EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY: PULSE COMBUSTION DRYING

TECHNOLOGY CODE: 4.1.4

AUTHOR: Tadeusz KUDRA, CANMET Energy Technology Centre, Varennes, QC, Canada J3X 1S6

Table of contents

1. Technology

1.1 Description of technology / working principle

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

The term *pulse combustion* (PC) originates from the intermittent (pulse) combustion of the solid, liquid or gaseous fuel in contrast to the continuous combustion in conventional burners. Such periodic combustion generates intensive pressure, velocity, and to certain extent, temperature waves propagated from the combustion chamber via a tailpipe to the process volume (applicator) such as a drying chamber. Because of oscillatory nature of the momentum transfer, pulse combustion intensifies the rates of heat and mass transfer thus accelerates drying rates.

The controlling mechanism behind the operation of a pulse combustor is a complex interaction between an oscillatory combustion process and acoustic waves that are propagated from the combustor. Pulse combustion starts when fuel and combustion air are drawn into the combustion chamber, mixed to form an explosive mixture, ignited by a spark plug, and combust instantly in the explosion-like burning. At this moment, the air and fuel inlet ports are closed which results in the rapid pressure raise. This pressure forces the combustion products to flow out through the tail pipe to the dryer. As the hot flue gases flow out, the resulting outward momentum causes the pressure in a combustion chamber to drop to the minimum so the inlet ports open, which admits fresh fuel and air into the combustion chamber. This new charge ignites itself due to contact with remnants of hot flue gases left in the tailpipe from the preceding cycle which reenter the combustion chamber during the minimum pressure period. These combustion cycles repeat at a natural frequency based on the geometry of the combustion chamber and characteristics of the tailpipe which, along with the dryer, ensures self-sustained oscillatory operation of the pulse combustor.

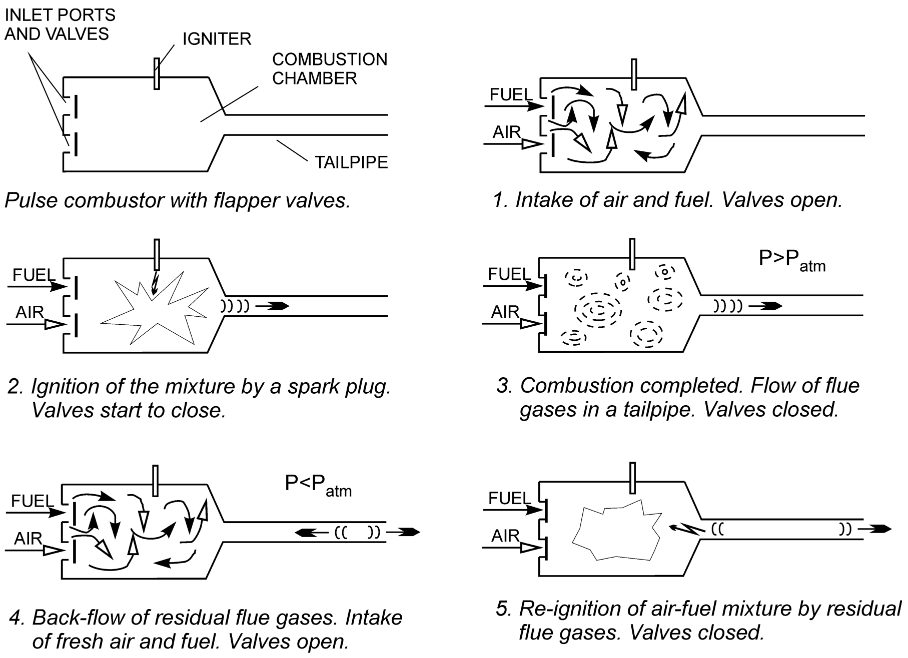

Fig. 1. Pulse combustor with flapper valves – principle of operation.

Typically, pulse combustors oscillate with frequencies that vary from 20 to 200 Hz. Pressure oscillations in the combustion chamber of ± 10 kPa produce tailpipe velocity oscillations of nominally ± 100 m/s and the gas jet velocity at the tailpipe exit pulsates from approximately 0 to 100 m/s. The input power for commercially available pulse combustors ranges from 20 to 1000 kW.

The major function of the pulse combustor in a drying system is to supply heat for moisture evaporation, and to generate large-amplitude high-frequency pressure pulsations within a drying chamber (e.g., rotary dryer), which enhances the drying rate. The advantage of a strong oscillating hot gas jet from a tailpipe has also been taken to promote dispersion of the feed, which is especially advantageous when drying biomaterials. Thus, in pulse combustion spray dryers the sound energy generated in a pulse combustor is used primarily for atomization of the liquid feed, which accelerates convective drying due to extended surface area of the liquid spray in addition to the thermal effect of the hot gas jet. The dryer can handle slurries (with solids up to 2 mm in diameter and up to 10 mm in length) with viscosities up to 16000 cP as well as solutions with viscosities up to 300 cP. In pneumatic dryers, the pulse combustion allows processing of wet, clumps-forming materials such as sawdust, corn fibers, spent grains, paper sludge with size of up to 25 mm.

1.2 Types and "versions"

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

A pulse combustor (PC) is an integrated part of any pulse combustion dryer. Pulse combustors may be categorized into three distinct classes according to the specific acoustic system on which their operation depends, namely: quarter valve PC, Helmholtz PC, and Rijke-tube PC. Without going into details, the pulse combustors consist of the inlet section, the combustion chamber, and the tailpipe. The inlet section admits fuel and combustion air which is burned in a combustion chamber and flue gasses exit the combustor through the tailpipe. The inlet section is equipped either in mechanical valves or in aerodynamic valves to prevent the flow of combustion products out of the pulse combustor through the combustor inlet during the positive pressure phase of the pulse combustion cycle.

The mechanical valves are designed as reed valves made from thin-sheet spring-steel, flapper valves, flapper valves that are not controlled through spring action but instead move freely, and rotary valves of various design, which periodically seal and open the inlet section according to the running frequency of the pulse combustor.

The aerodynamic valves have a specially designed inlet (e.g., a profiled orifice in the inlet pipe, contoured diffuser, or a shrouding duct) in which the fluid flow characteristics act as a physical barrier (fluid diode) to the backflow of combustion products. Such pulse combustors are termed the valveless combustors.

Some pulse combustors may be operated in a self-aspirating mode thereby eliminating the need for a fan to supply combustion air unless flue gases have to be diluted to reduce the processing temperature.

To excite large-amplitude pulsations in a dryer, the pulse combustor must operate at the same frequency as one of the natural acoustic mode frequencies of the drying chamber. Such resonance driven drying is achieved either by a trial and error method in a pilot scale apparatus, or by using a frequency-tunable combustor which actively follows the variations in the amplitude of pressure pulsations in the applicator.

The pulse combustor in a drying system can be used alone, or in combination with a conventional burner. The primary function of the pulse combustor is then to serve as a "speaker" which excites resonant pulsations in a drying chamber thereby improving the dryer performance.

Typical configurations of pulse combustion dryers are: spray dryers, rotary dryers, pneumatic dryers, and dryers with large-size chambers such as vertical or horizontal cylinders as shown in Fig. 2.

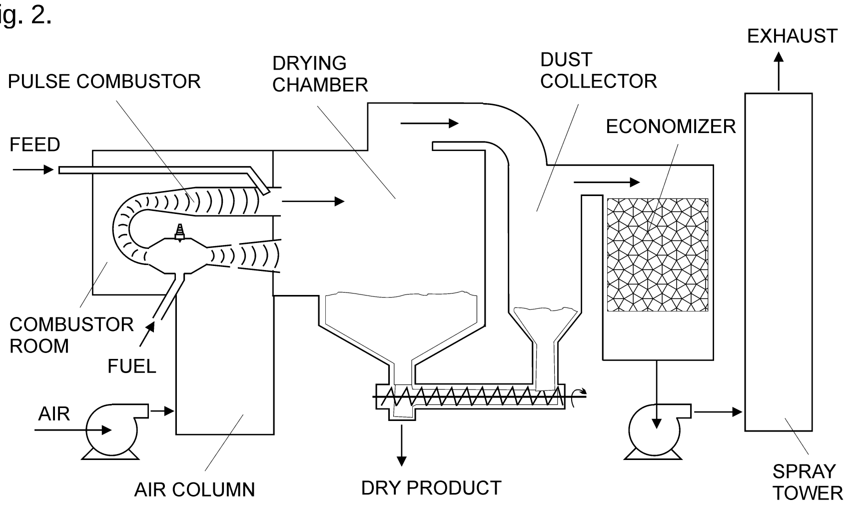

Fig. 2. Basic configuration of Pulse-Dryer with valveless burner
(Designed by Pulse Drying Systems, Inc., Portland, OR, USA)

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).

An analysis of the reported data indicates that the pulse combustion drying, as compared to classical (continuous) drying, enables one to:

- increase the drying rate by a factor of 1.2 to 3, depending on the configuration of PC dryer,
- reduce unit air consumption by up to 30%,
- eliminate distribution of characteristic process parameters (e.g. temperature, concentration, moisture content) within the dryer which improves the product quality,
- lower gas and product temperatures during processing,
- handle sticky materials which form lumps or aggregates without mechanical mixing or disintegration,
- disperse liquids, slurries and suspensions without the need for a disk atomizer or high pressure nozzle,
- lower air volumes discharged to the atmosphere.

Some quantitative data, which validate the generalized features, are presented in Table 1.

Table 1: Documented and expected benefits resulting from technology application

Benefit	Magnitude	Remarks
Higher combustion intensity (kW/m^3)	10000-50000	100-1000 (steady-state combustion)
Higher efficiency of burning (%)	90-99	80-96 (steady-state combustion)
Lower CO concentration in exhaust (%)	0-1	0-2 (steady-state combustion)
Lower NO_X concentration in exhaust (mg/m^3)	10-70	100-7000 (steady-state combustion)
Higher noise level (dB)	110-130*	85-100 (steady-state combustion)
Quantitative data for a single PC spray dryer compared to a conventional spray dryer with pressure atomizer (Mujumdar and Wu, 2004)		
Lower energy consumption in PC spray dryer (kJ/kg H_2O)	3300	5501 kJ/kg H_2O in conventional spray dryer
Energy savings (kJ/year)	1.6×10^{10}	PC spray dryer over conventional spray dryer
CO_2 abatement (t/year)	795	PC spray dryer over conventional spray dryer
Lower capital cost	~ 4x***	Relative to conventional spray dryer

* 70 dB is reported for some novel pulse combustors

** Based on literature data (Mujumdar and Wu, 2004) and typical pulse combustion spray dryer with 1000 kg/h of evaporative capacity operated 24/300 (Pulse Drying Systems, Inc.)

*** Estimated for 15x smaller dryer volume (Mujumdar, 2007; Chapter 53) as results from higher evaporation intensity in PC spray dryer (Mujumdar and Wu, 2004).

1.4 Stage of development

Even though pulse combustion dryers are in the market for years (First Dehydrated Poultry Waste Drying Site was established in 1974 by Sonodyne Industries, Newberg, OR, USA) the design and operation of pulse combustion dryers still belongs to art rather than science, mostly because of complex phenomena involved in pulse combustion and interaction of the sonic waves with the drying chamber and the drying material. As a result, the trial-and-error approach has been used by manufacturers to design a variety of commercial pulse combustion dryers. It became a standard procedure to perform drying tests in a pilot unit to identify drying conditions and modify the design, if needed. Such pilot units are operated by Pulse Drying Systems (Portland, OR, USA), Novadyne Ltd. (Hastings, ON, Canada), and Pulse Combustion Systems™ (San Rafael, CA, USA). The Pulse Combustion Systems™ offers toll drying service. Every university listed in Table 8 has the experimental pulse combustion dryer, and research is oriented towards process simulation using mathematical models validated by experiments. The exception is National University of Singapore where modeling and simulation is performed using data generated by others.

Note: Much research is devoted to particularities of the pulse combustion process and to the design of pulse combustion burners. However, presenting these research topics and listing the institutions involved is outside the scope of this report which deals only with pulse combustion dryers.

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)

Pulse combustion dryers belong to the class of direct-heated dryers where the drying gas consisting of fresh air, recycled air and the hot combustion gases from a burner is in direct contact with the material to be dry. Direct firing is most commonly applied in textile industry, paper manufacture, chemicals, and agri-food production.

Basically, pulse combustion burners can replace continuous burners in direct-heated dryers. Examples of proven industrial applications of pulse combustors are spray dryers, rotary dryers, fluid bed dryers and flash (pneumatic) dryers. However, the application of pulse combustion can fit well other drying technologies such as impingement drying, drying in impinging streams, drying in spouted bed, or conveyor belt drying.

Pulse combustion may be incorporated into a dryer at the design stage, or it may be retrofitted to an existing dryer but in this case not all advantages of pulse combustion (e.g. acoustic resonance) can be fully taken.

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)

Based on information provided by 3 major dryer manufacturers who report on 18 pulse combustion dryers sold to industry, the technology can be considered as commercially viable, yet not broadly applied in view of over 150 raw materials tested in a pilot unit rated at 1 ton/hour of evaporated water, and found to be suitable for pulse combustion drying (http://www.pulsedrying.com/experience.html). Pulse combustion dryers were positively tested for minerals and chemicals (e.g., iron oxide, magnesium oxide, boric acid, copper concentrate, sodium sulfate, titanium dioxide, calcium carbonate, kaolin, perlite, carbon black, latex, detergents, coal fines, calcium carbonate, diatomaceous earth, adhesives, organic polymers), food and agri-products (e.g., instant coffee, apple pumice, fish meal, cocoa powder, whole eggs, corn syrup, whey, lactose, starch, gluten, animal blood, molasses), biomaterials (e.g., soy protein, single cell protein, yeast, detergents, spirulina algae, vitamins, antibiotics, biopesticides). Pulse combustion drying is most often applied in agri-food, large volume and specialty chemicals, and semi-solid wastes.

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
Fine chemicals	Altair Nanotechnologies (Reno, Nevada, USA). Lithium-compound particles used in the electric car batteries.	Pulse combustion spray drying to produce large quantities of nanosized and uniform particles	Two dryers, each releases 0.4 GJ, giving evaporation rate of 72 kg/h	2007	Better powder than produced in conventional spray dryer (solid spheres with narrow size distribution)

Large volume chemicals	Canaan Fertilizers, Vereeniging, South Africa	Pulse combustion spray drying of fertilizers derived from chemical plant byproducts.	Three dryers, each releases 3 GJ and evaporates 500 kg/h of water	2006	Large increase in evaporative efficiency and throughput; ability to handle inconsistencies in the feed material.
Agri-food	Berghausen Corporation, Cincinnati, Ohio, USA	Pulse combustion spray drying of food additives and flavourings.	One dryer with a heat release of 1 GJ and evaporates 160 kg/h of water	2003	Improved powder quality, reduced energy consumption by 17-36%, increased dryer throughput.
Specialty chemicals and pharma products	Not specified	Valveless pulse combustion spray drying of Chinese medicinals	Evaporation rate 5 kg/h, initial moisture content 85-98% wb	2007	Not specified
Specialty chemicals and pharma products	Not specified	Valveless pulse combustion spray drying of medical supplies	Evaporation rate 0.5 kg/h, initial moisture content 98% wb	2005	Not specified
Agri-food	Ocean Proteins, Inc. (Charleston, Oregon, USA). Fish meal	Valveless pulse combustor with horizontal drying chamber	2 t/h of evaporated water	1980	Powdery product of superior quality.
Large volume chemicals	Tektronix, Inc. (Beaverton, OR, USA). Electro - chemical waste.	Two valveless pulse combustion burners in a horizontal drying chamber.	2 t/h of evaporated water	1981	Can handle versatile feed 15-25% solids (aluminum, iron, calcium ferrite, copper, nickel, silicates etc).
Large volume chemicals	Nuclear Metals, Inc. (Concord, MA, USA). Radioactive depleted uranium oxide.	Valveless pulse combustor. Material is fed to the divergent nozzle of the burner	1 t/h of evaporated water	1985	The only known nuclear application of PC. Allows isolation and control of hazardous waste.
Agro-food	National Starch&Chemical Corporation (Bridgewater,NJ, USA). Cold water swelling starch.	Valveless pulse combustor with horizontal post-drying chamber	NA	NA	An efficient process for simultaneously dispersing, pregelatinizing and drying to produce granular starch of superior quality.

NA – not available because of confidentiality agreement

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.)

Pulse combustion drying is already commercialized thus demonstrated in industrial scale. However, pilot units can be regarded as demonstration projects. Hence, the following units can be listed:

Pulse Combustion Systems™ (San Rafael, CA, USA) operates two pulse combustion spray dryers:

* PCS Model P-0.1 is a pilot scale dryer used for testing and development work. It releases 10^5 kJ of thermal energy and evaporates up to 18 kg/h of water.
* PCS Model P-1 is used for scale-up demonstrations and for custom-ordered drying of up to 180 kg/h of evaporated water and releasing 10^6 kJ of thermal energy.

The PCS Model P-0.1 is also used by Degussa-Hüls AG in Hanau-Wolfgang, Germany for product and process development (colorants, pharmaceutical intermediates, polymers, silica, pigments, catalysts and other industrial goods).

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 application	Reported effects
				•

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)

Drying of organic and inorganic materials from the groups of Industrial and agricultural wastes and by-products, Foods, Chemicals and Minerals. Moisture content in the feed is practically unlimited as the feed consistency extends from liquids (solutions and suspensions) through pastes to wet solids with size from micrometers to centimeters. Final moisture content in the product can be as low as 2% . The residence time in the region of high gas temperature (~1200°C) is in the order of milliseconds so continuing flash evaporation keeps the product at low temperature, typically around 50-60°C.

In addition to the materials tested by the dryer manufacturer and listed in Point 2.2, pulse combustion spray dryer was found advantageous over conventional spray dryer for silicon-based non-oxide ceramics (solid spheres and doughnuts giving higher density when compacted) and zirconium-based powders (narrow size distribution and no undesirable alteration to the product) (J.A. Rehkopf. Pulse combustion spray drying. http://www.pulsedry.com/downloads/index.php). Pulse combustion drying of solid wood (T. Kudra, A.G. Buchkowski, J.A. Kitchen. 1994. Pulse-combustion drying of white pine. Proc. 4th IUFRO Int. Wood Drying Conference, Rotorua, New Zealand. pp. 396-403), and thick-grade paper (Patterson T., Ahrens F., Stipp G. High performance impingement paper drying using pulse combustion technology. TAPPI Engineering Conference, Chicago, May 11-15, 2003) offered higher drying rates than continuous combustion. Simulation of pulse combustion spray drying and experiment validation with a common salt solution proved a possibility to dry highly heat sensitive materials (Z. Wu, A.S. Mujumdar. A parametric study of spray drying of a solution in a pulsating high-temperature turbulent flow. Drying Technology 24(6): 751-761, 2006)

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?
Modeling of pulse combustion drying and developing scale-up rules	For effective scale-up it is necessary to develop reliable mathematical models that are validated by detailed measurements of the flow and temperature fields.	R&D carried out at universities and research centers in cooperation with providers of PC burners and dryer manufacturers.
Matching the combustor with the dryer	Based on acoustic resonance, pressure waves generated in the pulse combustor can favorably be amplified in the drying chamber but the operating frequency of the combustor must match one of natural acoustic modes of the dryer. Because the frequency spectrum of the dryer changes with the variations with the dryer load, the combustor should be altered accordingly to attain resonance-driven drying.	Advanced research at universities and research centers on frequency - tunable pulse combustors.
Active control of pulse combustion	A complex interaction exists between the burner and the material load in a drying chamber, which affects the sonic wave patterns and operation of pulse burners. Pressure, temperature and/or humidity sensors could be used to modulate via actuators fuel flow, air flow and material feed.	Applied research performed by researchers on pilot-scale and demonstration units that are made available for testing by dryer manufacturers.
Design of the modular system	The modules of the drying system could easily be shipped to the end-user and assembled on the working site. It would be easy and inexpensive to replace worn parts.	Engineering and design conceived by dryer manufacturers in consultancy with researchers.

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?
Noise reduction	High noise level of about 110-130 dB is inherent in pulse combustion. Low noise level of 70 dB is claimed for novel pulse combustors. 50 dB is claimed 3 m from the combustor with sound suppression.	Studies on sound generation and propagation as well as sound suppression by design of a drying chamber. Joint work of scientists and engineers.
Mechanical reliability	Pulse combustors operate at high temperatures. Thermal resistance and strength of materials of construction is crucial for long-term operation. Mechanical reliability of moving parts such as valves is needed, especially for combustors with multiplicity of valves.	Selection of materials having better properties, modification to the design to reduce volumetric expansion, thermal shock, and mechanical stress. R&D at universities and research centers.

Increased stability of combustion	Deliberate or spontaneous variations in fuel- to-air ratio can result in shut down of some combustors.	An advanced R&D is needed on the combustion process and design of pulse combustors.
The use of energy sources other than fossil fuels	The presently manufactured pulse combustor dryers are fueled by natural gas, propane, diesel oil. An interesting option appears to be the use of biogas and other renewable gaseous and liquid fuels, as well as pulverized solid fuels such as lignite or wood residues.	Simulation studies on performance and operation of pulse combustion dryers fired with various fuels can be done by scientists whereas field tests can be performed by dryer manufacturers.
Micro-pulse combustors operated as an aggregate	Typical pulse convection dryers use one or two large capacity burners. It appears that favorable hydrodynamic and thermal effects can be achieved when using a set of multiple small pulse combustors to dry large sheet-type materials (e.g., paper) or moving beds (e.g., "Jet Zone" fluid bed dryer described in Handbook of Industrial Drying, A.S. Mujumdar (Ed), CRC Press, 2007, p. 491.	The challenge is how to aggregate a multiplicity of miniaturized pulse combustors to fulfill drying requirements without affecting the operation and performance of individual pulse combustors. Computer simulation should provide optimum arrangement.

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
T. Kudra, A.S. Mujumdar. Advanced Drying Technologies. 2002. Marcel Dekker, Inc. NY.	Book ISBN:0-8247-9618-7	Chapter No 14
A.S. Mujumdar (Ed.) Handbook of Industrial Drying. 3rd ed. 2007. CRC Press. Boca Raton,FL.	Book ISBN:1-57444-668-1	Chapter No 20
T. Nomura, N. Nishimura, T. Hyodo, Y. Tago, H. Hasebe, T.Kashiwagi. 1989. Heat and mass transfer characteristics of pulse-combustion drying process. Drying'89, A.S. Mujumdar, M. Roques (Eds), Hemisphere Publ. Corp. NY. pp. 543-549.	Research paper	Drying rate, pulsed vs. steady flow, heat transfer, flow visualization.
T. Kudra, A.G. Buchkowski, J.A. Kitchen. 1994. Pulse-combustion drying of white pine. proc. 4th IUFRO Int. Wood Drying Conference, Rotorua, New Zealand. pp. 396-403.	Research paper	Drying kinetics, gaseous emissions, pulsed vs. steady flow.
I. Zbicinski, I. Smucerowicz, C. Strumillo, J. Kasznia, J. Stawczyk, K. Murlikiewicz. 1999. Optimization and neural modeling of pulse combustors for drying applications. Drying Technology 17(3): 609-633.	Research paper	Effect of drying chamber on PC characteristics (noise, emissions, amplitude and pressure oscillations).

C. Strumillo, I. Zbicinski, I. Smucerowicz, C. Crowe. 1999. An analysis of pulse combustion drying system. Chem. Eng. Proc. 38: 593-600.	Research paper	Theoretical and experimental studies of pulse combustion spray dryer.
P. V. Akulich, P. S. Kuts. 2000. Studies on pulse combustors and their applications to drying. Proc. MIF-2000 Heat and Mass Transfer Minsk Forum. Minsk, Belarus. Vol. 9, pp. 3-11.	Research paper (in Russian)	Hydrodynamics, heat and mass transfer, novel design of tangential pulse combustor.
X. D. Liu, C. W. Cao, Z. H. Lang. 2001. Heat transfer between materials and unsteady airflow from a Helmholtz type combustor. Drying Technology 19(8): 1939-1948.	Research paper	Heating of brass sphere and drying of refractory clay particles to determine heat transfer coefficient.
I. Zbicinski, M. Benali, T. Kudra. 2002. Pulse combustion: an advanced technology for efficient drying. Chem. Eng. Technology 25(7): 687-691.	Review paper	Concise overview of major issues in pulse combustion drying.
P.S. Kuts, P.V. Akulich, N.N. Grinchik, C. Strumillo, I. Zbicinski, E.F. Nogotov. 2002. Modeling of gas dynamics in a pulse combustion chamber to predict initial drying process parameters. Chemical Engineering Journal 86: 25-31.	Research paper	A mathematical model was formulated and solved numerically to determine pressure, temperature, viscosity and velocity profiles along the combustion chamber and at the outlet from a tailpipe.
I. Zbicinski. 2002. Equipment, technology, perspectives and modeling of pulse combustion drying. Chem. Eng. Journal 86: 33-46.	Review paper	An overview of major issues illustrated literature and author's results.
T. Kudra, M. Benali, I. Zbicinski. 2003. Pulse combustion drying: aerodynamics, heat transfer and drying kinetics. Drying Technology 21(4): 629-655.	Research paper	Pressure, velocity and temperature profiles, heat transfer coefficient, drying rates, noise, gaseous emissions.
A. S. Mujumdar, Z. H. Wu. 2004. Pulse combustion spray drying. Topics in Heat & Mass Transfer. G.H. Chen, S. Devahastin, B. N. Thorat (Eds). IWSID-2004, Mumbai, India. pp. 79-91.	Research paper	Theoretical and experimental studies on heat and mass transfer in a PC spray dryer. Comparison with conventional dryer.

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.)

Table 7. Relevant patents

Patent	**Patent holder**	**Remarks, including names/types of products targeted by the patent**
Construction for Pulse Jet Combustor Dehydration Section. US 4,624,635. (1986).	Acquired from inventors by Pulse Drying Systems, Inc. Portland, OR	Design to be of universal application
Pulse Combustion Drying Apparatus For Particulate Materials. US 4,637,794. (1987).	Acquired from inventors by Pulse Drying Systems, Inc. Portland, OR	Drying of various particulate materials
Pulse Jet Combustor Dehydration Cone Construction. US 4,640,682. (1987).	Acquired from inventors by Pulse Drying Systems, Inc. Portland, OR	Design to be of universal application

Pulse Combustion Drying Apparatus For Particulate Materials. USA 4,695,248. (1987).	Acquired from inventors by Pulse Drying Systems, Inc. Portland, OR	Design to be of universal application
Feed System For Particle Drying Pulse Jet Combustors. US 4,695,249. (1987).	Acquired from inventors by Pulse Drying Systems, Inc. Portland, OR	Design to be of universal application
Elevated Temperature Dehydration Section For Particle Drying Pulse Jet Combustion Systems. US 4,701,126. (1987).	Acquired from inventors by Pulse Drying Systems, Inc. Portland, OR	Design to be of universal application
Pulse Combustion Process for the Preparation of Pregelatinized Starches. US 4,667,654. (1987).	National Starch & Chemical Company, Plainfield, NJ	Starch
Pulse Combustion Process For The Preparation of Pregelatinized Starches. US 4,859,248. (1989).	National Starch & Chemical Company, Plainfield, NJ	Starch
Pulse Combustion Fluidizing Dryer. US 4,395,830. (1983).	Jetsonic Processors, Ltd. Los Altos, CA	Foods and other products; drying in inert atmosphere
Pulse Combustion Drying System. US 5,252,061. (1993).	Bepex Corporation, Minneapolis, MN	Spray drying of foods, dairy products, flavors, chemicals, polymers, pharmaceuticals

4.3 Institutes/companies working on the technology

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

Table 8. Institutes and companies working on the technology

Institute/Company	Country	Remarks
Heat and Mass Transfer Institute (ITMO), Belarus Academy of Sciences. Prof. P.V. Akulich (akul@hmti.ac.by)	Minsk, Belarus	Experiments on pneumatic dryer with novel pulse combustor having conical chamber and tangential tailpipe.
Engineering College, China Agricultural University. Prof. Xiangdong Liu (xdliu@cau.edu.cn)	Beijing, China	Pulse combustion spray drying, liquid atomization in PC tailpipe
Department of Mechanical Engineering, National University of Singapore. Prof. Arun. S. Mujumdar (mpeasm@nus.edu.sg)	Singapore	Simulations of pulse combustion drying in spray dryers and spouted bed dryers
Faculty of Process and Environmental Engineering, Lodz Technical University. Prof. I. Zbicinski (zbicinsk@mail.p.lodz.pl)	Lodz, Poland	Experimental studies and modeling of pulse combustion spray drying and studies on interaction of PC with drying chamber.
Department of Hydraulics and Heat Engineering, Tambov State Technical University. Prof. V.I. Bichenok (lvi@gidra.nnn.tstu.ru)	Tambov, Russia	Theoretical and experimental studies on resonance frequency in pulse combustors heating chambers of large volumes. Design calculations for swirl-type pulse combustor.
Pulse Drying Systems, Inc. Sam Duncan, President (sgnduncan@pulsedrying.com)	Portland, OR, USA	Manufacturer; testing of various materials in a pulse combustion dryer rated at 1 ton/h

Pulse Combustion Systems. James A. Rehkopf, President (jrehkopf@pulsedry.com)	San Rafael, CA, USA	Manufacturer of pulse combustion spray dryers. Testing and toll drying of various materials in dryers with evaporation rate of 18 and 180 kg/h
Novadyne Ltd. Alan Buchkowski, Manager. (novadyne@nexicom.net)	Hastings, ON, Canada	Manufacturer of pulse combustion pneumatic dryers, testing of various materials. Burner duty 300 kW.
Pultech Corporation. Atsuyosi Kubota, President (qq2x8rr9k@jupiter.ocn.ne.jp)	Kobe City, Japan	Manufacturer of pulse combustion spray dryer with valveless burner.

5. Stakeholders

5.1 Suppliers and developers

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

Table 9. Supplier and developers

Institute/Company	**Country**	**Remarks**
Pulse Drying Systems, Inc. Sam Duncan, President (sgnduncan@pulsedrying.com)	Portland, OR, USA	Manufacturer of pulse combustion dryers with evaporation rates of 1 t/h and 2 t/h (www.pulsedrying.com).
Pulse Combustion Systems. James A. Rehkopf, President (jrehkopf@pulsedry.com)	San Rafael, CA, USA	Manufacturer of pulse combustion spray dryers with evaporation rate of up to 900 kg/h (www.pulsedry.com)
Novadyne Ltd. Alan Buchkowski, Manager. (novadyne@nexicom.net)	Hastings, ON, Canada	Manufacturer of pulse combustion pneumatic dryers.
Shandong Tianli Drying Equipment Co., Ltd., (lishengxiaoyao@yahoo.com)	Jinan, Shandong, PR China	The company fabricated an experimental pulse combustion dryer for China Agricultural University.
Pultech Corporation. Atsuyosi Kubota, President (qq2x8rr9k@jupiter.ocn.ne.jp)	Kobe City, Japan	Manufacturer of pulse combustion spray dryer with valveless burner. Evaporation rate from 25 to 4000 kg/h. Smaller dryers available for specialty materials. (www.pultech.co.jp)

5.2 End users

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

Starmet Corporation in Concord, MA, USA. Drying of radioactive uranium waste. Pulse combustion dryer of Pulse Drying Systems, Inc. 21 years on site.

Brinkerhoff-Signal Corp. in Denver, CO, USA. Drying of waste drilling mud from oil drilling in Alaska. Pulse combustion dryer of Pulse Drying Systems, Inc. 20 years operational.

Thiele Kaolin in Sandersville, GA, USA. Drying of kaolin clay, Pulse combustion dryer of Pulse Drying Systems, Inc. One year on site for product development.

Geosone, Inc. Peru, Drying of brewers yeast and brewers grains. First stainless steel mobile unit of Pulse Drying Systems, Inc, with evaporation rate of 2 ton/hr. 12 years in operation.

Note: Only existing end-users are listed as the manufacturers do not disclose potential customers because of confidentiality. The application list of pulse combustion dryers delivered by Pultech Corporation (Japan) comprises 20 entries from year 1994 to 2007 with evaporation rates from 0.5 to 6500 kg water/h for foods, ceramics, pharmaceuticals, and IT materials. No details are given, however.

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

Pulse combustion drying is a promising, energy efficient and environmentally friendly technology for various types of materials including minerals, chemicals, foods, as well as industrial/municipal wastes and by-products. This technology appears to be suitable for drying of heat-sensitive biomaterials, nutraceuticals and functional foods if direct contact with flue gases is permissible in a country of application. In spite of several dryer types on the market, the number of commercial applications is however relatively low, possibly due to lack of the scale-up and design rules made available to the dryer manufacturers. Such rules should follow from profound understanding of the complex transport processes taking place in the system configured of the pulse combustor and the drying chamber. Further studies, both theoretical and experimental performed by interdisciplinary scientists and practitioners are needed to establish process mechanisms, formulate mathematical models and to simulate various design options for particulate materials to be dried.

Acronyms

wb	wet basis (kg water/kg wet material)
NA	not available
PC	pulse combustion