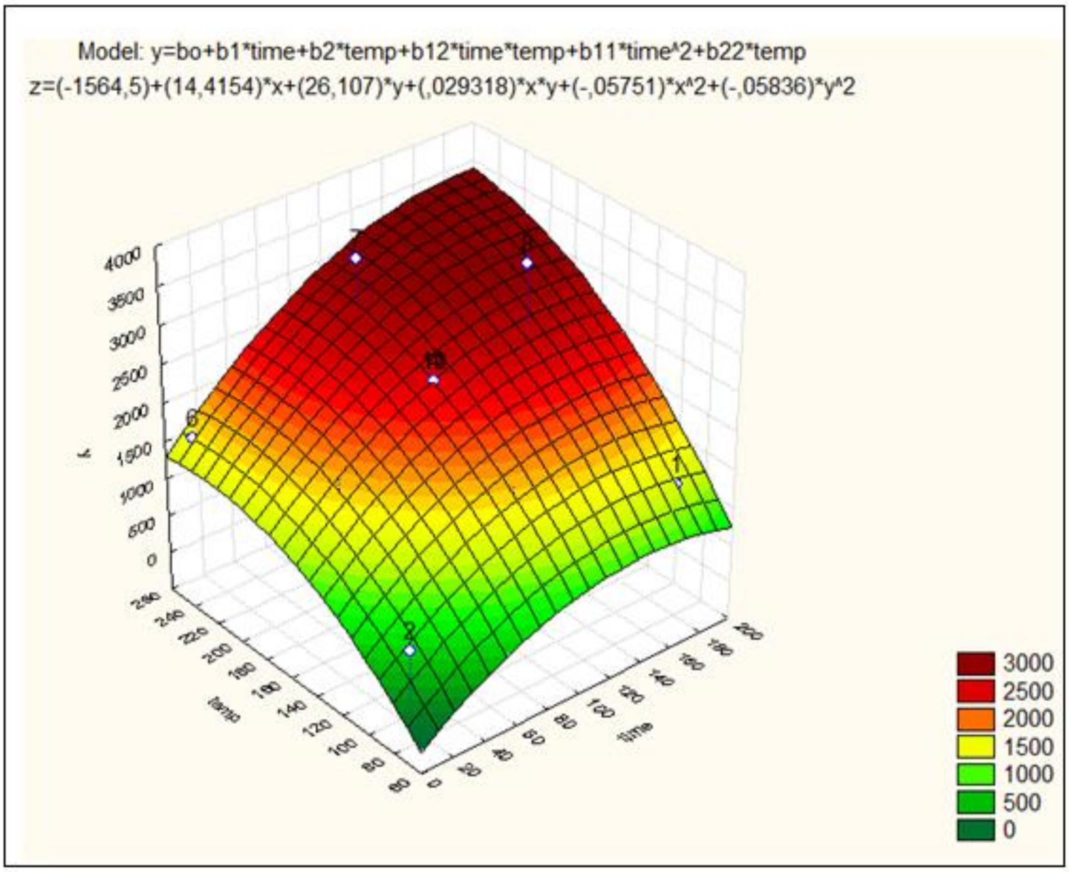

Figure 5.53 Relationships between drying time, temperature, and HHV of sludge in original base.

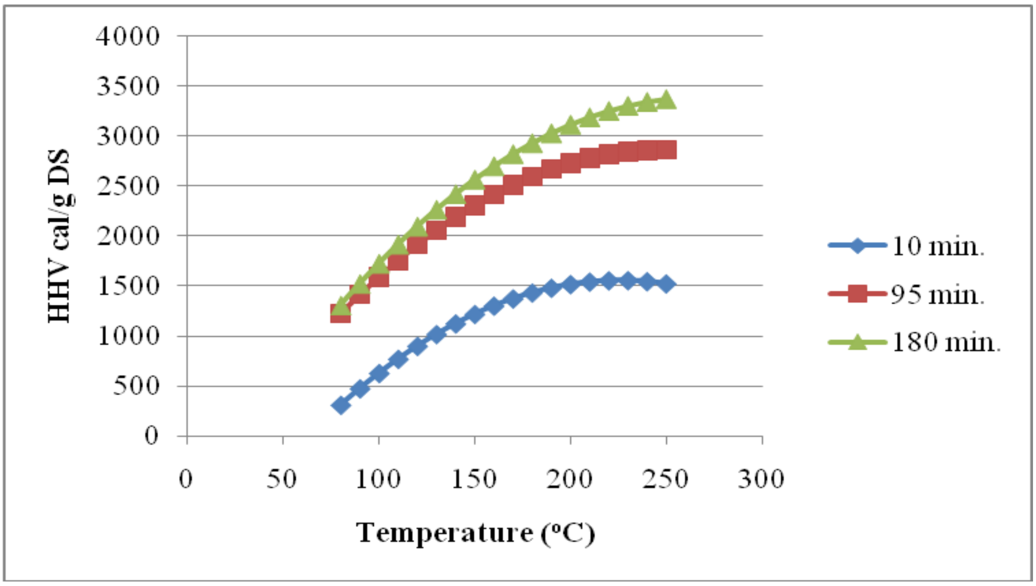

Figure 5.54 The effect of temperature on HHV of sludge in original base

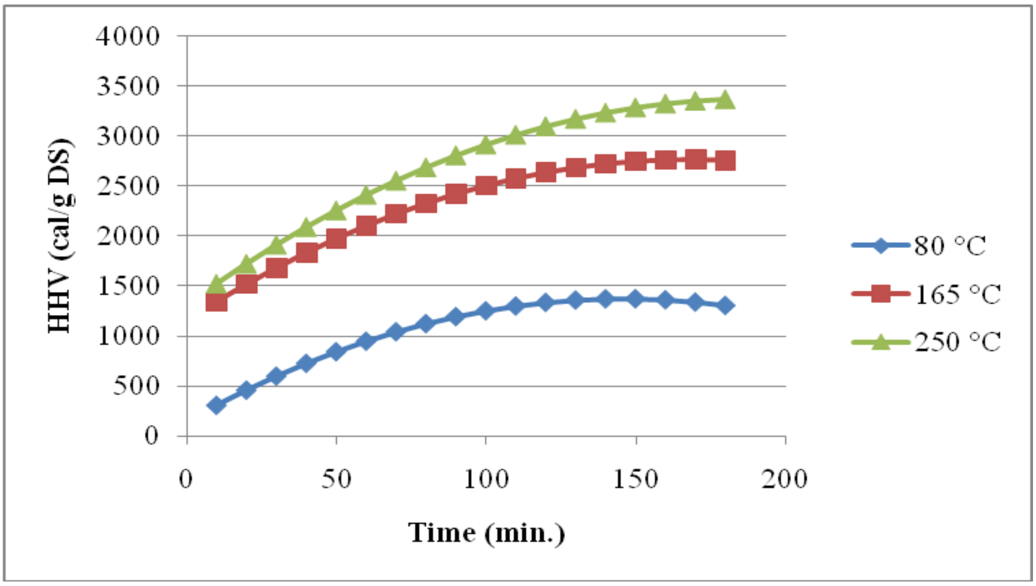

Figure 5.55 The effect of drying time on HHV of sludge in original base

d) High Calorific Value of Sludge in Dry Base

The estimated coefficients of the response functions and the predicted values of HHV in original base are shown in Tables 5.27 and 5.28, respectively. The regression coefficient was obtained as R^2= 0. 86696. Predicted and experimental values of HHV results were in good agreement.

Table 5.27 Coefficients of the response functions for HHV of sludge in dry base

B_O	B_1	B_2	B_{12}	B_{11}	B_{22}
2935.7544	4.5419	6.4534	-0.0175	-0.0136	-0.0184

Table 5.28 Predicted and residual values for high calorific value of sludge in dry base in the first experimental study

Time (min.)	Temperature (^{o}C)	Predicted Value	Residual Value
180	80	3457.605	3.349
10	80	3364.019	65.981
35	165	3539.456	-113.932
95	165	3532.100	24.900
180	250	2983.423	-53.423
10	250	3396.612	9.209
95	225	3387.776	55.224
155	165	3426.655	63.525
95	105	3543.631	-105.631
95	165	3532.100	24.900
95	165	3532.100	25.900

Relationships between drying time, temperature and HHV of dried sludge samples in dry base are shown in Figure 5.56. HHV results of dried sludge samples as a function of temperature and drying time are shown in Figures 5.57 and 5.58, respectively. The model results showed that the HHV values in dry base drastically decreased with the increasing time and temperature although slight increases in HHV were obtained with the mediocre level increased time and temperatures.

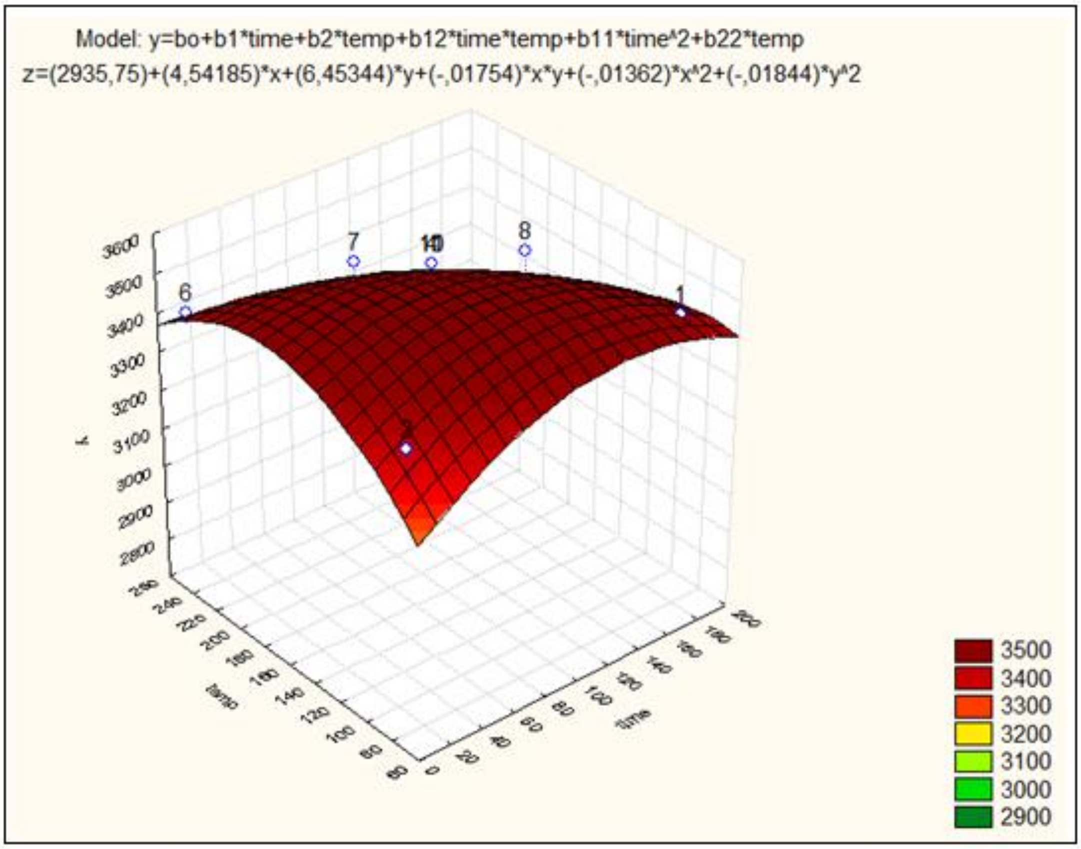

Figure 5.56 Relationships between retention time, temperature and high calorific value of sludge in dry base.

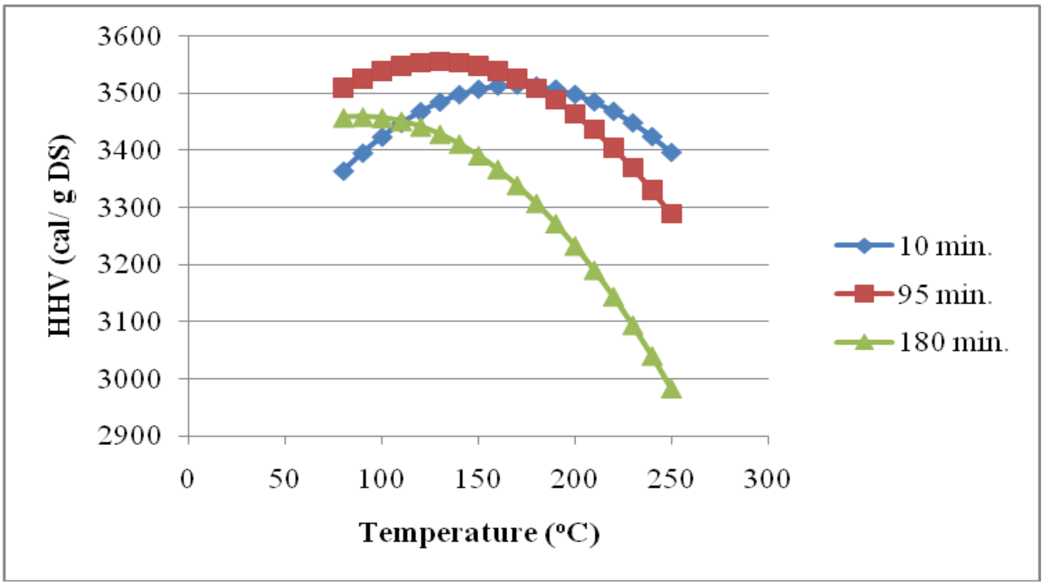

Figure 5.57 The effect of temperature on HHV of sludge in dry base.

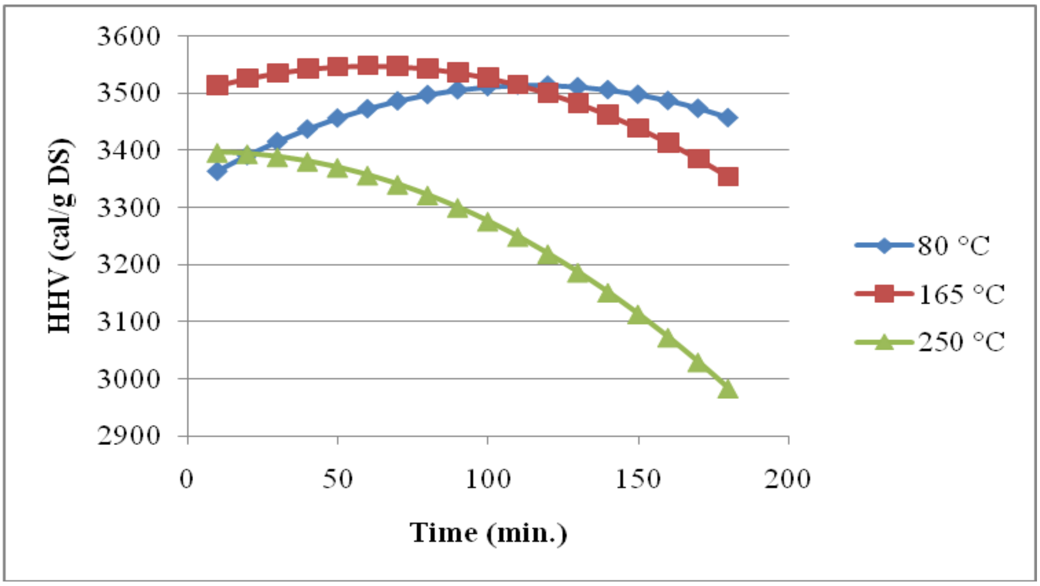

Figure 5.58 The effect of drying time on HHV of sludge in dry base.

5.4.4 TGA Analyses Results

The results of TGA for the sludge cakes are given in Figures 59 and 61 for different dying time and temperature conditions. It is clear from the figures that depending on the drying time increasing, water content and weight of the sample also decreased. At the same drying time, the increases in the temperature cause drastically increased in the DS content of sludge which means led to the lower water contents and weight.

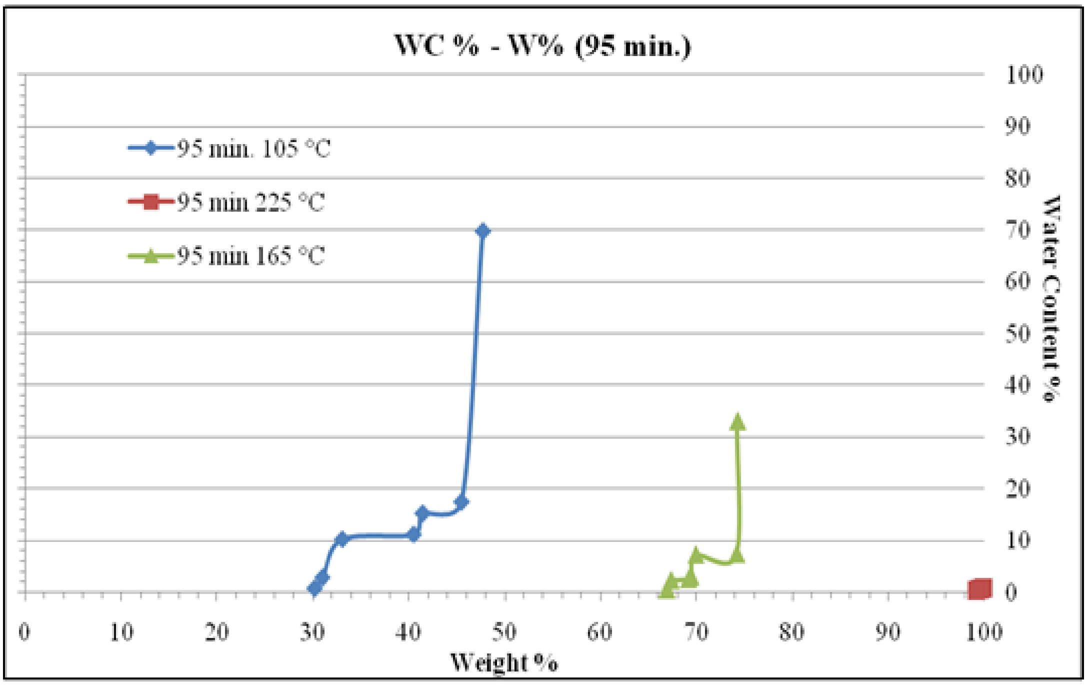

Figure 5.59 The decreases in the water content of sludge at the same drying time (95 min.)

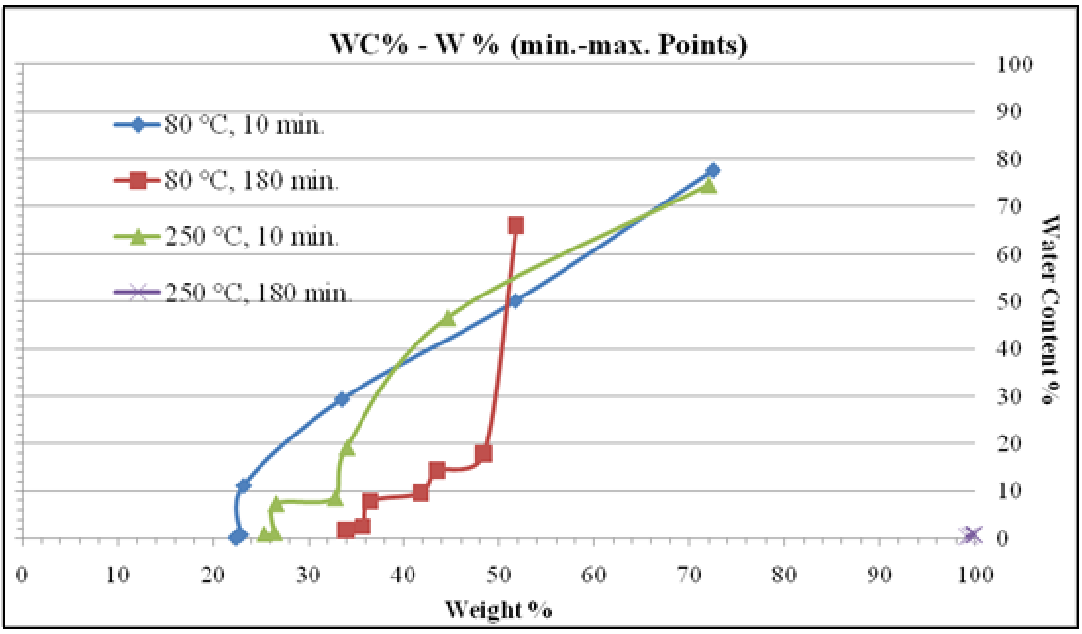

Figure 5.60 The decreases in the water content of sludge at different drying time and temperature

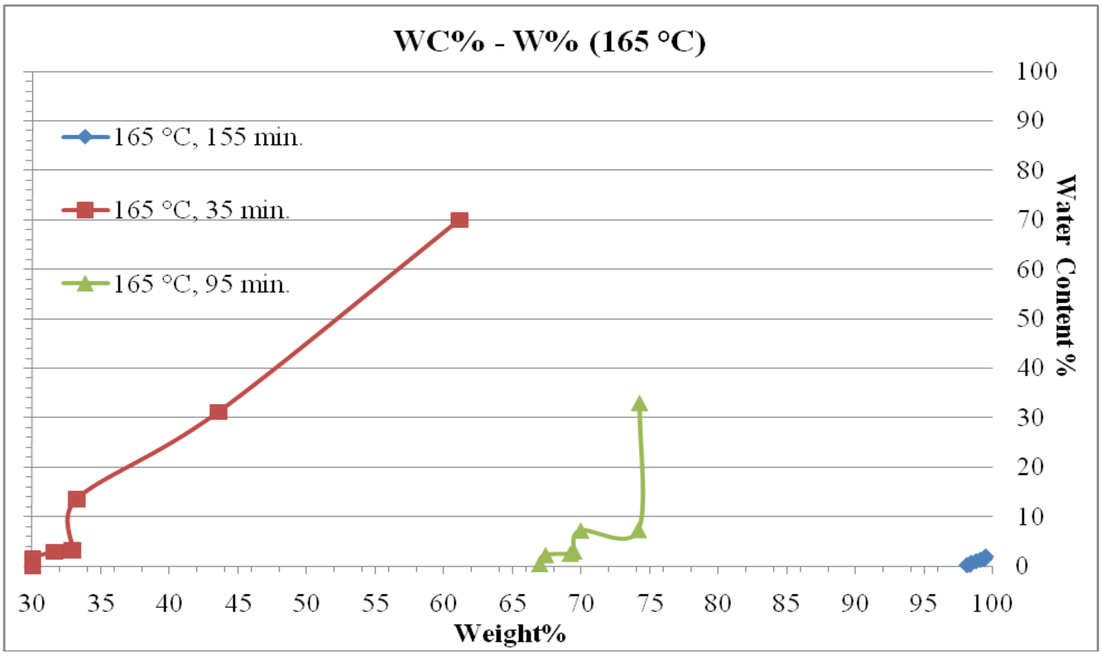

Figure 5.61 The decreases in the water content of sludge at the same drying temperature (165 ^{o}C)

The evaporation (drying) rates were also derived from the TGA data. The evaporation rates as a function of time are given in Figures 5.62 and 5.64. The decreasing evaporation rates showed that the moisture to be removed from the sludge is at very low level. At the higher drying times, the evaporation rates are lower when comparing it at the lower drying times. These curves have shown that the increased temperatures caused better water removal from sludges.

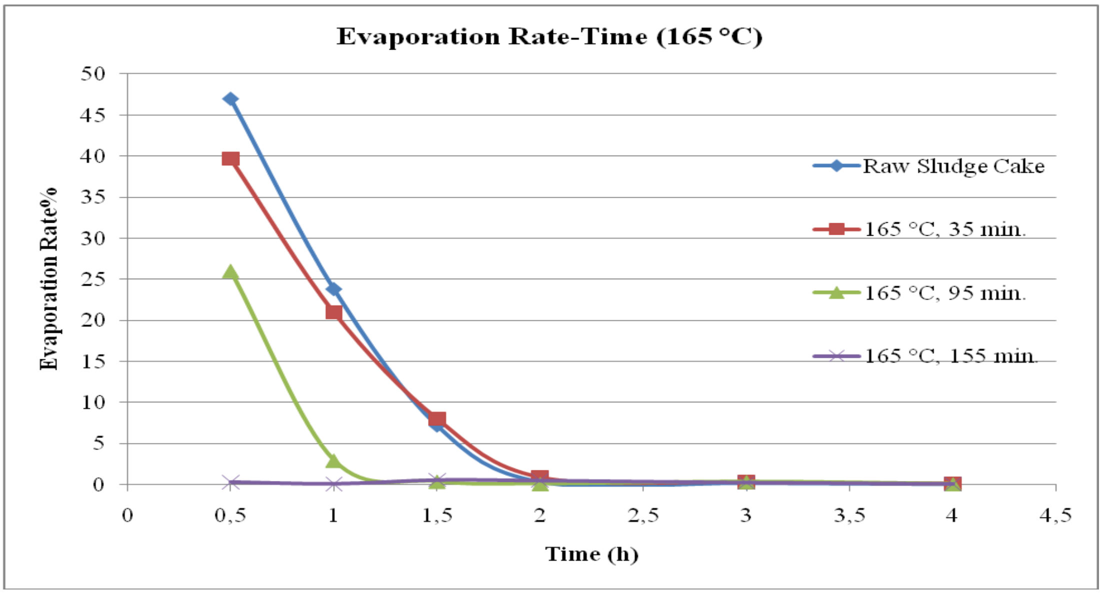

Figure 5.62 The evaporation rate as a function of time at 165 ^{o}C of drying temperature.

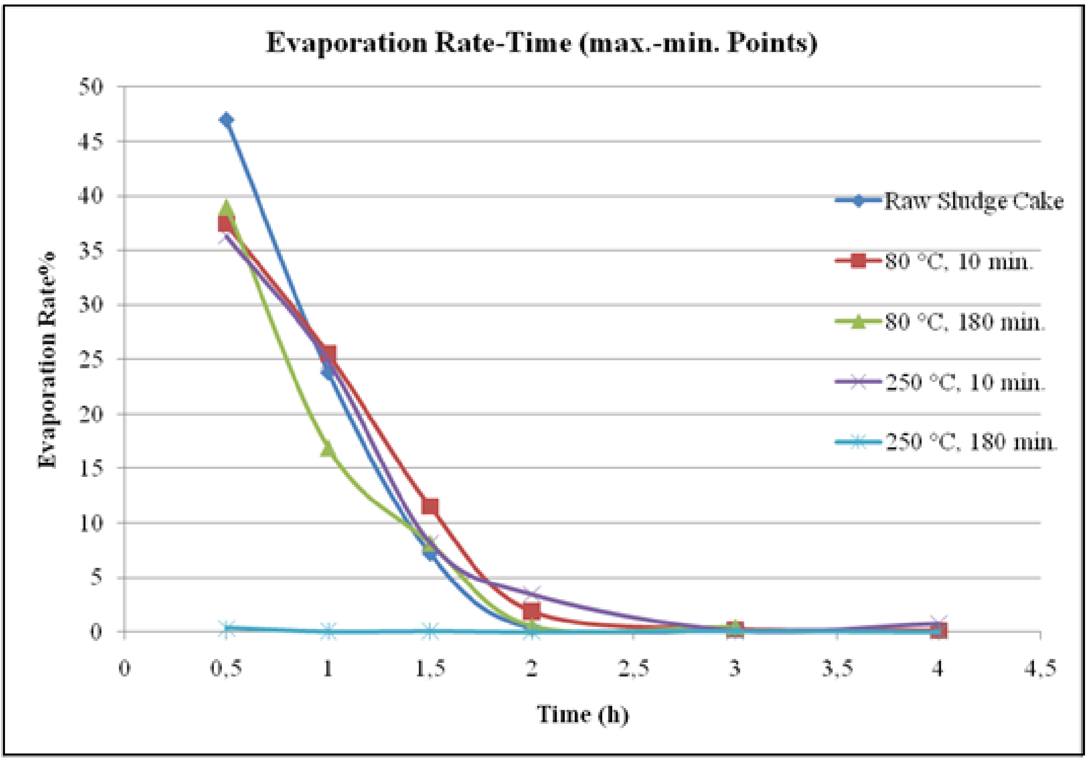

Figure 5.63 The evaporation rate as a function of time at different drying time and temperatures.

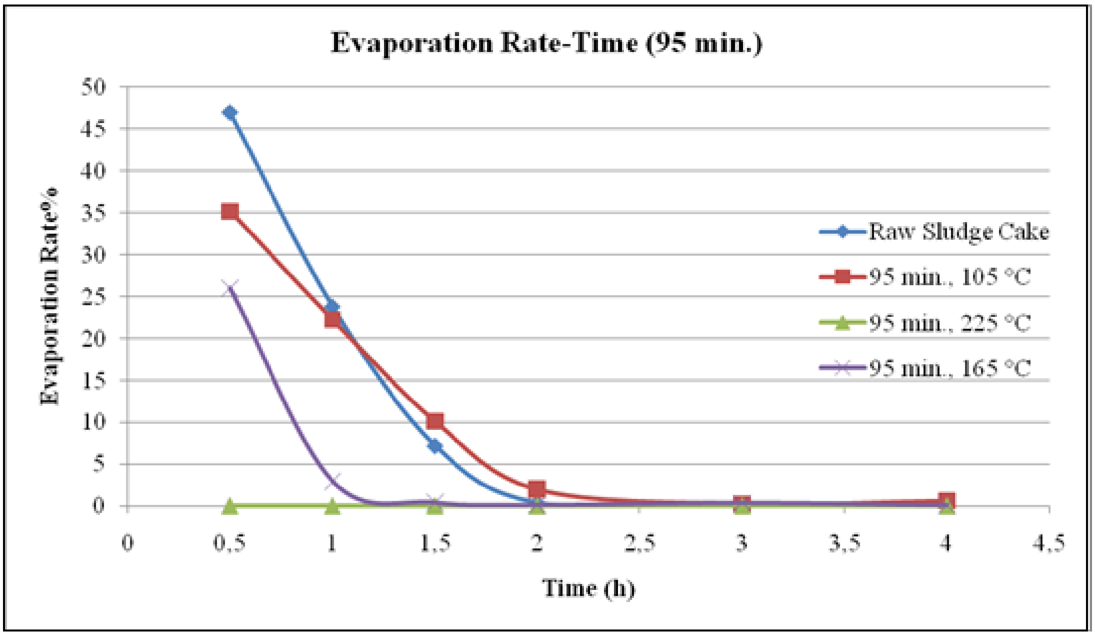

Figure 5.64 The evaporation rate as a function of time at 95 min. of drying time.

CHAPTER SIX
CONCLUSIONS and RECOMMENDATIONS

6.1 Conclusions

Time and temperature effects on sludge drying were examined in this study. Two experimental studies were carried out at different operational conditions. The first experimental study, in which retention time range was selected between 10-120 minutes and temperature range was between 50-180 ^{o}C was realized. In a similar way, the second one has a range of time from 10 to 180 minutes and a temperature range between 80 to 250 ^{o}C. In both of these studies, the Box Wilson statistical method was used to determine the operational conditions in which the experiments were done. Experimental results showed that the usage of the drying process as a final treatment or improved the sludge qualifications. The concluding remarks from this thesis can be given as follows:

- The first experimental study showed that the raw sludge cake has 23.84% DS while the maximum DS% (92.19%) was achieved in the maximum drying time and maximum temperature conditions which were 120 minutes and 180 ^{o}C.
- When the temperature was kept at 115 ^{o}C- which was the central point of temperature- the higher DS% was achieved as 48.1%DS at 104 minutes. Similarly when the drying time was kept at 65 minutes which was the central point for time, the higher DS% (54.8%) was achieved at 161 ^{o}C.
- The first experimental study results were run in the statistical programme and the results showed that the drying temperature and time increases affected the dry solid contents of sludge.
- In the first experimental study, although VS of the raw sludge cake was 47.0%, the maximum VS of was achieved as 53.03% in 104 minutes and at 115 ^{o}C.
- When the drying time was kept at 65 minutes which was the central point for time, the higher VS (52.96%) was achieved at 69 ^{o}C.
- The first experimental study results were run in the statistical programme and the results showedthat temperature and time increases do not sharply affect volatile solid content of sludge.

- The first experimental study showed that both parameters, time and temperature, are very effective when the low calorific value of sludge in original base is considered.
- Similarly according to the statistical programme results when the drying time and temperature increased, the high calorific value of sludge in original base increased.
- In contrary, when the time was at lower values and temperature was at higher values, low calorific value of sludge in dry base was affected negatively.
- In a similar way the rising of high calorific value of sludge in dry base was observed at lower temperature with long drying time and the decrease of high calorific value of sludge in dry base was observed with the rising of temperature.
- The second experimental study showed that DS content of raw sludge cake was 21.72%. The maximum DS was achieved as 99.9% at the maximum drying time of 180 minutes and the maximum temperature of 250 ^{o}C.
- When the temperature was fixed at 165 ^{o}C- which was the central point of temperature- the higher DS content was achieved as 99.0% at 155 minutes. Similarly when the drying time was applied as 95 minutues, which was the central point for time, the higher DS content (99.1%) was achieved at 225 ^{o}C.
- The second experimental study results were run in the statistical programme and the results showed that the increases intemperature and time led to increased dry solid content values.
- The second experimental study also showed that the raw sludge cake has has 57.67% VS. the maximum VS content was obtained as 60.74% in 180 minutes of drying time and 80 ^{o}C of temperature.
- When the drying time was kept at 95 minutues, which was the central point for time, the higher VS was obtained as 59.4 % at 105 ^{o}C.
- The second experimental study results were run in the statistical programme and the results showed that the maximum temperature and time applications affect the volatile solids content of sludge, negatively.
- Experimental results showed that the low calorific value of sludge in original base and high calorific value of sludge in original base increased with the increasing drying time and temperature.

- In contrary, when the time and temperature were at lower values, low calorific value of sludge in dry base affected, negatively.

6.2 Recommendations

In order to improve this study, the following future work can be done:

- Drying kinetics of sludge can be determined.
- Experimental studies were done in laboratory scale; for future work, a pilot scale dryer might be designed.
- Since the drying process has high capital investment and operation costs, it may be beneficial to carry out a cost analysis in addition to investigation of sludge drying properties.
- Different operational conditions may be applied to sludge samples in order to find out the optimum conditions.
- Air pollution should be controled during the drying process and odor emissions from the process can be analyzed.

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