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High hydrostatic pressure food processing: An overview

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■ **Abstract :** High hydrostatic pressure processing (HHPP or HPP or HHP or Pascalization) is a non-thermal food preservation and processing technology that can inactivate food borne pathogens, spoilage micro-organisms and unfavourable enzymes without significantly altering organoleptic properties and nutritional value of foods. The pressure transmission is uniform and quasi-instantaneous during HHP regardless of the size and geometry of food, rendering the technology more effective and energy efficient. HPP utilizes intense pressure (about 400–600 MPa or 58,000–87,000 psi) at chilled or mild process temperatures (<45°C). Pressure treatment can be used to process both liquid and high-moisture-content solid foods. Although lethal to microorganisms, pressure treatment does not break covalent bonds and has a minimal effect on food chemistry. Thus, HPP provides a means for retaining food quality while avoiding the need for excessive thermal treatments or chemical preservatives. In addition to lengthening the shelf-life of food products, HHP can modify functional properties of components such as proteins, which in turn can lead to the development of new products. In light of these reasons, the use of HHP for processing food has resurged with the industry's renewed interest in its application. Within the last decade, a number of companies have introduced commercial grade high pressure systems thus providing food processors an opportunity to preserve foods and offering a process of choice for applications where alternative processing methods would adversely impact product quality.

■ **Key words :** Food preservation, Microbial inactivation, New technologies, Non-thermal processes

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The growing consumers demand for fresh, safe, chemical, additive orpreservative free and minimally processed foods has insisted the food scientists and technologists to developmany non-thermal food processing technologies which cause minimum nutritional and sensory qualitiesimpairment in the processed foods. In this endeavour, consumers prefer minimally or non-thermally processed foods rather than the thermally processed one.The use of high hydrostatic pressures (HHP) for food processing is finding increased application within the food industry. One of the advantages of this technology is that because it does not use heat, sensory, and nutritional attributes of the product remain virtually unaffected, thus yielding products with better quality than those processed traditional methods. Therefore, it can be used to improve quality and safety of food products, and to extend the shelf life of products. During HHPP, foods (soft solids or liquids, packaged or unpackaged) may be subjected to pressures upto 1000 MPa (145,000 psi), which is equivalent to the pressure on a 15 mm diameter coin when three big elephants, each weighing 4-5 tons, are made to stand on it. For the sake of comparison, pressure on top of the Everest peak is 0.03 MPa and pressure at the deepest place in the Pacific ocean is about 100 MPa. Although the proof of concept of HHPP was demonstrated more than hundred years ago, its utility and successful applications to food products have been demonstrated only in the last couple of decades. HHP have the ability to inactivate microorganisms as well as enzymes responsible for shortening the life of a product. In addition to lengthening the shelf-life of food products, HHP can modify functional properties of components such as proteins, which in turn can lead to the development of new products. Equipment for large-scale production of HHP processed products are commercially available nowadays. In the present article, anattempt has been made to give an insight about the high pressure processing of foods, its principle, processdesign and effects of HHP on food products.

Brief History of development of high hydrostatic pressure food processing :

HHPP was first demonstrated as a possible food preservation process in 1899 by Bert H. Hite at West Virginia Agricultural Experimental Station (Hoover *et al.*, 1989 and Knorr, 1999). Hite showed that high pressure treatment can delay the souring of milk at ambient temperatures (Knorr, 2003). The technology did not attract wide recognition in this period due to non-availability of suitable high pressure equipment (Rastogi *et al.*, 2007) but it re-surfaced in the food industry in the late 1980s. Between 1982-1988, Daniel Farkas, Dallas Hoover, and Dietrich Knorr at the University of Delaware attempted to repeat Hite's work using a cold isostatic press and showed that pressures of 350 MPa (50,000 psi) can inactivate a wide range of pathogenic and spoilage microbes. During the same period, studies were undertaken in Japan on preservation of foods by high pressure. In 1992, commercialized high pressure processed products (high acid products including apple, strawberry, and pineapple jams) were marketed in Japan (Hayashi, 2002). Since then, high pressure processing has also been applied to fruit preserves, raw squid, grape juice, and mandarin orange juice in Japan (Hayakawa *et al.*, 1996 and Rastogi *et al.*, 2007).High pressure processed foods are available in the markets of Japan since 1992 (Suzuki, 2002), and in Europe and in the United States since 1996 (Knorr, 1999).

In the U.S., the impetus for high pressure technology came from the U.S. Army research center in Natick, Massachusetts, in order to develop better quality MREs (Meal Ready to Eat) for the troops. Collaborations between the University of Delaware and the Oregon State University lead to successful demonstration of preservation of spaghetti with meat sauce, spanish rice, yogurt with peaches and a fruit mix, using HHPP. Samples were shown to be microbiologically stable for upto 120 days at room temperature (Farkas, 2007). The first commercial high pressure product in the U.S. was Avo Classic Guacamole (a heat sensitive product) with extended refrigerated shelf life and manufactured by Avomex, Inc., Keller, TX. Recently, a leading Mexican manufacturer of juices and nectars, Grupo Jumex, utilized HHPP for their juice and smoothie product lines. Also, growing concern for seafood safety led seafood processors to explore this technology and show many benefits, such as, almost 100% meat separation from shell of clams, crabs, lobsters, and oysters, with increased yield without any mechanical damage to the meat. Other, commercially available high pressure processed products in Australia, Europe and the U.S. include juice, tomato salsa, smoothies, fruit and vegetable purees, and ready to eat meats. The high pressure technology is expanding rapidly for new product development and product improvements in others segments of food industry, such as, the dairy sector (cheese, yogurt, and mayonnaise). Since HHPP has minimal detrimental impact on thermally labile bioactive ingredients, the technology is becoming a topic of major interest for cosmetic, nutraceutical and pharmaceutical industry.

Basic principles of HHPP :

The two basic principles that govern the effect of high pressure processing of foods are Pascal's isostatic principle and Le Chatelier's principle. As mentioned earlier, HHPP can be used for both liquids and (soft) solid foods. Foods containing air pockets such as whole strawberries, breads, whole eggs, marshmallows are not suitable because these products can collapse under HHP. Also, products in rigid containers such as metal cans and glass bottles cannot process by HHP because the containers will crack or burst under HHP.

According to Pascal's isostatic principle high pressure acts uniformly and instantly throughout liquids and soft solids. Therefore, the process time is independent of the volume and shape of the food product. Isostaticity, *i.e.*, uniform pressure distribution, in a food product subjected to HHPP is valid for homogeneous, isotropic foods, but it may not hold for heterogeneous and unisotropic food products such as meats containing bones and muscle fibres. This issue of pressure non-uniformity remains unresolved and is an active research area.

The physico-chemical changes occurring during HHPP follow the Le Chatelier's principle, which states that any reaction, conformational change, or phase transition that is accompanied by a decrease in volume will be favored at high pressures, while reactions involving an increase in volume will be inhibited (Lopez-Malo *et al.*, 2000).

A thermodynamic outcome of high pressure processing is the heat of compression. Although many food and non-food materials are incompressible at atmospheric and low pressures, they get compressed under very high pressure. The work done to compress a material under pressure gets converted into heat which increases the temperature of the substance. This is called as adiabatic heat of compression and is usually expressed as temperature rise per 100 MPa increase in pressure. Typical values of adiabatic heat of compression are: 3° C for water, 6-9° C for cooking oils and fatty foods, and 30° C for synthetic chemicals such as hexane. For most foods containing water, carbohydrates, fats, protein, the range of values for adiabatic heat of compression is 3-6° C. Therefore, although HHPP is considered as a non-thermal process, in some situations pressure increase will result in significant temperature rise.

High pressure process and equipment description:

High pressure food processing is a batch operation wherein food products are processed usually in packages with very little head space or gas. Although the effect of high pressure on foods upto 1000 MPa (145,000 psi) has been investigated in laboratory scale vessels, for the commercial applications the equipment design limitations restrict the pressure levels to 690 MPa (100,000 psi). High pressure food processing equipment with pressures upto 690 MPa and temperatures in the range of 5^0 C to 120^0 C are currently available to the food industry for large scale processing (Henry and Chapman, 2002).

A high pressure food processing unit operation consists of a cylindrical steel vessel with high tensile strength, two end closures, a yoke for restraining end closures direct or indirect pressure pumps for pressure generation, pressure and temperature controls, and loading and unloading equipment. Commercial high pressure units are available in vertical or horizontal vessel orientations. The vertical vessels are more common for small and medium capacity (upto ~320 liters) pressure vessels. As the demand for high pressure processed products increased and the technology was more commercialized, there was a need for higher capacity vessels. From high pressure vessel design, safety and mechanical strength point of view, it is always recommended to increase length of the cylinder instead of radius for higher capacity vessels. Longer vessels in vertical orientation can pose various problems such instability, difficulty in loading, and high ceiling. Today most high capacity (~1000 litres) vessels come in horizontal orientation. In addition loading can be done from one end and unloading from the other end, which allows ease of separation of processed and unprocessed products.

In a typical HHPP operation, food products are vacuum packed (some products like shell fish are banded and placed in a mesh bag) in flexible pouches or containers and loaded in the vessel, the vessel is then filled with a pressure transmitting medium, usually filtered water. The high pressure process is then accomplished in three stages: compression (pressurization) stage where pressure is increased from ambient atmospheric pressure to the desired high pressure. During the pressurization the temperature of water and food products inside the vessel may increase due to adiabatic compression heating. The pressurization stage is followed by a pressure holding stage where the pressure is held constant at the elevated pressure level for several minutes. Finally, the pressure is reduced to atmospheric during depressurization stage. The product is then taken out for further handling.

High pressure can be generated in two ways: direct compression and indirect compression. In direct compression a piston with a large end and a small end is used. The large end of the piston is connected to a low pressure pump and small end is used to apply pressure on the transmitting medium. Indirect compression uses a high pressure intensifier to pump the pressurizing medium from a reservoir directly into a closed and de-aerated vessel until desired pressure is reached.

Two of the major manufacturers of high pressure equipment are Avure Technologies Incorporated (USA) and NC Hiperbaric (Spain). Other high pressure equipment manufactures include Elmhurst Research, Inc. (USA), Engineered Pressure Systems International (Belgium)/ Engineered Pressure Systems Incorporated (USA), UHDE Hockdrucktechnik (Germany), Stansted Fluid Power (UK), Resato International (Netherlands), Kobe Steel (Japan), ACB Pressure System-Alstom (France), and UNIPRESS (Poland).

Effect of HHPP on food products :

HHPP can result in products with novel structure and texture, or increased functionality of certain ingredients providing the possibility for development of new food products (Rastogi *et al.*, 2007). HHPP has been shown to be useful for improving shelf life of yogurt and defrosting frozen seafood (Hayakawa *et al.*, 1996). It has also been shown to improve rennet or acid coagulation of whey proteins and increase cheese yield (Trujillo *et al.*, 2000). HHPP can be used to design or improve existing products like cream caramel with fresher taste and better texture (Ponce *et al.*, 1998). HHPP treatment may increase mass transfer and juice yield, and enhance drying. HHPP can result in improved release of metabolites from plants and reduced fat uptake of French fries (Knorr, 1999). A reduction of 40% in oil uptake during frying was observed, when thermally blanched frozen potatoes were replaced by high pressure blanched potatoes (Rastogi *et al.*, 2007). De Ancos *et al.* (2000) have found that carotenoid and vitamin A in orange juice could be extracted better with increasing pressure from 100 to 400 MPa.

Combination of high pressure and high temperature :

Since HHPP at or near room temperature is unable to destroy bacterial spores (e.g., *Clostridium botulinum*), it is not suitable for processing low-acid foods. It was found that combination of high pressure and moderate to high temperatures can inactivate spores which led to a petition to the FDA for the commercial use of pressure-assisted thermal sterilization (PATS) (Balasubramaniam, 2009). In the case of PATS, high pressure is only used as a means to reach the regular commercial sterilization temperatures, more rapidly and uniformly, through adiabatic compression heating.

Pressure cycling :

Pressure cycling has also been explored as a method to boost the lethality of the process. In pressure cycling, the high pressure chamber depressurized and pressurized for multiple cycles. Pressure cycling has been found to be efficient in enhancing microbial inactivation (Bradley *et al.*, 2000).

Mass transfer during high pressure processing :

High pressure induced mass transfer has been investigated as an improvement over regular osmotic dehydration processes. High pressure processing disrupt the cell membranes of the substrate, which may allow a much faster mass transfer process and therefore dramatically reducing the time needed. (Dornenburg and Knorr, 1993; Rastogi and Niranjan, 1998; Rastogi *et al.*, 2000 and Mahadevan and Karwe, 2011). The improvement in mass transfer due to high pressure processing has not attracted nearly as much attention as microbial inactivation and extension of shelf life.

Effect of high pressure on bioactive compounds in foods :

In general, high pressure processing is considered to have slight effect on covalent bonds (Rastogi *et al.*, 2007). Based on current knowledge, HHPP at moderate temperatures can maintain bioactive compound stability in fruit and vegetable based products. HHPP carried out at elevated temperatures (e.g. PATS applications), however, can cause decay of these bioactive compounds. Bioactive compound stability is highly influenced by chemical reactions that are favored under high pressure. For example, chemical reactions accompanied by a decrease in volume, such as *trans*- to *cis*- isomerization in carotenoids (Qiu *et al.*, 2006 and Varma *et al.*, 2010) or anthocyanin condensation reactions forming pyran rings, are enhanced under pressure (Corrales *et al.*, 2008). Enzyme activity (activation/inactivation) is another major factor implicated in bioactive compound stability/ instability. Furthermore, presence of vitamin C or L-ascorbic acid in food products has also shown to influence bioactive compound stability under pressure. For example, folate oxidation in the presence of ascorbic acid is reduced (Indrawati *et al.*, 2004 and Verlinde *et al.*, 2008), however, ascorbic acid greatly enhanced oxidation of thiamin and thiamin monophosphate (Oey *et al.*, 2008).

Economics of high pressure processing :

For a new technology such as HHPP to be successful commercially it should provide opportunities for improving quality and safety of food products with minimal increase in cost. Although, at present HHPP is more expensive operation compared to conventional thermal processing, HHPP offers a technology to make value added products (by retaining nutritional components, color, flavor and texture) with longer shelf life. It has been successfully applied for niche products such as seafood, guacamole, and expensive fruit products. A typical investment for a commercial high pressure processing unit is in the range US$500,000 to US$ 2.5 million (depending on the equipment capacity) of which 50-60% is for the high pressure vessel, closures, and yoke. The main factors that govern the cost of processing are capital cost, energy requirements, ancillary equipment, and the maintenance. Similar to other food processing technologies, increasing the vessel volume decreases the cost per unit product. Generally, the energy cost is low, about 2-4% of the total cost. The maintenance of the system demands frequent replacement of the static or dynamic seals which is about 5% of the investment cost per year. Over the last 12 years, decreasing capital equipment cost and operating costs of high pressure technology has made the technology more affordable for certain products.

Future of HHPP:

High hydrostatic pressure processing is one of the most promising non-thermal food processing technologies and has been shown to be relatively more successful commercially for niche products such as shell-fish, avocado paste, and fruit pulps. Since HHPP cannot inactivate spores at room temperature, it cannot be used to increase the safety of low-acid (pH>4.5) food products. The mechanism of inactivation of microorganisms by HHPP is still not well known and remains an active research area. From a practical point of view, HHPP still remains a batch process, with relatively high capital investment and low to moderate production capacity, making it unsuitable for high volume products such as orange juice and milk. Since HHPP can be applied in post packaging, it could provide unique opportunities in processing and handling pharmaceuticals, biological tissues, and medical devices. HHPP has been shown to increase the extractive yield and accessibility of bioactive compounds from plant based materials, therefore, its applications in the preparation of Ayurvedic medicines should be explored.

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