HEAT RECOVERY FOR AN EFFICIENT MICROWAVE PROCESS

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Introduction

Microwave heating is a dielectric heating.[1-3] The microwave energy converts into heat energy due to the polar structure of the molecules, atoms and ions. This heating is suitable for poor electrical conductors while induction heating is suited for good electrical conductors. The coupling vector for dielectric heating is the electric field and for induction heating the magnetic field. The transfer of energy occurs without intermediary heating elements and therefore the process has no inertia.

From the point of view of the product, two main factors are high energy transfer rates and the uniformity in the mass.[4,5] This allows fast and homogeneous heating to process temperature reducing process time, machine size and product degradation. The latter is also helped by the fact that the product remains stationary on a belt while heating. Main microwave functionalities provided to the industry are heating, drying, conditioning, thawing, tempering; gluing, sterilising, blanching, and sintering amongst others. As the sole energy input is electricity, the process can be performed with 100% renewable energy sources lowering CO_2 impact of the process.

One of the interesting candidates for microwave processing is the drying of slag material after water quenching and/or slag material that has been stored outside exposed to the elements. These slags contain a significant amount of water that needs to be removed in order to allow the material to be ground in a fine powder.[6] As the dielectric loss factor of water is in general higher than that of the slag material, it is primarily the water that will take up the microwave energy and heat up.[7] This allows for a fast and efficient drying process. Dielectric loss factor of a slag material is determined by its composition of elements and their chemical nature.[8-9]

Results and discussion

First generation microwave ovens only transfer energy to the product in the form of microwave radiation. With a well-balanced load it is possible to transfer close to 100% microwave energy to the product. Magnetrons of 2.45 GHz convert around 70% of the electric energy to microwaves, the rest is dissipated as heat. Combined with a

90% efficiency of the high voltage transformer brings the total electric energy efficiency to around 63%. Magnetrons can be water or air cooled.

Second generation microwave ovens reuse the hot air from cooling the magnetrons to create a “microwave - hot air” hybrid dryer. The hot air is blown into the cavity of the microwave oven to remove moisture in the cavity and prevent condensation on the (cold) walls, insulate the product against the colder environment and increase air flow and evaporation rate in the product. The faster evaporation rate increases drying speed while lowering process temperatures.

In conventional hot air dryer, energy transfer speed is proportional to the temperature gradients (Equation (1)). This means that high temperature gradients are required for fast energy transfer (and thus drying speed). This applies for energy transfer from hot air to product, but also from the surface of the product to the core of the product, whichever is slowest governs the energy transfer. Drying speed can also be increased by increasing product surface like is done in fluidised bed or spray drying. This is however not always possible or can have drawbacks like product fragmentation and dust generation.

$$T_{Air} - T_{product} = \Delta T \quad and \quad T_{surface} - T_{core} = \Delta T \qquad (1)$$

With microwaves, the energy transfer is governed by the local electromagnetic field (E_{loc}), frequency of the used electromagnetic waves (f), volume of the product (V) and dielectric loss factor (ε_2) (Equation (2)). Apart from dielectric loss factor that can change by product temperature, there is no influence of temperature on the energy transfer speed. This means that products can still be dried quickly at low temperatures.

$$P = 2.\pi.f.\varepsilon_0.\varepsilon_2.E_{loc}^2.V \qquad (2)$$

For the drying of slag materials there are two categories: The slag has either a low dielectric loss factor or it has a high dielectric loss factor. In the first case, the water will take up the bulk of the microwave energy, heat up and evaporate. As the water content lowers, the amount of energy absorbed also goes down until all the water is removed (V_{water} = 0) and the product cools down. In case of slag with a high dielectric loss factor, both the slag and the water will heat up but the slag will keep on heating after all the water is evaporated. In the first case, controlling the drying process is easy because the energy absorption is self-limiting. In the second case, the temperature or water content should be monitored to avoid a thermal runaway. Because of the higher energy uptake in the second case, the drying speed will be higher, especially towards the end.

In drying, a thermal runaway is not desired as the microwave dryer is generally not designed to handle very hot materials (> 150°C). For thermal processes at higher temperatures, it is desirable to have a material with a high loss factor as it makes the material easy to heat.

Microwave drying of slag materials is more energy efficient at low process temperatures for three reasons. Firstly, lower process temperatures require less energy to heat up the slag material. Secondly, less heat is lost during the process due to equipment heating, radiative loss *etc*. Thirdly, the loss factor of water is lower at higher temperatures, resulting in a reduced energy transfer at higher temperatures and more reflection losses of the microwave radiation.

Figure 1 shows three drying curves from slag material, performed in the MEAM Explorer. This is a 1.2 kW batch microwave with thermal IR camera, sample weighing and cavity openings that allow an adjustable air flow over the sample. For this experiment, input power is regulated to keep the sample at 55°C while drying. Drying with a hot air current (air temperature = 65°C) results in fast drying from 17.9% moisture to 1.69% moisture (wet weight). The input power was 1201 W on average. The cold air (12°C) drying was slower as still 8.68% moisture (wet weight) remained after 13 min drying. Power input was 371 W on average. Without air current over the sample, the input power was on average 341 W and 12.6% moisture remained (wet weight).

When a completely dry sample was heated in the MEAM explorer, the temperature increased to 125°C and stabilised there. Meaning the heat loss to the environment was equal to the microwave energy uptake at that temperature. The exact loss factor of the slag material was not measured but can be considered intermediate to low: it does heat up after the water is removed, but is too low to cause a thermal runaway.

An air current over the sample increases evaporation rates and allows a higher input power without increasing the drying temperature. The lower drying speed for the cold air sample was partly due to the lower air speed (1.07 m/s) compared to the hot air (1.84 m/s). Another reason is that for the same absolute moisture content, hot air has a lower vapor pressure for water than cold air and this will cause a faster evaporation of water in the sample and thus a greater evaporative cooling effect. Another way to lower vapor pressure of water is to decrease the pressure: vacuum microwave drying can operate at even lower temperatures.[10]

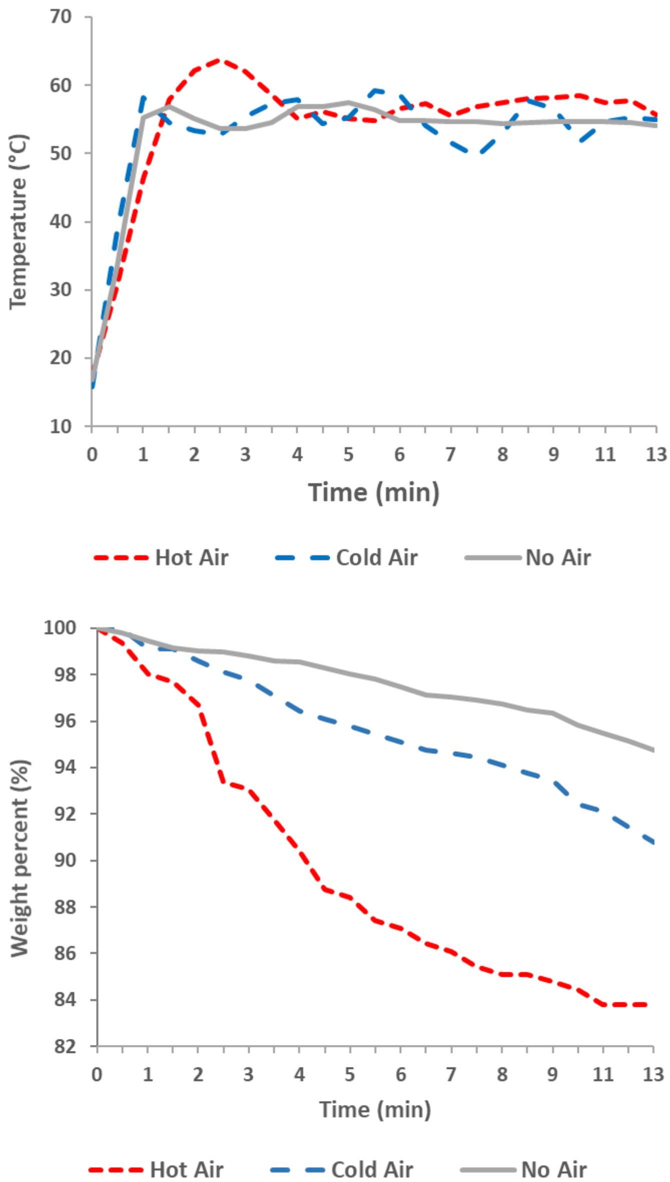

Figure 1: Influence of air current and temperature on microwave drying curves of slag material at 55°C

Figure 2: MEAM dry S48: a 71 kW microwave hybrid tunnel dryer with heat recuperation for preheating ingoing product

After using the waste hot air to increase evaporation rates and remove moisture from the cavity, it still contains a lot of usable energy. This energy can be used to preheat the ingoing product as long as the final temperature of the air remains above the dew point. This is why MEAM developed the “3th generation” microwave that can operate at an even higher efficiency by the addition of a heat recovery unit. A stable production run of 7.30 h was done on the MEAM dry S48 to determine the efficiency of the use of hot air and heat recuperation. The MEAM dry S48 has 22 air cooled magnetrons (1.8 kw MW power) and 2 water-cooled magnetrons (1.8 kW MW power). Total energy consumption of the machine at maximum capacity including electronics and fans is 71 kW.

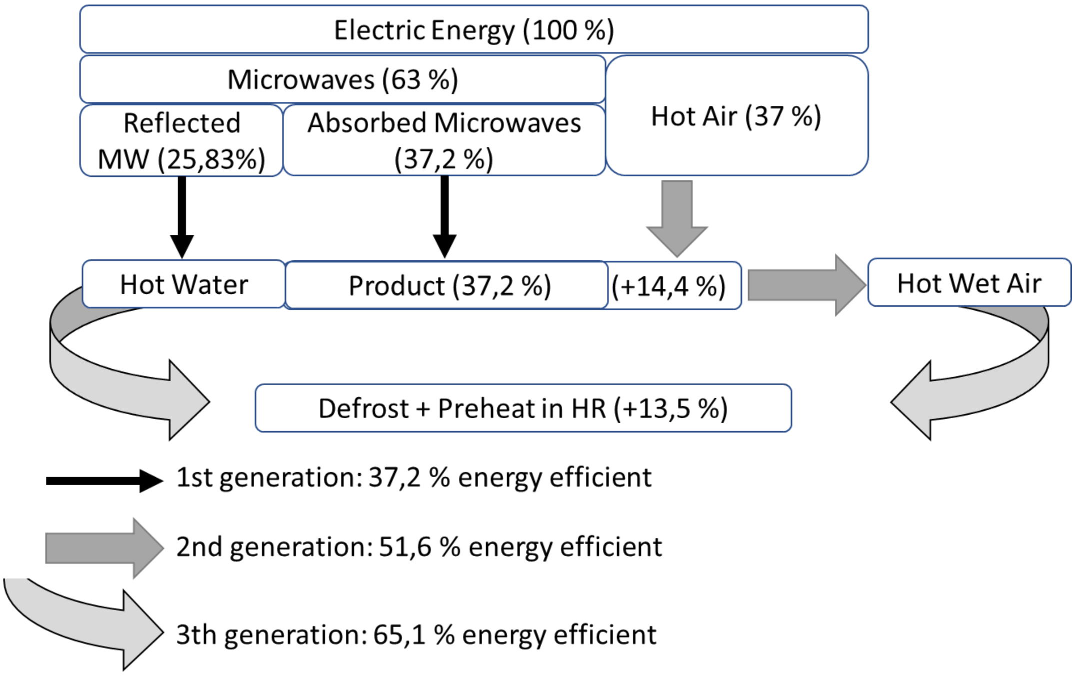

Figure 3: Experimental energy efficiency MEAM dry S48: a 66 kW microwave hybrid tunnel dryer with heat recuperation for preheating ingoing product

Frozen product (-5°C; 80% moisture) was dried to 16.6% moisture (dry based) with a final product temperature of 50.6°C. The theoretical energy requirements to dry the product is 1.89 MJ/kg product or 43 kW with a throughput of 82 kg of product/h. Power consumption of the MEAM dry S48 was 66 kW resulting in an electric energy efficiency of 65% in total. During the test the load of the machine was not well balanced, resulting in a high amount of reflected MW power (41%). The reflected power is absorbed in the isolator by cooling water. By better balancing the load of the machine, the reflected power can be lowered to less than 10% resulting in a much higher electric efficiency. Figure 3 shows the various energy flows and efficiencies in the machine, showing the efficiency gains for the use of hot air (+14.4%) and heat recovery (+13.5%).

Conclusion

Slag materials were dried under different airflow conditions at a fixed temperature. The evaporation speed was positively corelated with airflow and temperature, allowing higher microwave energy input when the sample was in a hot airflow while the drying temperature low. Slag material could be dried from 17.9 wt% moisture to 1.69% in 13 min at a drying temperature of 55°C. Production data on an industrial size microwave dryer shows that utilisation of waste hot air increases efficiency by 14.4%. If the material is to be defrosted before drying, another 13.5% gain in efficiency can be obtained by using heat recovery.

References

1. A. C. Metaxas, R.J. Meredith, *Industrial Microwave Heating, no. 4*, Institution of Engineering and Technology, 1983.
2. R. J. Meredith, *Engineers' Handbook of Industrial Microwave Heating*, Institution of Electrical Engineers, 1998.
3. A. C. Metaxas, *Foundations of Electroheat: a Unified Approach*, John Wiley and Sons, 1996.
4. R. S. Rao, *Microwave Engineering*, PHI Learning Pvt. Ltd., 2012.
5. T. Brazil, *Microwave Engineering,* John Wiley and Sons, 1995.
6. H. Wang, J. Wu, X. Zhu, Q. Liao, L. Zhao, "Energy-environment-economy evaluations of commercial scale systems for blast furnace slag treatment: Dry slag granulation vs. water quenching", *Appl Energy*, **171** 314-324 (2016).
7. X. Liao, G. Chen, Q. Liu, J. Chen, J. Peng, *"Investigation on drying characteristics of high titanium slag using microwave heating", Green Process Synth*, (October 2015).
8. K. Morita, M. Guo, Y. Miyazaki, N. Sano, "The heating characteristics of CaO-$Si0_2$-Fe_tO system slags under microwave irradiation"*, ISIJ Int*, **41** (7) 716-721 (2001).
9. K. Haque, "Microwave energy for mineral treatment processes a brief review", *Int J Miner Process*, **57** 1-24 (1999).
10. V. Goovaerts, "Control of evaporation temperature in a microwave vacuum drying system", 16^{th} AMPERE conference, 2017.