# COMPARISON OF SLUDGE DRYING PERFORMANCE BETWEEN MICROWAVE AND CONVECTIVE DRYING

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## ABSTRACT

Drying of the sludge which reduces its volume and mass is an important aspect for sludge management. Experiments were carried out to compare the efficiency between microwave and convective drying. The results showed that microwave drying is more efficient than convective drying up to about 30 times. This is mainly caused by the different drying mechanisms. Microwaves penetrate into the total mass of sludge and cause water molecules to vibrate rapidly. Vibration of water molecules creates frictional heat and sludge heated volumetrically that avoids limitations of the poor heat conductivity of the material. It was clearly indicated by the core temperature profiles during drying. In microwave drying, the core temperature achieved 85°C in less than one minute, while convective drying took about 500 minutes to achieve the same temperature. Higher power level of microwave gave higher drying rate. Hence, the energy and time required for the drying process were reduced significantly.

**Keywords:** microwave; convective; drying; core temperature; sludge treatment

## INTRODUCTION

The safe and economical disposal of sludge has always been of major concern. Industries face huge problems of sludge waste disposal due to its high disposal costs. Most of this sludge contains high percentage of water, up to 90% wet basis (wb) in certain cases. Hence, the industries could save up to 90% of the disposal costs by removing this water. Municipal wastewater treatment plants operated by Indah Water Konsortium generate a large quantity of sludge. Each year, Malaysia produces 3.2 million cubic meters of domestic de-watered sludge and this figure will increase to 4.3 million cubic meters by the year 2005. The current method of sludge drying using sand bed is not effective and requires large spaces. Thus, new treatment technology has to be developed to manage this amount of sludge.

Mechanical de-watering is the first stage of sludge drying. Water is removed from sludge mechanically by using equipment such as belt filter presses or decanter. In this stage, sludge can be reduced to a level of about 80% water content (wb). One of the options for sludge waste disposal is incineration due to environmental pressures and lack of landfill areas [1]. Incineration converts de-watered sludge into ash as well as drastically reducing the volume and mass of residual solids materials. The de-watered sludge with approximately 80% water content (wb) is considered too wet to be incinerated due to its low calorific value. Thus, more auxiliary fuel is needed to evaporate water from the sludge, directly increasing the treatment costs. Further drying is therefore required prior to incineration process. Convective drying is applied after the mechanical de-watering. The rate of internal heat transfer is always the limiting factor during convective drying. As the free water is exhausted at moisture content (wb) less than approximately 30%, the bound or hygroscopic water will evaporate. Thus, the drying rate during this stage decreases. In order to increase further the rate of sludge drying, the rates of internal heat and mass transfer have to be increased.

Microwaves cover a region of frequency range from 300 MHz to 300 GHz in the electromagnetic wave spectrum. For drying purposes, microwaves always operate at frequencies of 915 MHz and 2450 MHz. Microwave drying is characterised by rapid volumetric heating (from the inside out) within the material that avoids surface limitations. Microwaves interact with dielectric material such as water and giving up energy to increase the material's temperature. There are two main mechanisms occurring when microwaves produce heat in dielectric materials: ionic polarisation and dipole rotation. Water forms a polar component of sludge material and its molecules vibrate at the rate of the microwave frequency as an alternating electric field is applied [2]. The vibration of the water molecules by the microwaves creates heat and thus increases the molecular energy of the water. This tends to weaken the attraction between the substance and the water, thereby aiding the migration of the water molecules to the surface. When applied to drying, it results in a high thermal efficiency and a shorter drying time.

This study mainly focuses on the analysis of the effectiveness of different parameters and drying mechanism of the sludge drying process. Microwave drying as an alternative application instead of convective drying was investigated for process efficiency study. Results were discussed from the aspects of core temperature profiles, drying curves and drying rate curves.

## METHODOLOGY

### Sludge Sample

Sludge sample was obtained from Indah Water Konsortium municipal wastewater treatment plant which located in Lima Kedai, Gelang Patah, Johor. This sludge was shaped into sphere with a diameter of about 4.0 ± 0.1 cm and weight approximately 37.5 g at average initially moisture content of 3.3 g $H_2O$/g dry solid. All samples used for the experiments were from the same batch of sludge.

### Apparatus

The performance of convective drying of sludge was investigated in a pilot plant scale tray dryer (Armfield, UK) as illustrated in Fig. 1. The dryer consisted of a proportional controller controlling the temperature and airflow. Experiment was operated at airflow of 0.7 m/s and operation temperature at 85°C (dry bulb) and 40°C (wet bulb). The microwave drying experiments were performed in a microwave oven model SHARP R-958A (Fig. 2) operated at 2450 MHz. The microwave oven cavity had a dimension of 410 mm × 245 mm × 410 mm (approximately 1.5 cubic feet) fitted with air circulating fan. Experiments were carried out at different power levels. The sludge was placed in a microwave-safe plastic plate inside the cavity and hung to a digital balance which is incorporated above the oven.

A shielded thermocouple with a 1 mm diameter probe was used to measure the core temperature. For microwave drying experiments, the thermocouple was inserted into the oven through a small hole with a 2 mm diameter. The thermocouple was modified to prevent electromagnetic effect from overheating the shielding metal and arcing. Any conductor in microwave environment will experience overheating when surface current of high magnitude flows in it. On top of this, induced voltage on the conductor will produce sparks, particularly at sharp points or edges where charges may accumulate on those spots. To keep the thermocouple from overheating, conductor with high conductivity was used. Thus, the part of thermocouple probe inside the microwave environment was covered by a 3 mm diameter copper tube. The copper with low resistivity (1.7 μΩ·cm) can tolerate the current flow without overheating and also by grounding the copper tube at one end, the problem of induced voltage was minimised.

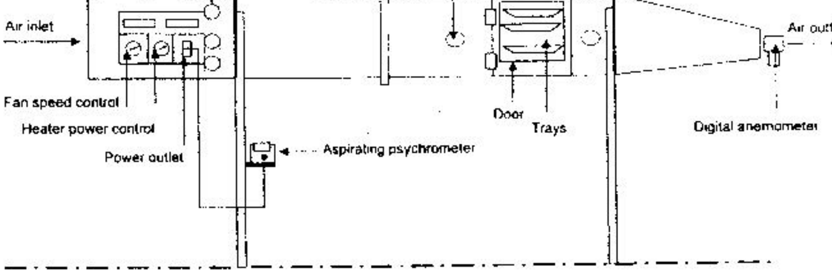


**Fig. 1: Schematic diagram of tray dryer.**

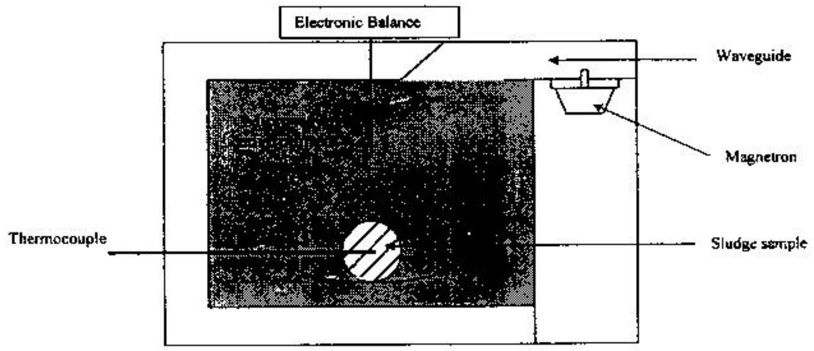


**Fig. 2: Schematic diagram of microwave oven.**

## RESULTS AND DISCUSSION

### Output Power Determination

The different power setting of the oven is done as a simple on-off operation. The oven is turned on at full power for some time during the cycle of 32 seconds and switched off during the rest of the cycle [3]. The time fraction of on-off operation represents the duty cycle as defined as:

$$\text{Duty cycle} = \frac{t_{on}}{t_{on} + t_{off}} \quad (1)$$

One litre water with initial temperature of 31°C was heated in the middle of oven at different power levels for 320 seconds. The results of the experiments are tabulated in Table 1. Some assumptions were made to evaluate the output power. The output power was assumed to be totally absorbed by the water; the $C_p$ of water held constant and heat loss to environment was ignored. By measuring the temperature rise in °C, the output power was determined by the following equation:

$$P = C_p \Delta T m/t \quad (2)$$

By substituting $C_p$ = 4183 J/kg·K, m = 1 kg and t = 320 s, the Eq. (2) can be simplified to:

$$P = 13.072 \times \Delta T \quad (3)$$

**Table 1: Microwave oven output power determination.**

| Power Level | $t_{on}$ (s) | $t_{off}$ (s) | Duty Cycle | $\Delta T$ (°C) | Output Power (Watt) $P = C_p\Delta Tm/t$ |
|---|---|---|---|---|---|
| High | 32 | 0 | 1.0000 | 52 | 679.74 |
| Medium High | 24 | 8 | 0.7500 | 38 | 496.73 |
| Medium | 18 | 14 | 0.5625 | 28 | 366.01 |
| Medium Low | 12 | 20 | 0.3750 | 19 | 248.37 |
| Low | 6 | 26 | 0.1875 | 7 | 91.50 |

From the data above, the output power is proportional to duty cycle that represented in an empirical equation below:

$$P = 666.02 \times \text{duty cycle} \quad (4)$$

**Core Temperature Profiles**

Core temperature poses an important role in a drying process. The core temperature profiles of sludge for microwave and convective drying are shown in Fig. 3.

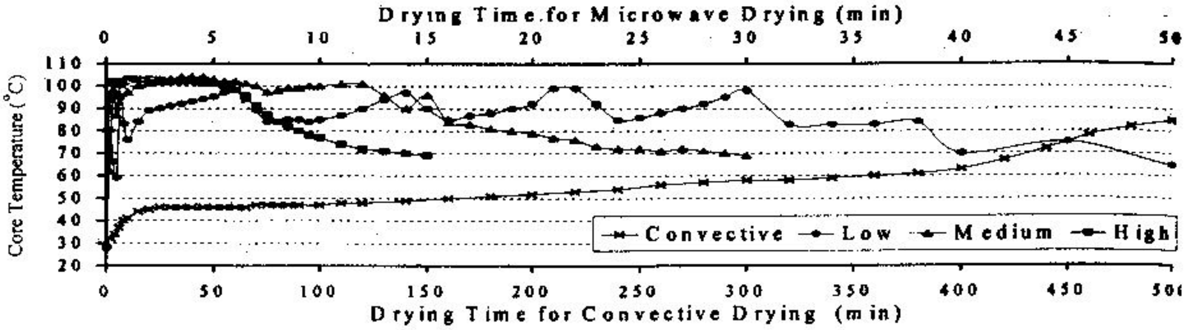


**Fig. 3: Core temperature profiles for microwave and convective drying.**

In convective drying process, heat is transferred to surface of sludge through convection and from surface to the core of sludge by conduction. Sludge is a low thermal conductivity material. Its core temperature increased gradually and achieved cavity temperature of 85°C in around 500 minutes.

All power levels of microwave drying have shown an advanced increasing of core temperature initially. The core temperature increased rapidly and achieved the temperature of 85°C in less than one minute after drying. This is due to the microwave energy coupled directly into the core of sludge and overcomes the surface limitations. After that, the core temperature reached the boiling point of water several degrees in excess of 100°C because the sufficient pressures may develop in the core [4]. The core temperature remained in a plateau level and then decreased gradually. This phenomenon can be explained with the thermal energy balance equation below:

$$\text{Energy accumulation, } \Delta E = E_G + E_I - E_O \quad (5)$$

where, $E_G$ is the energy generated by microwave heating, $E_I$ is the air-particle heat transfer (transfer direction from air to particle is positive and vice versa), $E_O$ is energy loss due to evaporation (always greater than 0). A positive $\Delta E$ leads to an increase in temperature [5].

Initially, sludge temperature was less than air temperature ($E_I > 0$) and moisture content was high. Therefore, $E_G$ was relatively high. As a result, the core temperature increased rapidly within the first minute ($\Delta E > 0$), although there was heat loss due to evaporation. Later, the core temperature remained stable. The generated energy, $E_G$ due to microwave heating was balanced by evaporative cooling and heat transfer from sludge to air ($\Delta E \approx 0$). The core temperature reduced gradually during the end of drying, as the moisture content in sludge get lesser, thus resulted the $E_G$ decreased. Thus, the core temperature was reduced due to the evaporative cooling and heat transfer from sludge to air ($\Delta E < 0$).

The non-stable of the core temperature indicated in Medium and Low power was caused by the on-off operation. During the time on of microwave generation, the core temperature increased while it decreased when the power switched off. For lower power, the core temperature reduced slower because of the moisture content reduction lasted for a longer time.

**Drying Curves**

The microwave and convective drying curves which represented by moisture content in dry basis (db) versus time are shown in Fig. 4.

The surface of the sludge was initially at high moisture content. These water molecules were unbounded and it can be easily evaporated as heat was transferred to them. This constant-rate period will continue as long as water molecules supply from the interior of the sludge is as fast as the rate of water evaporated [6]. Materials with comparatively good mass and thermal diffusivity give a longer constant-rate period and vice versa.

The drying process proceeded to the falling-rate period when the rate of water molecules moved towards surface started to decrease and the surface was no longer wetted. The amount of moisture removed during the falling-rate period was relatively small but the time and heat requirement were large. This ineffectiveness encountered in convective drying was due to the low diffusivity and low capillary forces of the sludge.

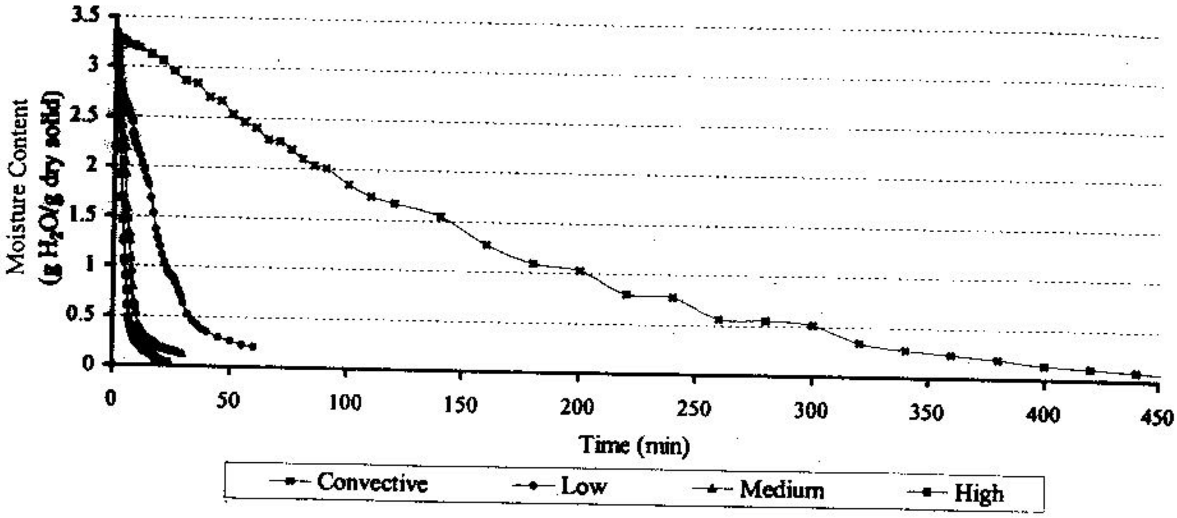


**Fig. 4: Drying curves for microwave and convective drying.**

Microwave drying is more effective than convective drying of sludge. The sludge moisture content of 10% (db) could be achieved in about 15 minutes using microwave energy (High power level) compared to 450 minutes using convective drying. Drying time for the process could be reduced up to approximately 30 times. Microwave energy penetrates into the total mass of sludge and vibrates the water molecules inside extremely fast. Frictional heat was then generated. Sludge was heated inside out, a total pressure gradient was created and water molecules were forced to migrate to the surface, where evaporation removes the water. This was totally different with convective drying, which heating was outside in, whereas the sludge thermal conductivity was so poor.

At higher power level, the drying curve was steeper. But they tended to end at about the same time. The similar result was obtained by other researcher in microwave drying using banana as sample [7]. An empirical equation that expresses the time required to complete the drying for different moisture content at different output power is derived as below:

$$t = 1000kP^{n} \qquad (6)$$

where, $k = 1.67M^{-0.43} - 1$ and $n = 0.09M - 0.85$

**Drying Rate Curves**

From the tangents of drying curves, which give values of dM/dt at given values of t, the drying rate curves can be obtained by calculation using Eq. (7) and plotted against moisture content (db) as shown in Fig. 5.

$$R = -W_s \frac{dM}{dt} \qquad (7)$$

Fig. 5 shows a significant difference between drying rates of microwave and convective drying techniques. Average drying rate over the period of convective drying was approximately 0.1 g $H_2O$/min, while microwave drying were 4.0, 2.7, 0.7 g $H_2O$/min for High, Medium and Low power level respectively. The results indicated that mass transfer within the sludge was more rapid during microwave drying compared to convective drying.

Sludge underwent shrinkage as moisture removed from it. A hard layer developed on the surface which is impervious to the flow of moisture and hence slows the mass transfer rate. This presents a barrier to moisture migration and is known as case hardening [6]. The core temperature of sludge was relatively cold than ambient condition. Thus, a pressure gradient was not developed to accelerate the migration of moisture from interior part.

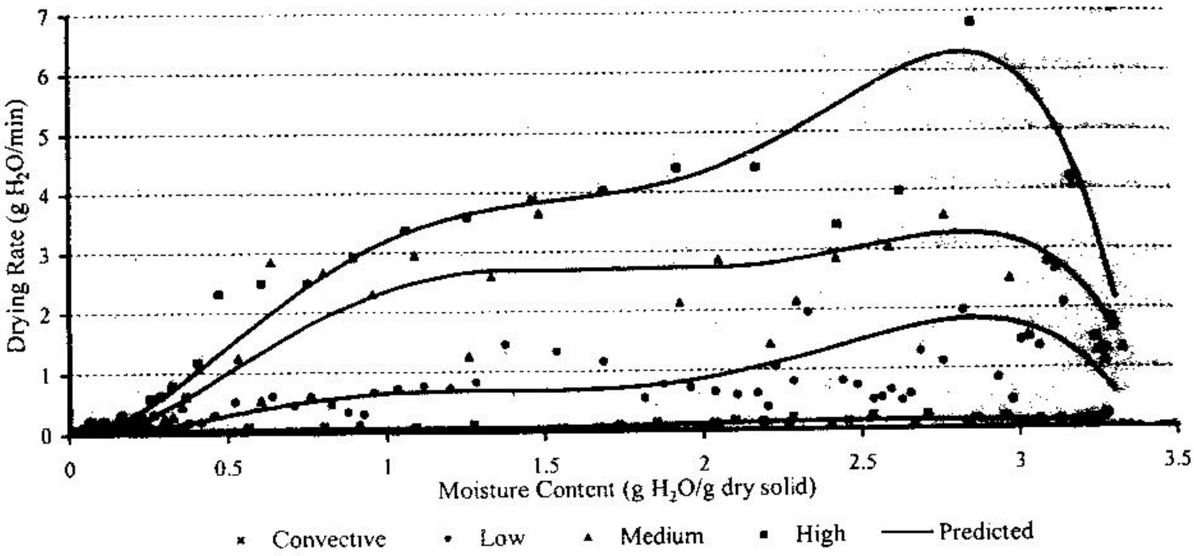


**Fig. 5: Drying rate curves for microwave and convective drying.**

In microwave drying, the core temperature of the sludge approached the boiling point of the liquid within one minute and creating a large vapour pressure differential between the core and the surface of sludge [8]. Mass transfer was now driven by the total pressure gradients. Moisture was forced to migrate towards the surface due to rapid formation of the vapour phase inside the sludge, even removed as liquid when the material contains very high water content. During this period, the rate of moisture removal increased beyond the constant-rate limit, which we called liquid movement period that does not exist in convective drying. The drying process proceeded to constant-rate period where moisture supply from interior to surface continuously to replace the water being evaporated. Hence, the time consumed during the falling-rate period had been greatly reduced.

## CONCLUSIONS

The microwave drying overcame the surface limitations, shortened the falling-rate period and increased the drying performance significantly. Generally, the process efficiency could accelerate up to about 30 times using microwave High power compared with convective drying. In microwave drying, core temperature achieved 85°C in less than one minute, while convective drying took about 500 minutes to achieve the same temperature. The output power of microwave oven was empirically found to be proportional to the duty cycle. An empirical equation has been derived to estimate the drying time for required moisture content with different output power. Industrial microwave application in sludge drying is more efficient than conventional convective method. Hence, the energy consumption can be reduced. The energy saved reduces the utilisation of fossil fuel that consequently contributes to a cleaner environment.

## NOTATION

| | |
|---|---|
| $C_p$ | Heat capacity, J/kg·K |
| db, wb | dry and wet basis, dimensionless |
| $\Delta E$ | Energy accumulation, J |
| $E_G$, $E_I$, $E_O$ | Energy generation, in and out, J |
| k, n | Correlation factors, dimensionless |
| M | Moisture content (db), g $H_2O$/g dry solid |

| | |
|---|---|
| m | Mass of water, kg |
| P | Output power, Watt |
| R | Drying rate, g $H_2O$/min |
| $\Delta T$ | Temperature rise, °C |
| t | Time, s |
| $t_{on}$, $t_{off}$ | Time on and off of microwave generation, s |
| $W_s$ | Weight of dry solid, g |

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