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EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY:
Microwave Heating/Microwave Drying

TECHNOLOGY CODE: 3.3.3.1/3.3.3.2

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1. Technology

1.1 Description of technology / working principle

(Feel free to modify/extend the short technology description below)

Microwave (or dielectric) heating of materials has been known for a long time and development of microwave ovens has more than 50 years of history.
In general, microwave frequencies range from 0.3 to 300 GHz, which corresponds to the wavelength between approximately 1 mm and 1 m. Much part of this range is occupied by the radar and telecommunication applications and in order to avoid interference the industrial and domestic microwave appliances operate at several standard allocated frequencies, most often at 2.45 GHz. Molecules that have a permanent dipole moment (e.g. water) can rotate in a fast changing electric field of microwave radiation. Additionally, in substances where free ions or ionic species are present, the energy is also transferred by the ionic motion in an oscillating microwave field. As a result of both these mechanisms the substance is heated directly and almost evenly. Heating with microwaves is therefore fundamentally different from conventional heating by conduction. The magnitude of this effect depends on dielectric properties of the substance to be heated.

Also in solid materials microwaves are used on industrial scale for heating purposes. The ability of the solid material to absorb the microwave heating depends on two properties: the dielectric constant and the loss tangent. Some materials absorb the microwave energy very easily; others are transparent or impermeable to it.

The difference in sensitivity of various substances to microwaves makes the latter an interesting technology for the selective heating of materials/products. For instance, dielectric drying of microwave-transparent materials can be done at low energy expense, since the energy of microwave is selectively absorbed by the moisture.

1.2 Types and "versions"

(Describe the most important forms/versions of technology under consideration, including their characteristic features, differences and similarities)

For heating/drying of materials multimode microwave ovens are commonly used, which can be broadly divided into two categories:

Continuous belt heaters/dryers
In this category a tape conveyor moves continuously through an oven composed of several cavities with magnetrons (see Fig. 1). Continuous belt units are equipped with power adjustments, smoke detectors and fire extinguishers, air pre-heating, central cooling air, microwave leakage detection, product-specific ventilation systems and temperature controllers.

Chamber heaters/dryers:
These devices operate in the batch mode. The material to be processed is placed either on a roller conveyor (Fig. 2a) or on the racks (Fig. 2b).

Fig. 1. Continuous belt heater/dyer (Linn High Therm)

(a)

(b)

Fig. 2. Microwave chamber dryers/heaters with roller conveyor (a) or with racks (b).

1.3 Potency for Process Intensification: possible benefits

(In Table 1 describe the most important documented and expected benefits offered by the technology under consideration, focusing primarily on energy; CO_2 emission and costs, providing quantitative data, wherever possible. Add other benefits, if needed).

Table 1: Documented and expected benefits resulting from technology application

Benefit	Magnitude	Remarks
Energy savings	**Substantial** in some cases, **97%** saving reported in manufacturing of fast-cooking rice	When used purely for heating of a non-reacting liquid, microwave requires ca. 30% more primary energy than the conventional steam heating (due to electricity as the intermediate stage). Here however, the microwave is used to heat up selectively the moisture in the processed materials. No or very little energy is dissipated in the bulk of the material.
	80%	Heat treatment of porcelain
	15-40% (primary energy)	Drying of wood and paper
Shorter processing times	Up to **75%**	Drying operations
	By a **factor of 3-13**	Microwave-assisted freeze drying
	By a **factor of 20**	Microwave drying of ceramic articles with complex geometries
	73%	Heat treatment of porcelain
Space savings	**50-90%**	
Cost savings	No industrial data so	

	far, however can be substantial (> 50%)	
Better product quality	No quantitative data	E.g. due to faster processing, in milder conditions. In ceramic products – reduced breakage rate due to absence of thermal gradients

1.4 Stage of development

Microwave furnaces for heating/drying purposes are available on the commercial scale from numerous equipment vendors.

2. Applications

2.1 Existing technology (currently used)

(Describe technology (-ies) that are conventionally used to perform the same or similar operations as the PI-technology under consideration)

In conventional processes heating is usually realized via the steam, flue gas or electrical heating. Also direct heating with gas burners is sometimes used. Drying is most often carried out in the convective way using hot air or flue gases in rotating kilns, drum or fluidized-bed dryers. Infrared dryers are also used.

2.2 Known commercial applications

(Is the technology broadly applied on commercial scale? In which process industry sectors is the technology most often applied: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? What is the estimated number of existing applications? In Table 2 provide the most prominent examples of realized applications and provide their short characteristics)

The microwave (pre)heating finds its applications in several sectors of process industry:

- Polymer & plastics industry (pre-heating of resins and rubbers, bonding, curing, welding, shrinking – see TR 3.3.3.4.3)
- Petrochemical and chemical industry (pre-heating of catalysts – see TR 3.3.3.4.2)
- Food industry (drying, cooking, tempering, pasteurization, sterilization, thawing)
- Pharmaceutical industry (esp. vacuum drying, see Fig. 3)
- Ceramics (drying, joining, sintering)
- Paper and wood (drying, glueing)
- Textile (drying, dye fixation, control of moisture content)

Fig. 3. Microwave vacuum dryer for pharamaceutical applications (Niro T. K. Fielder, Inc.)

Table 2. Industrial-scale applications of the Technology (existing and under realization)

Sector	Company - Process/Product name/type	Short characteristic of application	Production capacity /Plant size	Year of application	Reported effects
Specialty chemicals & pharma	Major international company in Midwest (US)	Pre-heating of resin prior to extrusion	460 kg/hr	2001	See also TR 3.3.3.4.3. • 2x more capacity • 2x shorter processing time; • 25% reduction of catalyst consumption • 10x less maintenance cost • Total cost saving of 865000 $/yr
Specialty chemicals & pharma	Henkel Surface Technologies	Heating of plastic car components	No data	2001	See also TR 3.3.3.4.3. • 7x decrease in energy consumption
Food	Ca. 50 applications worldwide	Bacon cooking	Ca. 60000 slices/hr each	-	No data
Food	Ca. 300 applications worldwide	Tempering of frozen meats	Ca. 2 mln tons/yr in total	-	No data
Food	METRO (Hungary)	Production of fast-cooking rice	300 kg/hr	2003	• Energy saving 97%
Polymers/ plastics	Unknown	Drying of polyurethane foam	No data	-	• Drying rate increased by 250% • Skinning, blistering, scorching and discoloration eliminated

2.3 Known demonstration projects

(Are there any demonstration projects known related to the technology under consideration? In which process industry sectors are those projects carried out: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? In Table 3 provide the short characteristics of those projects.)

Table 3. Demonstration projects related to the technology (existing and under realization)

Sector	Who is carrying out the project	Short characteristic of application investigated, including product name/type	Aimed year of applicati on	Reported effects
Food	Institute of Energy Technology (Norway), in collaboration with Synøve Finden ASA and Holmens AS	Heat treatment and dry-substance concentration of food articles (pilot plant)	-	Energy savings, better product quality

2.4 Potential applications discussed in literature

(Provide a short review, including, wherever possible, the types/examples of products that can be manufactured with this technology)

Microwave heating/drying is widely described in the literature. Next to the applications listed in 2.2, where only specific, application-oriented R&D takes place, some new ideas are being explored in the literature, including

- microwave-assisted production of nanoparticles
- microwave-assisted synthesis of zeolites
- microwave-based steel making
- microwave-assisted processing of catalysts (drying, calcination)

3. What are the development and application issues?

3.1 Technology development issues

(In Table 4 list and characterize the essential development issues, both technical and non-technical, of the technology under consideration. Pay also attention to “boundary” issues, such as instrumentation and control equipment, models, etc.) Also, provide your opinion on how and by whom these issues should be addressed)

Table 4. Technology development issues

Issue	Description	How and by whom should be addressed?
Energetic efficiency of MW heating	Further increase of the efficiency of conversion from electricity to absorbed microwave energy is needed	Optimization and new concepts of cavity geometries (e.g. cylindrical heaters) and materials by the equipment vendors
Investment cost of MW furnaces	Current capital cost of MW equipment vary between 2000 and 5000 euro per kW installed. More standardization of equipment needed	Equipment vendors

3.2 Challenges in developing processes based on the technology

(In Table 5 list and characterize the essential challenges, both technical and non-technical, in developing commercial processes based on the technology under consideration. Also, provide your opinion on how and by whom these challenges should be addressed)

Table 5. Challenges in developing processes based on the technology

Challenge	Description	How and by whom should the challenge be addressed?
Small irradiation depth of the microwave.	The irradiation depth of the microwave in water medium does not exceed 2 cm. This brings an important question concerning the maximum production capacity achievable in a microwave furnace.	This challenge should be addressed in the R&D projects on engineering & design concepts for commercial-scale MW ovens (geometrical configurations of cavities, such as “rotary-kiln” designs, positioning of magnetrons, etc.).
Narrow applicability of microwaves in terms of the type of media used in the process	MW are only applicable to the materials of specific dielectric properties.	Feasibility studies at the end-user for each specific case
Development of inverse temperature profiles, hot-spots and thermal runaways in the heated materials	Generation of heat in the material volume may mean that the inner part of it will become much hotter than the surface.	Oven geometry/control studies by the equipment vendors
Safety	Operations involving microwaves require certain safety precautions as MW irradiation is dangerous for the human health. Current technology of MW ovens enables a fully safe use of these devices.	Process development has to involve the vendors of the MW-devices.

4. Where can information be found?

4.1 Key publications

(Provide the list of key publications in Table 6)

Table 6. Key publications on the technology

Publication	Publication type (research paper/review/book/ report)	Remarks
A. C. Metaxas, Microwave heating, downloadable at:” www.pueschner.com/downloads/MicrowaveHeati	Review	

ng.pdf		
E. Kubel, Advancements in Microwave Heating Technology, IndustrialHeating.com, January 2005, 43-53	Review	
A. K. Haghi, Application of Microwave Techniques in Textile Chhemistry, Asian J. Chem., 2005, 17(2), 639-654	Review	
A. Altmeyer, Vakuummikrowellentrocknung in der Pharmazie, Vakkumm ion der Praxis, 1994, No. 2, 117-121	Review	
E. Sanga, et al., Principles and Applications of Microwave Drying, In: Drying Technology in Agriculture and Food Sciences, Edited by A.S. Mujumdar, Science Publishers, Inc. Enfield, NH (2000).	Review	
G. Du., et al., Microwave Drying of Wood Strands, Drying Technol., 2005, 23, 1-16	Research paper	
G. Osepchuk, Microwave Power Applications, IEEE Trans. Microwave Theory and Techniques, 2002, 50, 975-985	Review	
New Energy-Saving Process For Fast Cooking Rice Production, Food Marketing & Technology, 2005, June, 26; downloadable from: http://www.linn-high-therm.de	Technical information	
M. R. Riedhammer, Benefits of the Use of Microwave Technology in Ceramic Production Processes, L'Industrie Céramique & Verriere, 1998, 939, 426-431	Review	
H. S. Shulman, Microwaves in High-Temperature Processes, Industrial Heating, 03/10/2003, downloadable from; www.ceralink.com	Review	
Food Processing Using Microwaves, EPRI Process Industry Coordination Office, Vol.2, No.1, 1990	Leaflet	
V. G. Raghavan, et al., Energy Aspects of Novel Techniques for Drying Biological Materials, Drying 2004 – Proc. 14th Int. Drying Symp., Sao Paulo, Brazil, 22-25 August 2004, vol. B, 1021-1028	Review	

4.2 Relevant patents and patent holders

(Provide the list of relevant patents in Table 7. Under "remarks" provide, where applicable, the names/types of products targeted by the given patent.)

There is a huge number of patents dedicated to microwave heating of drying. The vast majority of those patents, however, are product-related. All major manufacturers of the microwave furnaces and dryers do own patents in the field. In the table below the relevant patents owned by Industrial Microwave Systems L.L.C. are presented.

Table 7. Relevant patents

Patent	Patent holder	Remarks, including names/types of products targeted by the patent
U.S. Patent #5,958,275 "Method and Apparatus for Electromagnetic Exposure of Planar or Other Materials",	Industrial Microwave Systemss, L.L.C.	

issued on September 28th, 1999.		
U.S. Patent #5,998,774 "Method and Apparatus for Providing Uniform Electromagnetic Exposure", issued on December 8th, 1999.	Industrial Microwave Systemss, L.L.C.	
U.S. Patent #6,075,232 "Method and Apparatus for Electromagnetic Exposure of Planar or Other Materials", divisional issued on June 13th, 2000.	Industrial Microwave Systemss, L.L.C.	
U.S. Patent #6,087,642 "Electromagnetic exposure chamber for improved heating", issued on July 11th, 2000.	Industrial Microwave Systemss, L.L.C.	
U.S. Patent #6,121,594 "Method and Apparatus for Rapid Heating of Fluids", issued on September 19th, 2000.	Industrial Microwave Systemss, L.L.C.	
U.S. Patent #6,246,037 "Method and Apparatus for Electromagnetic Exposure of Planar or Other Materials", divisional issued on June 12th, 2001.	Industrial Microwave Systemss, L.L.C.	
U.S. Patent #6,259,077 "Method and Apparatus for Electromagnetic Exposure of Planar or Other Materials", divisional issued on July 10th, 2001.	Industrial Microwave Systemss, L.L.C.	
U.S. Patent #6,265,702 "Electromagnetic exposure chamber with a focal region", issued on July 24th, 2001.	Industrial Microwave Systemss, L.L.C.	
U.S. Patent #6,396,034 "Method and apparatus for electromagnetic exposure of planar or other materials"	Industrial Microwave Systemss, L.L.C.	
U.S. Patent #6,590,191 "Method and Apparatus for Electromagnetic Exposure of Planar or Other Materials", issued on July 8, 2003.	Industrial Microwave Systemss, L.L.C.	

4.3 Institutes/companies working on the technology

(Provide the list of most important research centers and companies in Table 8)

No institutes are known to work specifically on the development of microwave furnaces for heating/drying purposes. The development work takes place exclusively at the vendors of such equipment listed in Table 9. In Table 8 some research groups carrying out research on new applications of MW heating are listed.

Table 8. Institutes and companies working on the technology

Institute/Company	Country	Remarks
MIT	U.S.A.	Synthesis of zeolites with microwaves
National University of Singapore	Singapore	Synthesis of nanotubes and nanoparticles

Pennsylvania State University	U.S.A.	Synthesis of nanoparticles, synthesis of zeolites
Guangxi Normal University	China	Synthesis of nanoparticles
EFPL Lausanne	Switzerland	Synthesis of nanoparticles
Kyushu University	Japan	Synthesis of zeolites

5. Stakeholders

5.1 Suppliers and developers

(Provide the list of key suppliers/developers in Table 9)

Key suppliers/developers of the microwave furnaces are listed in Table 9.

Table 9. Supplier and developers

Institute/Company	**Country**	**Remarks**
CM Furnaces	U.S.A.	Microwave + electric hybrid furnaces
Cober-Muegge	U.S.A.	Microwave vulcanization equipment
Industrial Microwave Systems	U.S.A.	Continuous microwave systems (cylindrical & planar)
Linn High Therm GmbH	Germany	Microwave furnaces and dryers (continuous, batch, dual frequency)
Microdry Corp.	U.S.A.	Industrial microwave systems
Püschner GmbH	Germany	Microwave furnaces, dryers
Advanced Manufacturing Technologies (AMT)	Australia	Manufacturer of commercial MW furnaces for sintering
Takasago Industry Co.	Japan	Hybrid microwave-gas kilns
Mino Yogo Co.	Japan	Hybrid microwave-gas kilns

5.2 End users

(Describe the existing and potential end-users, other than those already listed in Table 2)

Potential group of end users includes companies operating in the polymers, rubber, food, paper, wood and pharmaceutical sectors, as well as some manufacturers of ceramic products.

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

Microwave furnaces for (pre)heating and drying purposes are commercially available and are potentially attractive for numerous niche applications in various sectors of process industry. Despite the fact that microwave consumes electricity with an efficiency of ca. 50%, in some applications significant energy savings can be achieved, with respect to the conventional heating techniques. High investment cost presents one of the main barriers in a broader application of these devices.