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Equipment, technology, perspectives and modeling of pulse combustion drying

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Abstract

The paper presents the analysis of potential and real benefits of pulse combustion process applied in drying. The phenomenon of pulse combustion, its mechanism, pulse combustors designs, advantages and disadvantages of this technology were described and reviewed. Pulse combustion applications in industry were analyzed and evaluated. Experimental investigations carried out at the Faculty of Process and Environmental Engineering, Technical University of Lodz, on development of pulse combustion spray drying system were also presented. Laser techniques were used to characterize precisely flowfield in a drying chamber, spray structure and evaporation kinetics. An example of computational fluid dynamics (CFD) calculations of pulse combustion spray drying process was also given. The prospects of future development of this technology were discussed. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Mechanism of pulse combustion; Industrial applications; CFD calculations of transient flow; Drying process intensification

1. Introduction

Studies concerning modifications of the existing technologies, drying equipment and searching for new drying techniques have been carried out for many years. The pulse combustion technique is one of the opportunities for efficient and environmental friendly drying technology for various types of materials. Pulse combustion drying technique uses the technology of combustion-driven oscillations to produce high temperature and high velocity pulsating jets in order to atomize and dry. The phenomenon of pulse combustion was probably discovered by Higgins in 1777, who observed the so-called hydrogen "singing" flames in tubes. Later, in 1859, Rijke discovered that strong acoustic oscillations appeared when a heated metallic grid was positioned in the lower half of a vertical tube opened at both ends. The first pulse combustor with mechanical valves was built in France in 1906 and was used as a drive for a gas turbine [1].

A precursor to pulse combustors with mechanical valves was the Schmidt burner patented in 1931 (Fig. 1) [2]. Pulse combustion technology developed by Schmidt was utilized in V-1 "buzz" flying bomb during the Second World War.

In the following years the interest in pulse combustion declined. Again the major development in the field of pulse combustor was made in the 1950s when mechanical valves were replaced by an inertial gas valve. Since the 1970s the pulse combustion technology has been re-examined for use in different applications, where high combustion efficiency with low toxic components of the combustion gases is necessary.

2. Operating principles of the pulse combustor

Pulse combustion is a periodic ignition and extinguishing of combustible mixture of fuel and air. It is achieved by a special construction of a combustion chamber equipped with the one-way flapper valves or by aerodynamic inertial gas valves.

The pulse combustor performance may be described as follows (Fig. 2). When the engine is ignited, on the boundary of overpressure and atmospheric pressure two waves are initiated: a compression wave 'a' which approaches the outlet, and an expansion wave 'b' which moves towards the inlet closed by the valves. When the compression wave approaches the open end of the engine, the outflow starts. The compression wave 'a' is rebounded by the open end of the engine as the expansion wave 'c'. During this time, because of the outflow, the pressure in the combustion zone of the engine falls down to the level of the atmospheric pressure, so that the approaching expansion wave 'c' is rebounded from the opening valves as an expansion wave 'd' and causes underpressure in the open end of the pipe. As a result, secondary flow of atmospheric (cooler) air to the engine from the outlet takes place (supercharging). This phenomenon

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Nomenclature

A	surface area (m^2)
ΔH	latent heat of evaporation (J/kg)
K_H	heat transfer coefficient (W/m^2 K)
T_g	gas temperature (K)
T_m	material temperature (K)
w_D	drying rate (kg/s)

promotes afterburning of CO–CO_2 and decreasing temperature of the process which results in smaller NO_x production. The pollutant emission depends on the fuel composition, the conditions of combustion performance and the combustion efficiency.

Pulse combustion offers the potential for higher efficiency of combustion process and heat transfer and lower pollutant emissions than conventional steady-state combustion. Some of these features are presented in Table 1 [3].

A drawback which prevents a broad application of pulse combustors is, in some cases, their unacceptable noise level. There are three main sources of this noise:

- detonating character of combustion (this is an intrinsic feature of the combustor operation);
- vibrations of metal walls of the combustor;
- velocity difference between gases flowing from the combustor and ambient air.

An example of the map of noise emission from a valved pulse combustor is presented in Fig. 3 [4]. The highest noise level can be observed in the close surrounding of the tailpipe

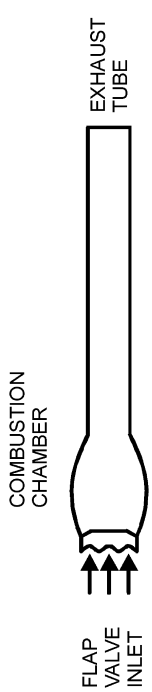


Fig. 1. Schmidt pulse combustor.

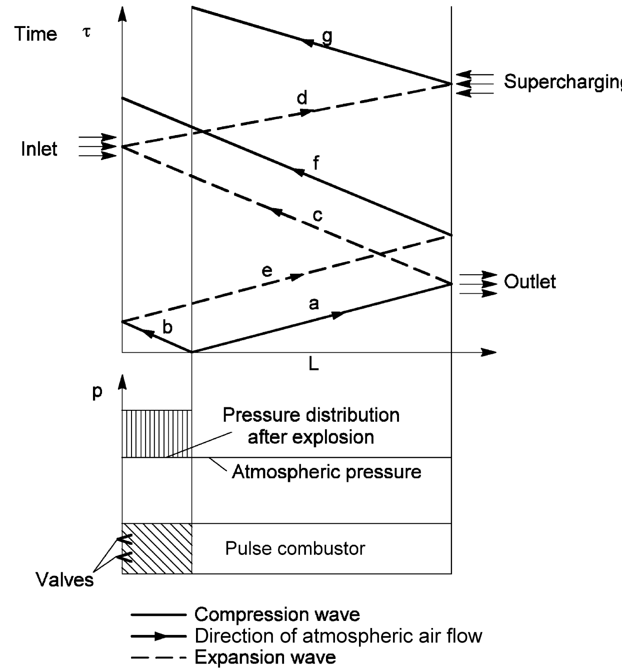


Fig. 2. The principle of pulse combustor operation.

outlet achieving 110 dB. Noise decreases to the acceptable level of 85 dB at a distance of about 5–6 m.

During several decades a number of methods to decrease efficiently the noise level have been developed [5].

The most effective are the three following ones:

- coupling of two combustors so that they work in counter-phase;
- application of ejectors at the combustor inlet and outlet;
- shielding the space between the ejectors, inlet and outlet.

Two types of pulse combustors are identified:

- valved pulse combustors—with mechanical membrane or rotary valves;
- valveless pulse combustors—with inertial gas valve.

Table 1
Comparison of steady-state and pulse combustion [3]

Process parameters	Steady-state	Pulse
Combustion intensity (kW/m^3)	100–1000	10000–50000
Efficiency of burning (%)	80–96	90–99
Losses due to chemical underburning (%)	0–3	0–1
Losses due to mechanical underburning (%)	0–15	0–5
Temperature level (K)	2000–2500	1500–2000
Concentration in exhaust		
CO (%)	0–2	0–1
NO_x (mg/m^3)	100–7000	20–70
Convective heat transfer coefficient (W/m^2 K)	50–100	100–500
Noise produced (dB)	85–100	110–130
Time of reaction (s)	1–10	0.01–0.5
Excess air coefficient	1.01–1.2	1.00–1.01

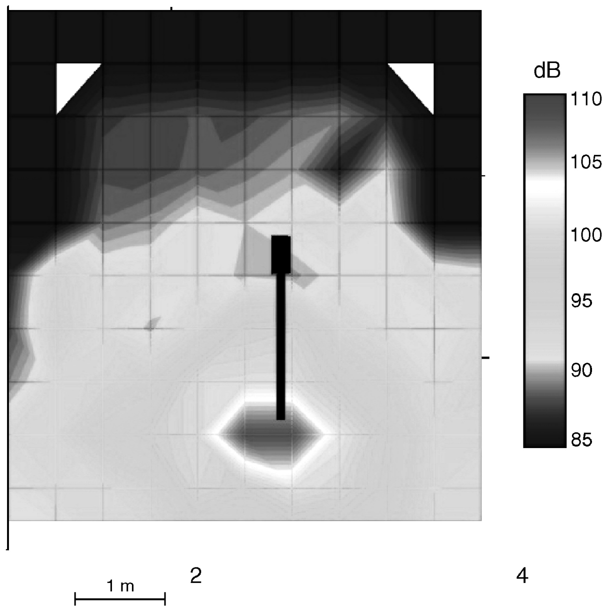


Fig. 3. Map of noise emission from valved pulse combustor.

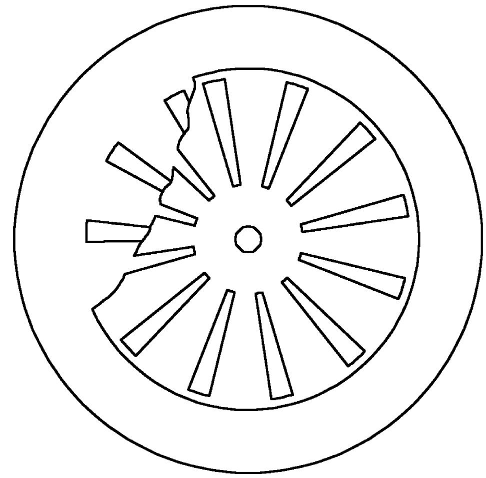


Fig. 5. Rotary valve.

Fig. 4 shows an example of valved pulse combustor construction equipped with a set of one-way flappery valves [6]. A mechanical membrane oscillates in the valve blocking and opening fuel inflow to the combustion chamber.

A rotary valve (Fig. 5) consists of two valve plates with identical orifices. One plate is static, while the other one rotates. The air flows into the combustion chamber when slots in the two plates overlap, otherwise the valve is closed. The rotation of the valves has to fix the oscillations frequency. The valves must be open when underpressure occurs in the chamber to get the engine into acoustic resonance. Pulse combustors with rotary valves are mechanically more resistant than units with membrane valves, due to fatigue of membranes during a long-term work.

A different method of flow regulation is used in the pulse combustors with inertial gas valves, called also the valveless pulse combustors. An example of valveless pulse combustor is shown in Fig. 6. The valveless pulse combustor is characterized by simple construction (two Venturi nozzles connected by a combustion chamber) with no movable parts.

However, valveless units are more difficult to develop and control (due to self-aspirating operation mode) than valved units. We also observe a lower noise level during valved units operation which is a result of closing of the valves during about half the cycle.

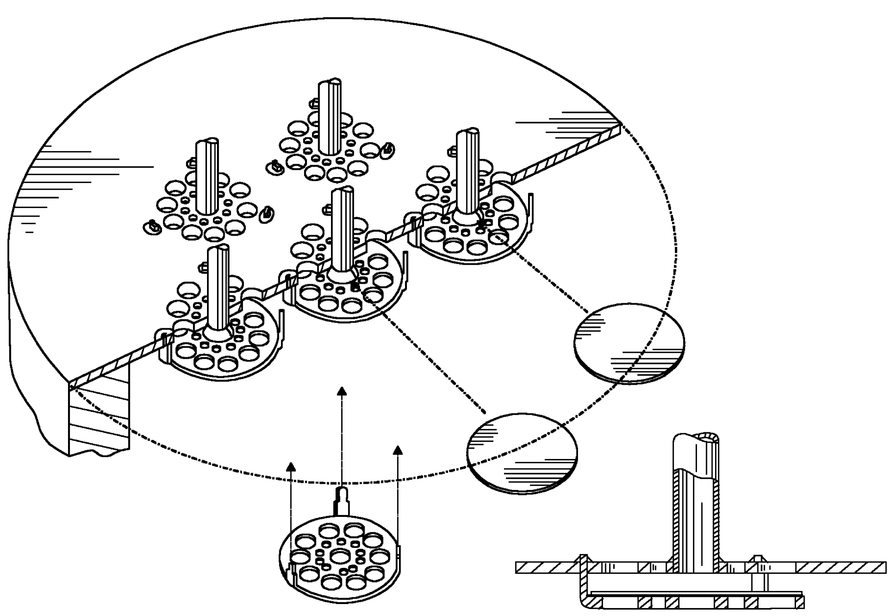


Fig. 4. Plate with membrane valves [6].

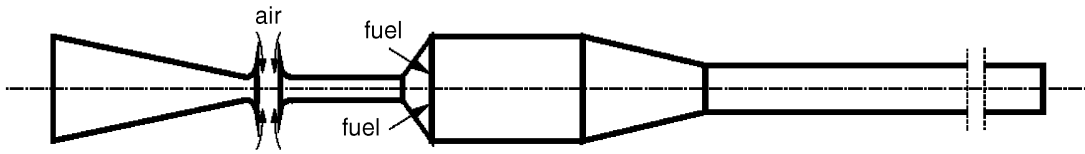


Fig. 6. Valveless pulse combustor.

At the present state of knowledge on unsteady turbulent flow through the pipe of a complex geometry, accompanied by a chemical reaction and heat and mass transfer, it is most improbable to construct a pulse combustor which would operate correctly and according to the foredesign from the beginning.

3. Potential benefits of pulse combustion application in drying

One of the most significant advantages offered by pulse combustors is a high energy efficiency attributable to the mechanism of the process.

Let us analyze the effect of pulsations on drying process. Enhancement of drying rate might be caused by an increase of heat transfer coefficient (K_H), increase of heat transfer area (A) and/or driving force ($T_g - T_m$), Eq. (1):

$$w_D = \frac{K_H A (T_g - T_m)}{\Delta H} \tag{1}$$

1. Heat transfer coefficient should be significantly affected due to strong velocity oscillations and stripping of the boundary layer. Analysis presented in [7] (Fig. 7) shows periodical changing of the position of stagnation point during oscillating flow around a cylinder which must influence local and global Nusselt number (Nu) (Fig. 8).
2. We might also expect that during pulse combustion spray drying, the secondary atomization occurs which increases the heat transfer area due to finer particle size distribution.

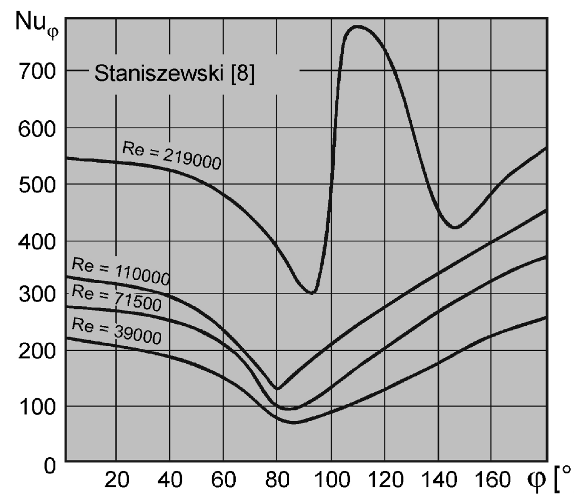


Fig. 8. Local Nu number (flow around a cylinder) [8].

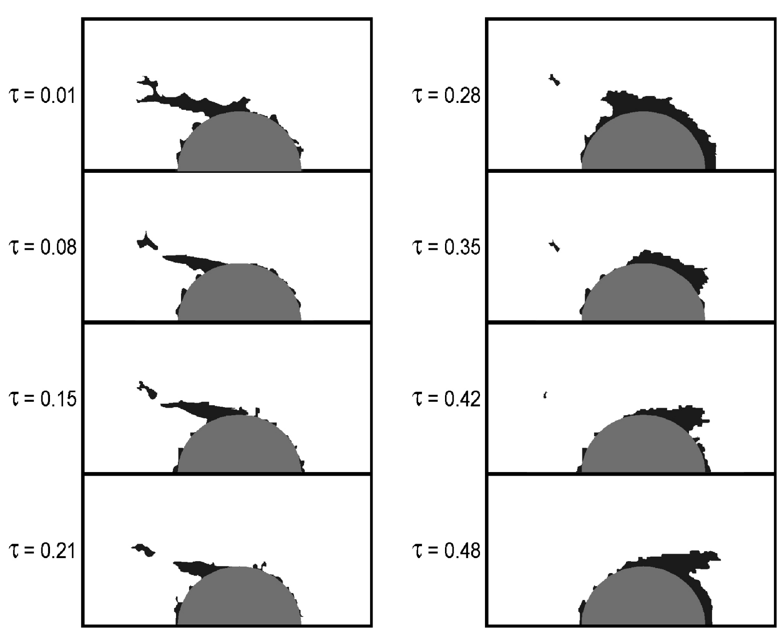


Fig. 7. Image processed shear layer vs. time cycle (flow direction to the left).

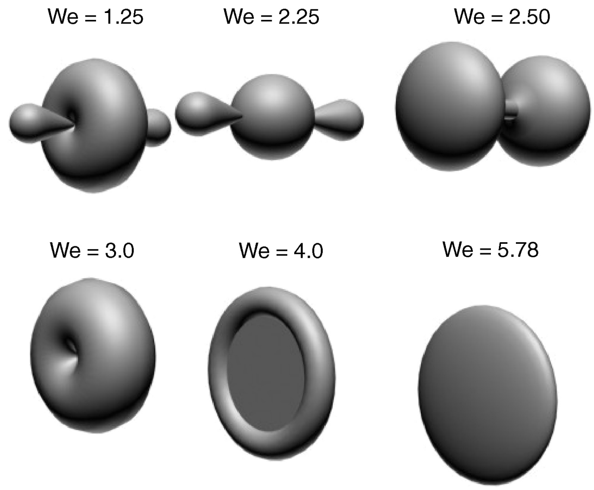


Fig. 9. Weber number-induced droplet break up.

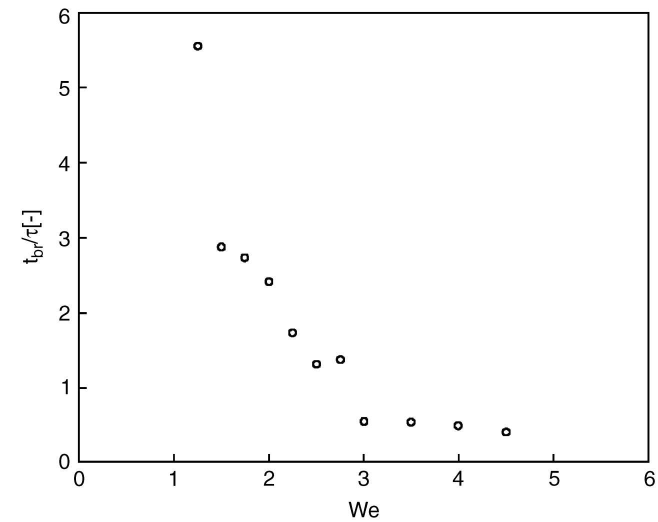


Fig. 10. Time required for droplet break up for various Weber numbers.

The expectations have been supported by Murray and Heister [9], who studied the influence of the acoustic frequency, intensity and gas/liquid density ratio upon the droplet behavior. They confirmed droplet break up and showed three regimes of the process: ‘nipple’, ‘kidney’ and ‘toroidal’ (Fig. 9). For high Weber numbers (*We*) the droplet rapidly flattens in a plane perpendicular to the acoustic wave. Break up times were roughly inversely proportional to *We* (Fig. 10).

Table 2
Capacity and energy consumption in pulse combustion dryer and selected conventional dryers

Dryers	Typical evaporation capacity	Typical consumption (kJ/kg H_2O evaporate)
Pulse combustion dryer	250–2000 kg H_2O/h per combustor	3000–3500
Conventional dryers		
Tunnel dryer	–	5500–6000
Band dryer	–	4000–6000
Impingement dryer	50 kg H_2O/h m^2	5000–7000
Rotary dryer	30–80 kg H_2O/h m^3	4600–9200
Fluid bed dryer	–	4000–6000
Flash dryer	5–100 kg H_2O/h m^2 [a]	4500–9000
Spray dryer	1–30 kg H_2O/h m^3	4500–11500
Drum dryer (pastes)	6–20 kg H_2O/h m^2	3200–6500

[a] Depends on particle size.

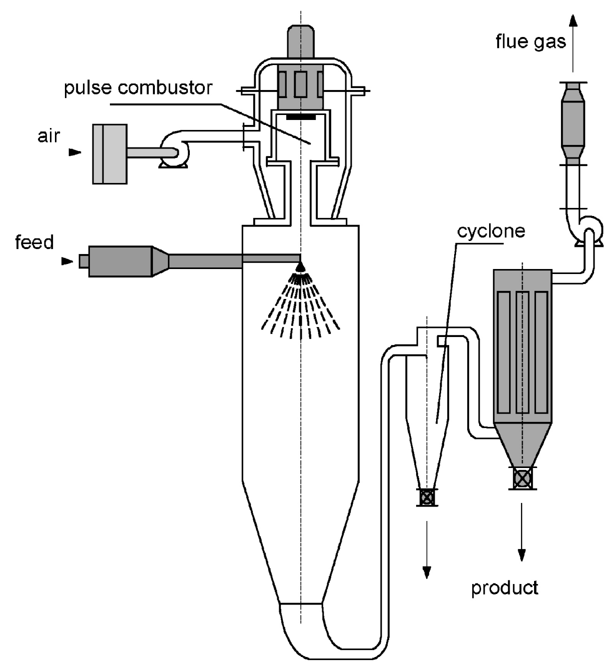
Table 3
Exposure to heat conditions

Dryers	Typical residence time					
	0.01–1 s	1–10 s	10–30 s	5–10 min	10–60 min	1–6 h
Pulse combustion dryer	X					
Conventional dryers						
Belt conveyor dryer					X	
Flash dryer		X				
Fluid bed dryer					X	
Rotary dryer					X	
Spray dryer			X			
Tray dryer (continuous)						X
Conduction dryer					X	
Drum dryer			X			
Steam jacket rotary dryer					X	
Tray dryer (batch)						X
Tray dryer (continuous)					X	

> It was confirmed in the literature that the high velocity free jet can atomize slurries and pulps containing pieces up to 2 mm in diameter and up to 10 mm in length with viscosity for slurries up to 2000 cP and solutions with viscosity up to 300 cP [7]. Pulse combustion drying systems can be used to dry a wide range of materials, including low and high viscosity liquids, pumpable pastes, all non-cohesive filter cakes (and most cohesive ones) and many powders and granules. No other dryer type offers such a variety of feedstocks to handle.

Third factor affecting drying rate is driving force of the process. Due to high driving force (∼700 °C) it is possible to reduce theoretical air consumption by 300–400% [7]. However, the product being dried often imposes limitations upon the system so that reductions more often range from 10 to 50%. At least twice as low energy consumption to evaporate 1 kg of water was achieved (Table 2) [10].

Another advantage is a short contact time of drying agent-dried material (0.01–1 s, Table 3). For this reason this technique can be applied even to extremely sensitive materials [11].



4. Applications of pulse combustion in drying

Recently, the area of applications of pulse combustors has increased significantly. The combustors become attractive because of the combustion efficiency, economic use of fuels and environmental friendly operation.

Pulse combustion industrial applications in the drying process may be found mainly in the following techniques:

- spray drying;
- fluid bed drying;
- flash drying.

Hosokawa Bepex Corporation and Sonodyne Industries Inc., USA, have conducted the most extensive research on pulse combustion application in the drying process. The Hosokawa Bepex Corporation has patented a new type of pulse combustor with cylindrical rotary valves and developed spray drying installation presented in Fig. 11. The pulse combustion frequency ranged between 80 and 150 Hz and heat release rates achieved up to 300 kW. Hosokawa Bepex Corporation tested over 60 different materials and the results have been encouraging with most products where equal or better quality than that produced by spray dryers was observed [7]. In some cases, such as biopesticides and antibiotics, products with 8–11% higher potency than spray-dried products were reported. For shear sensitive materials atomization by pulsed jets has maintained the cell wall yielding a high quality product. Also less blow holes and microballoons on product particles during pulse combustion drying than during spray drying were obtained. It means that the finer, softer product will not require milling prior to compounding.

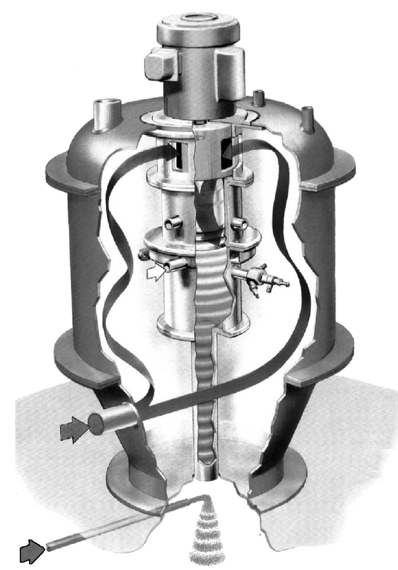


Fig. 11. Hosokawa Bepex Corporation drying system pulse combustor with cylindrical rotary valve.

This device has been used to dry many chemical and pharmaceutical products, food, polymers and so on. Low production costs and high quality products have been obtained. During experiments an intensive heat transfer, 30–40% lower air consumption per 1 kg of evaporated water and excellent atomization of pastes and sludges were observed.

However, further research was terminated because of problems with feeding system and dried material deposition on walls near the air inlet.

Mobile spray drying installation was developed by Sonodyne Industries Inc. [3]. The drying system with capacity of 2 t/h of evaporated water is equipped with the valveless pulse combustor as a source of a drying agent (Fig. 12). A device

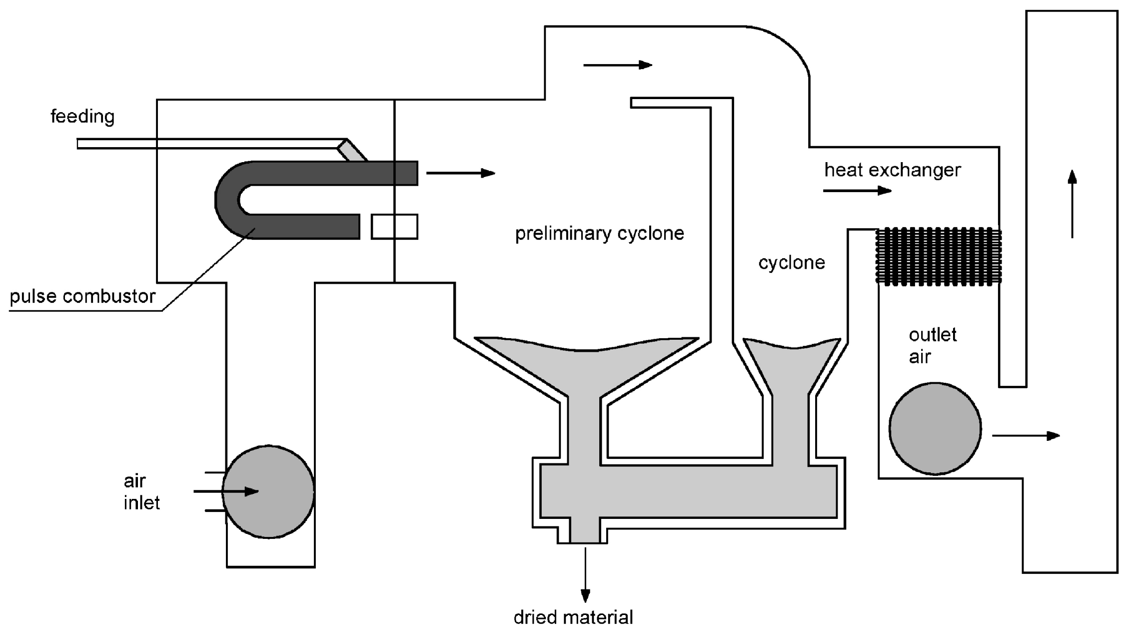


Fig. 12. SONO-DRI, Sonodyne Industries Inc.

called SONO-DRI has been applied to dry over 100 various products such as sensitive thermal food products or industrial sewage. Drying tests confirmed advantages of pulse combustion drying: high quality product, high energy efficiency, low air consumption per 1 kg of dry product and handling of a wide range of materials. The dryer requires 2900 kJ/kg of water evaporated which compared with the ~2500 kJ/kg theoretically needed, shows high efficiency of this device.

Pulse combustors are also used in systems for drying industrial waste. An example of such installation is given in Fig. 13 [12]. The wet product from the extruder is preliminarily dried by the heat from the afterburner, then is delivered to the drying chamber and falls on a vibrating grid where it is dried by a stream of hot gas which flows through the bottom of the grid from the pulse combustor. This device has capacity of 20,000 t per year of evaporated water. Pulse fluidized bed drying has been successfully used for drying of acid wastes, biological deposits, used brewery yeast, sawdust, deposits from tanneries, toxic wastes, urban deposits, deposits after plating, sludges, dangerous wastes and many more.

Recently Novodyne Ltd., Canada, has conducted an intensive research to construct pulse combustion flash drying system designed mainly for wood industry. The newest design of Novodyne Ltd., is shown in Fig. 14 [13]. This flash dryer with the valved pulse combustor is used for sawdust and wood waste drying. Material can be dried from moisture content of 50% down to 30% in a single pass. Results obtained in this system showed the following:

- device operation is stable and safe;
- thermal efficiency is similar to the efficiency of the flash dryers;
- electrical energy consumption is 40–50% less than for the conventional flash dryers, it reaches 0.016 kW/kg of H_2O and evaporation rate is 230 kg of H_2O/h;
- capital costs are 10–15% less in comparison to classical flash dryers what is caused by a compact design of the system;
- toxic substances emission is low.

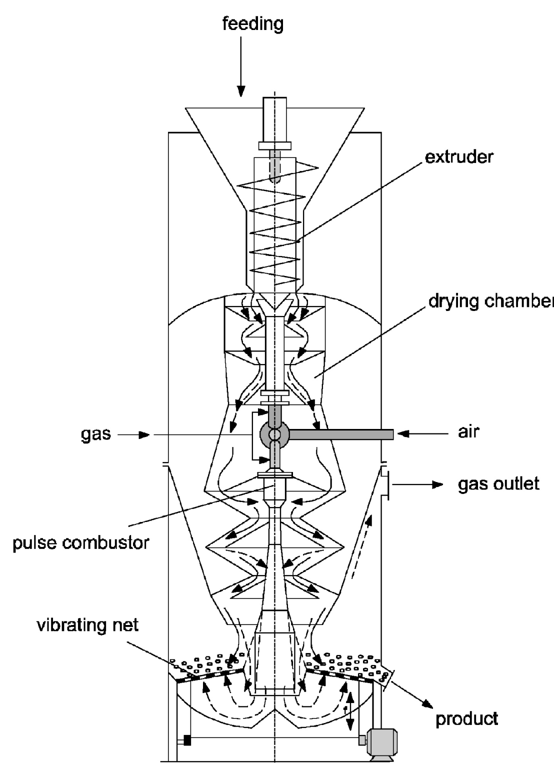


Fig. 13. Installation for industrial waste material—IMPULS vibrofluidized bed dryer.

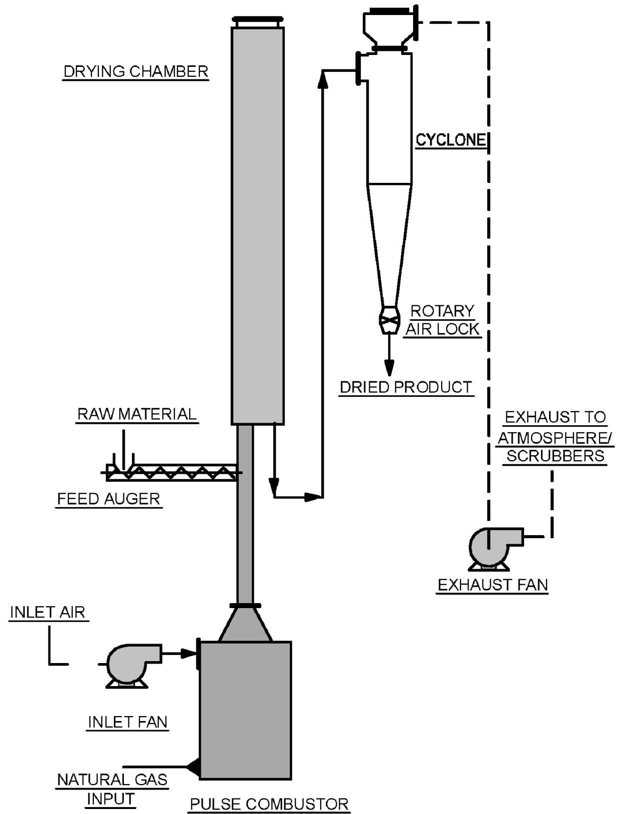


Fig. 14. Novodyne Ltd. flash dryer drying.

Summarizing we may conclude that pulse combustion drying has potential to be competitive, due to lower investment costs than those of the standard installations with steady combustion burners.

5. Experimental analysis of pulse combustion drying

There is limited literature describing experimental analysis of pulse combustion drying process. All published data are restricted to input and output relations only.

Extensive research on in situ analysis of the mechanism of the process was carried out in the Department of Heat and Mass Transfer, Technical University of Lodz. Pulse combustion spray drying system with valved and valveless pulse combustors was constructed and examined [14].

The experimental setup of valved pulse combustion spray drying system is presented in Fig. 15. The system consists of a valved pulse combustor connected to 1.2 m long, 0.29 m diameter drying chamber. Dry product and water vapor are conveyed from the chamber into the cyclone where the dry particles are separated.

In the project the flow field produced by the pulse combustor in a drying chamber was measured using the laser Doppler anemometry (LDA), FlowLite System, manufactured by Dantec, Denmark. To perform velocity measurements, transparent quartz windows were installed in the drying

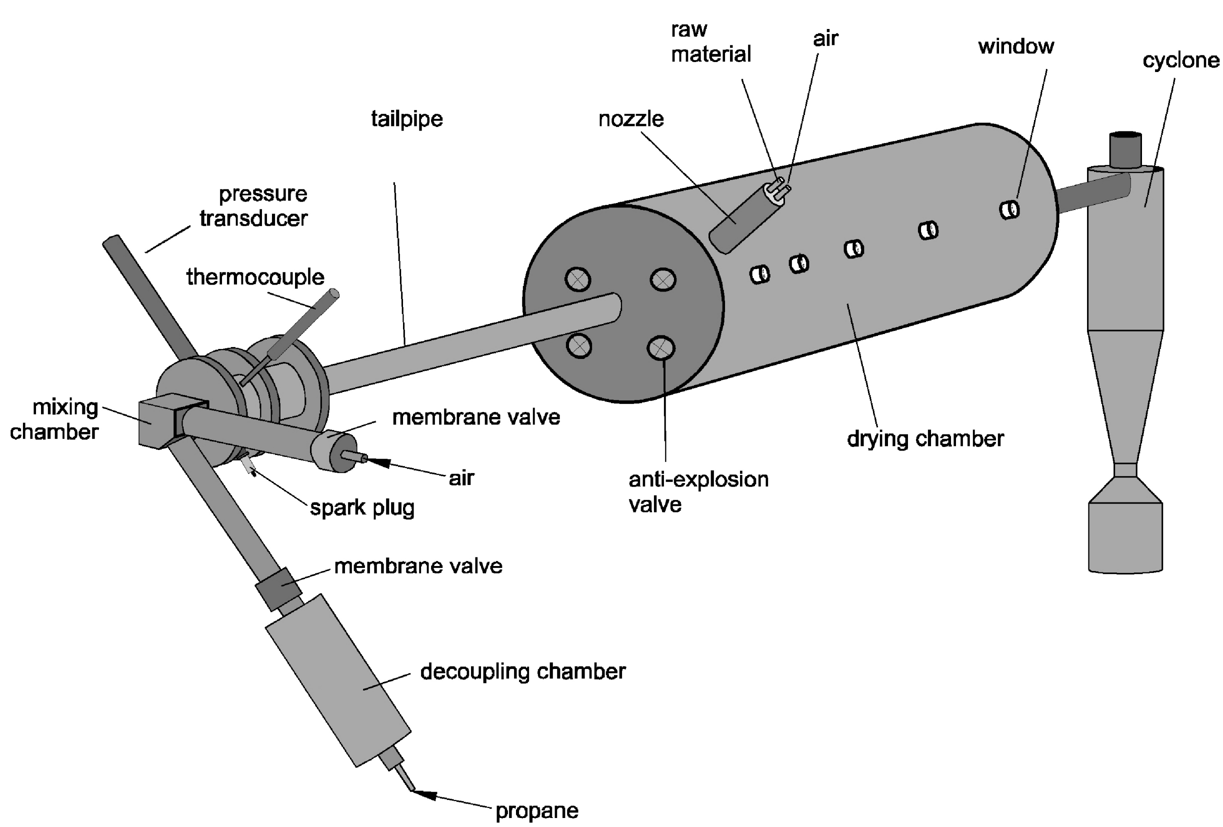


Fig. 15. Experimental valved pulse combustion drying installation.

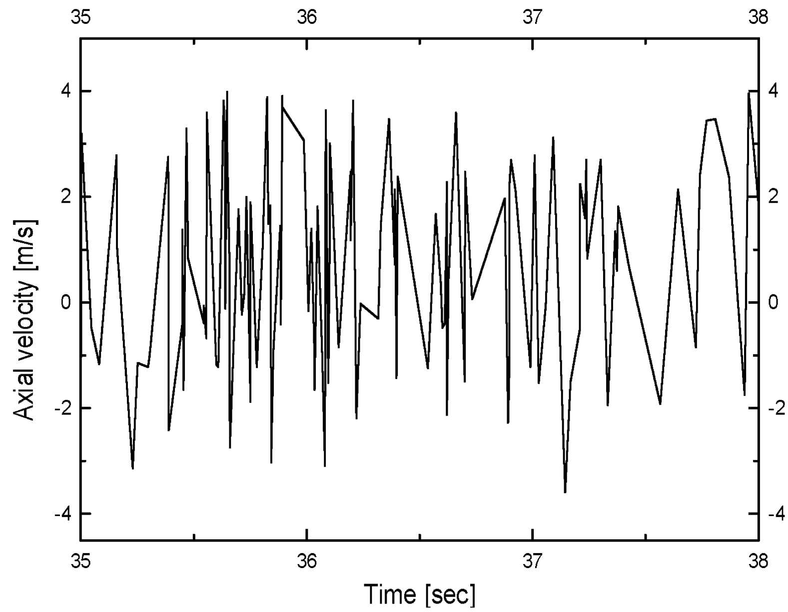


Fig. 16. Oscillations of axial velocity.

chamber. The gas velocity was determined using the LDA technique by measuring the velocity of tracer particles (MgO) in the control volume. An optical probe was installed on a traverse and measurements were made along the diameter of the drying chamber. Fifteen hundred samples were taken at every measuring point.

Examples of results showing axial velocity oscillations and average axial velocity profiles produced by the valved pulse combustor are presented in Figs. 16 and 17. Fig. 16 shows oscillations of axial velocity at the distance of 27 cm from the atomizer. The velocity oscillations should have a harmonic shape similar to the pressure oscillations. However, because of the low data rate (~40 Hz) the LDA system could not determine the shape of velocity oscillations. From Fig. 16 one can only evaluate the average amplitude of velocity fluctuations.

It should be stressed that oscillations of the axial velocity exceeded a couple of hundred percent of average value which is relevant to the suggestions presented in [15].

Analysis of the results confirms a complex nature of the pulsating flow in the drying chamber (Fig. 17). The flow in the chamber cannot be classified as an axisymmetric flow. Judging by this character of flow field we might expect intensification of heat and mass transfer in the drying process.

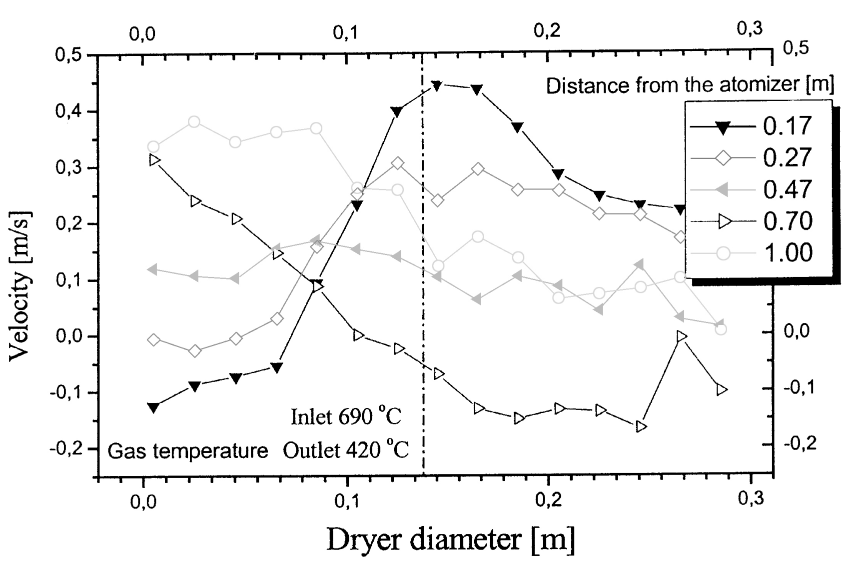


Fig. 17. Axial velocity profiles in a drying chamber.

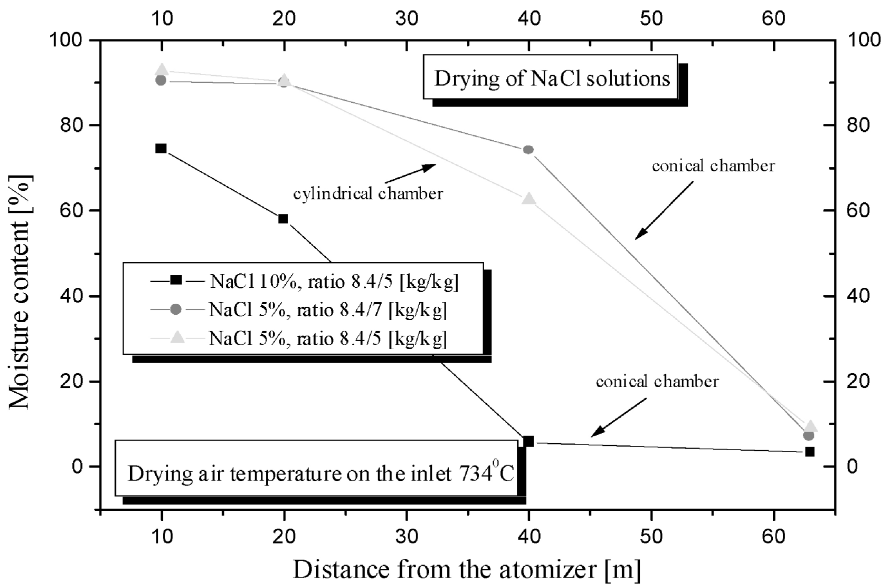


Fig. 18. Kinetics of drying process for NaCl solutions.

A set of 24 evaporation and drying tests was carried out for water and 5 and 10% aqueous NaCl solutions in two different geometries of the valved pulse combustor. Because of the extremely difficult and tiresome conditions during experiments, the valveless combustor was not used as a source of drying agent (unacceptable noise level (130 dB), relatively high emission of toxic substances).

Evaporation and drying tests consisted of measurements of dry and wet bulb temperature to obtain temperature distribution of air and material inside the dryer and moisture content measurements for NaCl solution. The phase Doppler anemometry (PDA) technique was used to determine particle size distribution, velocity of the particles, mass concentration of the liquid phase in the cross section of spray stream, etc. For water evaporation, the PDA technique was used also to determine the evaporation level as a function of the distance to the atomizer. An example of the results is shown in Fig. 18. Rapid decrease of material moisture content proves intensive drying process.

6. A mathematical model of pulse combustion drying process

The analysis of the literature showed that despite wide variety of pulse combustion applications and the advantages of this process, knowledge of the process mechanism is limited. There are a number of attempts of mathematical modeling of pulse combustion process encountered in [16–20]. Available models of transient pulsating flow of the gas phase reveal serious drawbacks and qualitative character, so they cannot be used in more sophisticated problems.

Heat and mass transfer in the two-phase oscillating flow belongs to the least described by validated mathematical models problems [21,22]. Complex character of this kind of flow is under the continuous investigation, but the limitations still lay in the available tools for such calculations—both software and hardware.

According to our knowledge there have been no attempts to model pulse combustion drying process. One of the goals of our research was to model the velocity flow field generated by a pulse combustor and a drying process in the pulsating flow of flue gases.

All calculations were performed for geometry of the pulse combustion spray dryer installation developed in the Faculty of Process and Environmental Engineering, Technical University of Lodz. To model this specific flow and drying process, Fluent 5.02—a commercial software of Fluent Incorporated, USA—was used [23].

In the work transient, two-dimensional axisymmetric, unsteady, turbulent flow was modeled. Examples of the results describing stream lines pattern in a drying chamber obtained during these calculations are presented.

We can observe changes of the stream lines pattern for two different times in one oscillation period: 19.500 and 19.507 s from the beginning of the process, when pseudo-stabile flow conditions were achieved. The main flow is moving from the dryer axis to the walls. One big recirculation zone is formed near the dryer inlet and a second is formed temporarily in the conical section of the dryer as a result of reverse flow. Recirculation zones are responsible for negative values of axial velocity near the wall. Oscillations of the flow which reflects natural frequency of the pulse combustor operation (121 Hz) might promote intensive mixing and robust heat and mass transfer between disperse and continuous phase. The character of the stream lines is similar to the stream lines in the classical spray dryers presented by many authors [24,25].

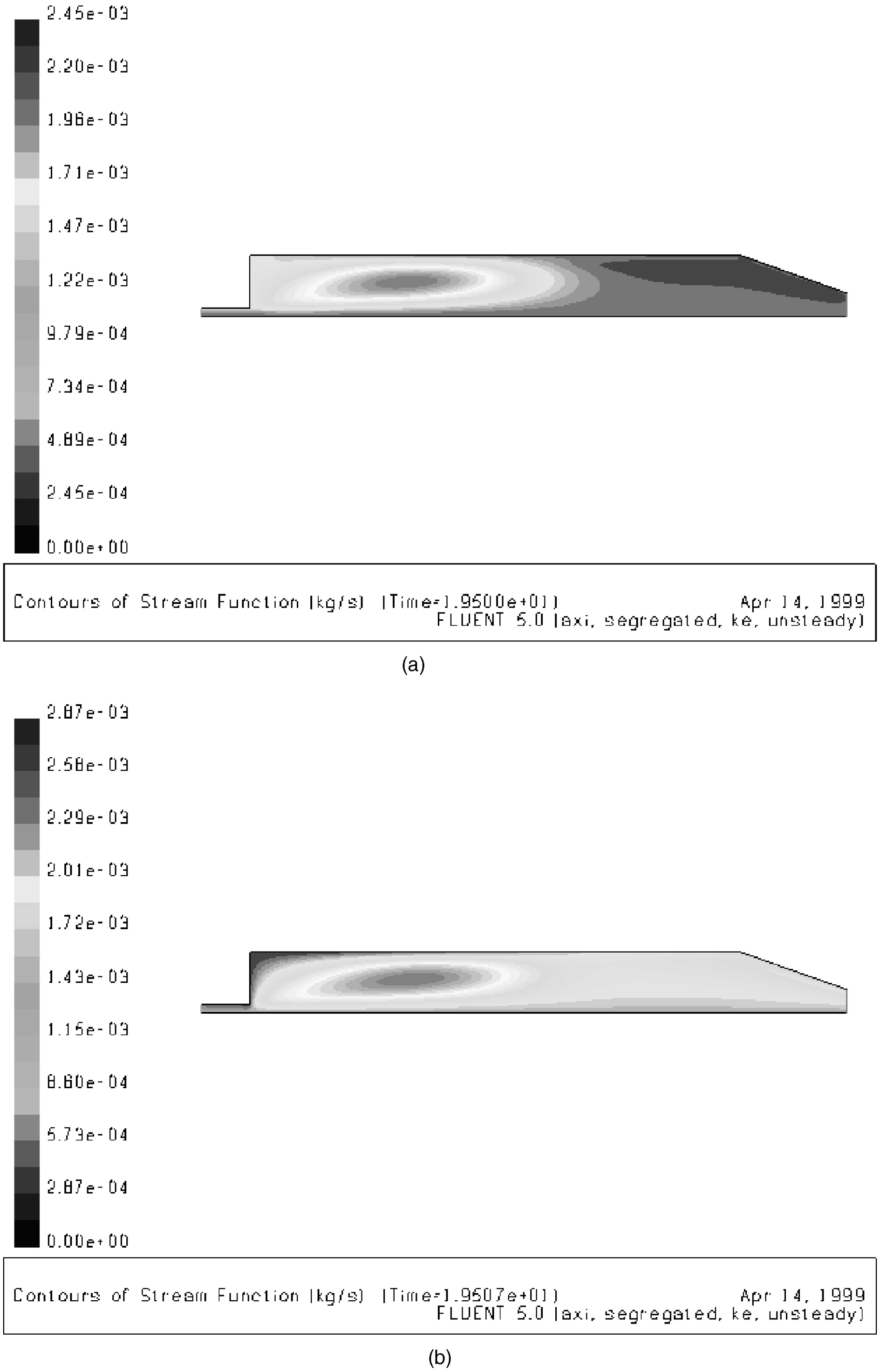


Fig. 19. Stream lines after (a) 19.500 s and (b) 19.507 s.

Simulations of water evaporation and drying of 5 and 10% NaCl aqueous solutions were performed. The initial injection parameters were defined using the Rosin–Rammler size distribution for particles and also by total mass flow rate, point of injection, temperature, velocity and time of injection.

Examples of results obtained during two-phase flow calculations are presented. Figs. 19 and 20 present particle trajectories (of water and 5% NaCl solution) in the dryer investigated after 1 s since the injection was initiated for the smallest feed rate, 5 kg/h and moderate angle of atomization (half cone angle = 28°). The initial gas temperature at the

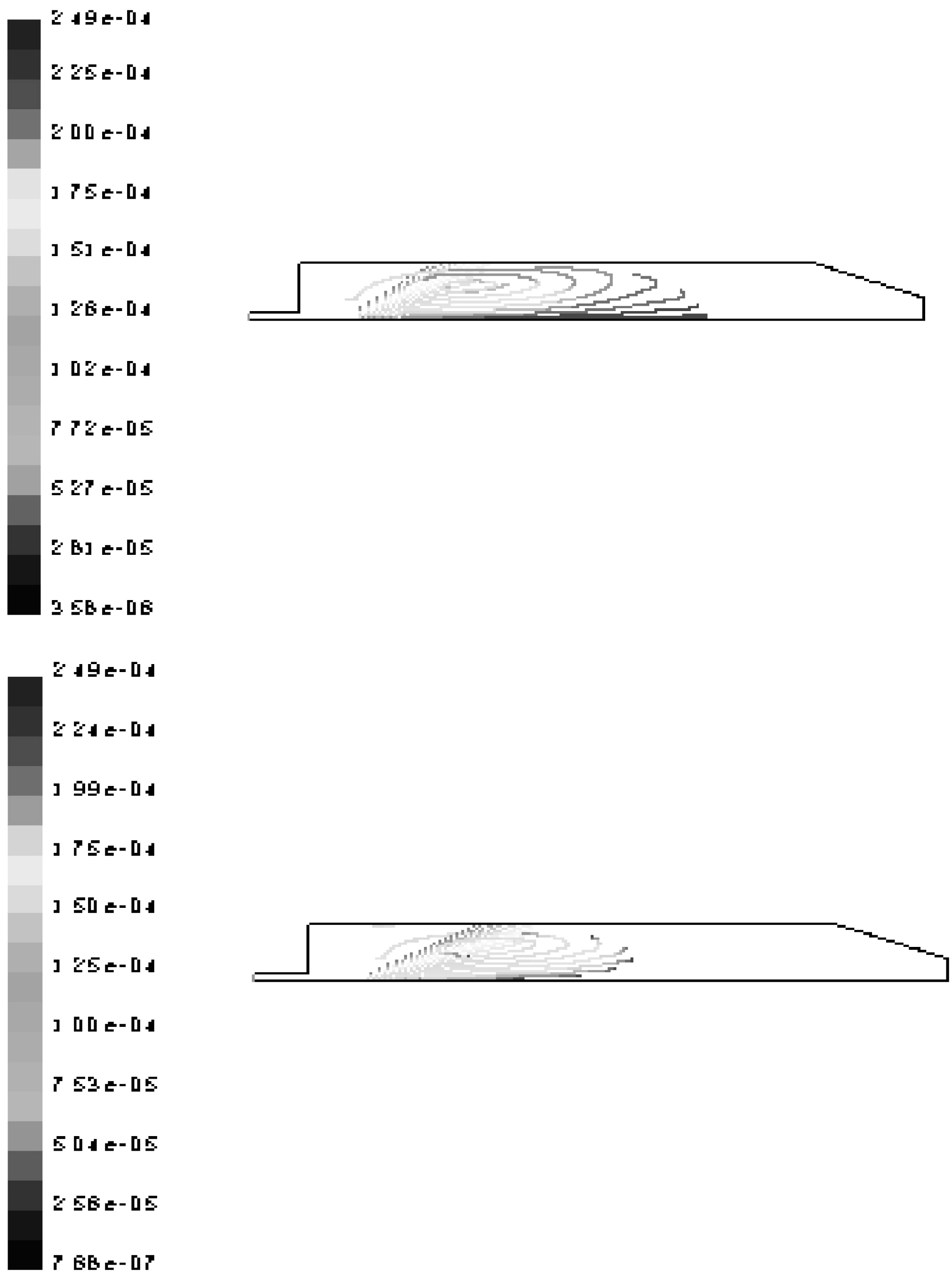


Fig. 20. Particle trajectories for water (8.4/5) and 5% NaCl solution (8.4/5).

inlet of modeled system was equal to 1105 K. Particles are colored by particle diameter.

Fractions with diameter greater than 170 μm hit the dryer wall. Fractions 30–125 μm recirculated in the dryer chamber. The evaporation was completed at 70 cm down from the dryer inlet which was confirmed experimentally.

Experimental analysis of the process proves that pulse combustion drying seemed to be an effective and economic way of dehydration. In relation to a classical spray drying process substantial intensification of drying rate was observed. In most cases water was evaporating rapidly in the vicinity of the atomizer. Similar conclusions were drawn from a mathematical analysis of the process. According to our knowledge, it was the first attempt to model the drying process in such environment and the results showed acceptable agreement.

The complexity of pulse combustion phenomenon and heat and mass transfer in pulsating flows require further investigations in this field and looking for more effective and complex models.

There are a number of literature attempts to estimate intensification of pulse combustion drying process in relation to classical drying processes. Nomura et al. [26], who performed extensive research on drying of bricks in the flow field generated by pulse combustor, showed five times higher drying rate than in a steady flow. Most of the researchers, like Kezerle [27], consider this value as too high. Kezerle mentioned the measured enhancement of droplet evaporation of only about 5%. Similar conclusions were presented in [13] for pulse combustion flash drying process (10%) and Zinn from 4.8 to 10.7% (according to [15]).

The results of our own calculations and experiments showed the intensification of drying process in the pulsating flow varying from 3 to about 25% in relation to the classical spray drying process. The comparison was made using the predicted values of drying rate.

7. Conclusions

Extensive experimental and theoretical research and literature survey on pulse combustion and pulse combustion spray drying allowed us to point out the following advantages of the pulse combustion applied in drying:

- compact drying equipment (improved heat transfer, high difference between the material and flue gas temperature, high drying rate);
- environmental friendly operation (low emission of toxic substances, low amount of air discharged to atmosphere, efficient combustion);
- wide variety of feedstock handled (sticky materials, heat sensitive products);
- better atomization and handling (no need of atomizer or HP nozzle);
- savings on auxiliary equipment (smaller motors, some of the equipment eliminated, a combustor delivers energy to run the dryer and displaces fan and requires less electrical energy).

The process of intensification comes from secondary atomization and stripping of the boundary but the effects cannot be separated due to the lack of suitable data. However, the most important factor accelerating the drying rate is definitely the high driving force of the process. The difference between gas and dried material temperatures (which may reach about 700–800 K at the inlet) controls drying time and creates rapid and efficient drying process.

Despite an increasing number of industrial applications and theoretical considerations the pulse combustion drying technique is still under development. Application and development of computational fluid dynamics (CFD) technique is recommended in designing of pulse combustion drying processes to avoid tiresome and costly experiments.

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