Progress and Innovations of Ice Slurry Generation Based on Scraped-surface Method

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Abstract. In recent years, as a new type of ice storage medium, ice slurry has been widely applied in multiple fields. The scraped-surface method has remained the focus of researches, thanks to its advantages such as technical maturity, low cost and stable performance, etc. In this paper, the attributes of ice slurry was briefly introduced and then an analysis and comparison of several common ice slurry generation methods was presented with a summary of the advantages of the scraped-surface method. Then, the current research status of scraping-type ice slurry generation method was introduced. In the final place, this paper would summarizes the existing research fruition and propose a zigzag scraper, and future development and trend are looked forward to.

1. Introduction
Ice slurry, also recognized as pumpable ice, is a new kind of secondary refrigerant, which has both the ice storage capacity of ice and the fluidity of aqueous solution. Compared with traditional counterparts, ice slurry has a fast cooling rate, high ice storage density, and are small and round as well as convenient for transportation, etc. Ice slurry is also widely used in many applications, such as aquatic product preservation, medical and health care, mine cooling, regional cool supply, etc. Ice slurry has outstanding advantages in the food industry, especially in the preservation of aquatic products. In previous years, it has become more prevalent for ice slurry to be applied in aquatic products preservation. It is reported that ice slurry can greatly prolong the shelf life of aquatic products, and that the effect is more significant with specific additives. With the mounting demand, the preparation techniques of ice slurry have enjoyed extensive attention from related research and development departments, universities as well as enterprises. The scraped-surface method, as a widely accepted method, has yielded numerous results.

2. Characteristics of ice slurry
Ice slurry refers to a two-phase solution composed of ice particles with a diameter of less than 1mm (typically 0.1 to 1 mm in diameter) and a carrier solution, which has sensible heat and transformation latent heat in low temperature. Ice slurry with good performance is usually precipitated from aqueous solution containing freezing point inhibitors through cooling and crystallization. The particles produced thereby are round, smooth and more fluid.
Irregular in shape and sharp in edges, most of the traditional ice is inclined to bruise the epidermis of aquatic produce. On the contrary, the small and soft spherical crystals will guarantee the quality rather than cause damage to the surface of aquatic products in the process of storage and transportation. Ice slurry particles are tiny in size, and the size of seawater ice slurry is about 1/500\(^1\) of that of traditional forms of ice, allowing them to flow into crevices between aquatic products and create a hermetic zone. In this way, oxidative deterioration of aquatic products can be effectively avoided, and faster and uniformed cooling is thereby provided. With the use of ice slurry in preservation, it is possible to delay the corruption of aquatic products and extend the shelf lifespan of aquatic products; The preparation process should be sealed continuously and clean to forestall secondary contamination in aquatic products.

3. Ice Slurry Production Methods

At present, the production methods of ice slurry primarily include the scraped-surface method, supercooling method, vacuum method, fluidized-bed method and direct contact method. Supercooling dynamic ice slurry generation technology uses the supercooling phenomenon of water to generate ice crystals by removing the supercooled phenomenon in presence of interference from specific equipment when water reaches the freezing point. Vacuum method is based on the principle that water co-existence at three-phase point. The surface of water droplets evaporates and absorbs heat in a vacuum with low pressure, and then through internal exothermic reaction and crystallization an ice-water mixture is produced. Fluidized-bed method, as a novel type for ice slurry production, designed by Meewisse [2] and Pronk [3] on the basis of industrial fluidized-bed heat exchangers, is still in experimental stage up to now. The method that injects refrigerant insoluble in water into the fluidized ice generator, making refrigerant directly contacting and exchanging heat with water [4] to make ice, is called direct contact method. Each method has its own merits and drawbacks, as shown in Table 1.

Table 1. Comparison of advantages and disadvantages of common fluid ice making methods.

| Ice production method   | Advantages                                      | Disadvantages                                      |
|------------------------|------------------------------------------------|---------------------------------------------------|
| The scraped-surface method | Stable performance, ice particles generated are fine and even | Low efficiency, scrapers wear easily |
| Supercooling method     | Technical maturity, mass production available  | Ice blockage, low ice packing fraction             |
| Vacuum method           | Secure and environment-friendly, higher thermal efficiency | High requirements for ice production condition, hard to put into mass production |
| Fluidized-bed method    | Shell and tube structure, easy to operate      | Hard to control making process, larger refrigerant consumption |
| Direct contact method   | Simple structure, higher heat transfer         | Larger refrigerant consumption, impurities in particles, ice blockage in nozzle occasionally |

The scraped-surface method outstrips other counterparts with regard to following aspects:

1) Technical maturity and popularity. The scraped-surface method is technologically developed and easy to operate and enjoys high popularity, in comparison with methods such as vacuum method, fluidized-bed method and flow film method.

2) Stable performance and the ice grains are even and fine. The scraped-surface method is moderately stable, and the ice particles are fine and uniform.

3) Mass production feasible in accordance with commercial interests. The scraped-surface method is outstanding in that it can realize large-scale ice making. At present, as ice slurry mass production methods are inadequate, only the scraped-surface method and supercooling method can achieve commercial use to a certain degree. As ice blockage problem is salient in supercooling method, the
scraped-surface method is the most extensively adopted method and considered to be more stable in ice production.

4. Ice Slurry Production by scraped-surface method

4.1. Principle of Ice Slurry Production by scraped-surface method
Refrigerant is introduced into a shell-and-tube ice slurry generator consisting of inner and outer concentric tubes, and the heat transfer between the refrigerant and aqueous solution occurs, hence the ice crystals are generated on the wall. A rotational scraper with scrapers mounted in the center of the tube works driven by ice slurry generation reducer to prevent the ice crystals from depositing on and sticking to the wall surface. The ice crystals scraped off the from the inner wall surface mix with the solution to form ice slurry which flows out at the outlet and is finally deposited in a storage tank. According to the difference in nucleation mechanisms, the ice slurry generation methods are divided into two categories, i.e. homogeneous nucleation and heterogeneous nucleation. The scraped-surface method falls into the latter, which requires antifreeze be added to the solution. Antifreeze commonly used includes ethanol, sodium chloride, ethylene glycol, calcium chloride, etc.

4.2. Equipment for Making Ice slurry by Scraped-surface method
The devices using scraped-surface method for ice slurry generation are various, and there are many options according to conditions, usage, etc. Although a device has diverse forms, it is basically composed of evaporator, condenser, compressor, decelerator, scraper, drying filter, thermal expansion valve, gas-liquid separator and ice storage tank, etc. Among which, the evaporator, i.e. ice slurry generator plays an important role, where the heat transfer occurs between the solution and refrigerant and engenders ice crystals. The scraper of the ice generation device is mounted in an ice slurry generator and driven by a decelerator. It scarpes off ice crystals deposited on the wall surface, and the rotating speed of the scraper can be adjusted by changing the frequency. There are mainly two methods for ice slurry generators to scrape off ice particles according to scraping forms, namely rotary scrape and planetary rotary scrape, as shown in Figure 1.

5. Research status and innovation

5.1. Research status On ice slurry generation with scraped-surface method
Researchers both at home and abroad have conducted a plethora of exploration and study with regard to the scraped-surface method in ice slurry production. Stamatiou et al. [5] made a thorough summary on the method and principle of ice slurry production. It is pointed out that the ice crystals scraped off
the wall surface cannot be well mixed with the solution, and uniform ice slurry can only be obtained by means of stirring machines, thus increasing the mechanical energy consumption. In addition, factors involving that the scraping equipment is intricate, that scrapers are easy to wear, and that the ice agglomeration on the wall will engender ice blockage, limit the further advancement and application of the scraped-surface method. At present, attention has been paid mostly to equipment enhancement and innovation on systematic efficiency, scraper design and ice blockage solution, etc., and to parameters relevant to better performance, such as the scraper speed, influx and efflux, and temperature, etc.

In terms of simulation. Yang xukai et al. [6] used Fluent to simulate the solidification of sodium chloride solution, and found that the simulation results were consistent with the theory. Nonetheless, in reality, the solidification of sodium chloride solution was more complicated, and the model was a simplified ideal one which remained to be further improved. Yataghene et al. [7] made an analysis of the forced convective heat transfer encompassing viscous dissipation in scraping heat exchanger, and carried out experimental and numerical research on temperature rise incurred by viscous dissipation, using Fluent to solve momentum and energy equations and conducting simulation of heat transfer including viscous dissipation. Qin et al [8] studied the heat transfer of the heat exchanger in the scraping ice maker by establishing the mathematical model of the crystallization wall and carrying out experimental study. Jia Xueying et al. [9] stimulated the dynamic crystallization of solution in scrapper ice maker by establishing a multidimensional model of crystals, and with which obtained and analyzed the distribution of grain density and nephogram under diverse external conditions such as scraper rotation speed, temperature, and ice making time, etc. Pascual et al. [10] numerically simulated the effect of scraper shape on ice scraping and mixing degree of ice slurry and analyzed the results, providing theory for scraper design. Wang puze et al. [11] simulated the heat exchanger of the scraping type of ice maker with Simulink, and analyzed the response attributes of the ice maker, which serves as references for further optimization of the machine and improvement of its components.

In terms of the improvement of ice slurry generation performance. Matsumoto et al. [12] expounded the influence of the changes in parameters such as scraping force, supercooling degree of solution, freezing time, solution concentration, surface temperature and surface roughness of carbon steel on the ice slurry generation performance, and classified the scraping behavior of carbon steel surface. Leiper et al. [13] mixed ice particles crushed from larger ice with solution containing freezing point inhibitors for ice making, and compared the process with one in absence of crushed ice particles which was later proved to be energy-saving through the experiment. Martinez et al. [14] analyzed the heat transfer phenomenon of the heat exchanger, by the ice slurry generation experiment with sodium chloride brine 7% by mass percent, and measured the heat transfer coefficient and ice-producing rate under intermittent operation mode. Wang Feibo et al. [15] conducted experiments using sodium chloride solution and ethylene glycol solution as ice generation solutions. The research showed that the speed of ice generation with sodium chloride solution was faster while the ice generation with ethylene glycol solution obtained higher refrigeration performance, and reduced the mass fraction of the solution, and that raising properly the solution flow rate can curtail the ice generation time and increase the cooling capacity. Rao Zhiming et al. [16] conducted a study on ice storage system performance with scraper type, and calculated the energy efficiency ratio based on the analysis of the inlet and outlet temperatures of the condenser and evaporator as well as the flow curve of cooling water.

In terms of equipment innovation. Huang cheng et al. [17] proposed a new spiral scraping method for ice slurry generation. This method integrates the scraped-surface method with supercooling method, which is conducive to solve the problems such as easy ice blockage and low ice packing fraction, etc., and alleviates the common scraping methods’ drawbacks of insufficient heat transfer area and low yield. However, only taking glycol solution as the ice slurry generation solution, it is unpredictable whether other solutions will have the same effect. As the traditional scraped-surface method consumes a large quantity of energy, Goulet et al. [18] proposed a new scraped surface approach with spiral tube, which not only outperforms in energy saving, but also in improving the
turbulence level and heat transfer efficiency of solutions. Wang Zepu et al. [19] put forward a fluidized ice machine with dual evaporator to ameliorate the failure of traditional single evaporator to match well the performance of compressor in the pre-cooling stage, hence improving the overall efficiency. It was proved that the cooling rate and coefficient of performance were improved, especially in the absence of larger flow rate of ice generation solution. Cheng zhiming et al. [20] proposed the seawater ice slurry generation equipment with improvement in the PLC of the electrical control system, which could regulate and control the working conditions of seawater ice generation equipment. Wang zhen [21] optimized the tube of the evaporator, replacing the circular tube with a semicircular tube, which increased the heat transfer efficiency by 35%. Adeniyi et al. [22] designed a mixed ice filter, which can separate ice slurry from mine waste waters and reuse it. Martínez et al [23] proposed an innovative embedded thermocouple wall temperature measurement technique, which helped overcome the difficulty in wall temperature measurement.

5.2. Innovation On ice slurry generation with Rotary scraped-surface method

There are two shortcomings in the common rotary scraped-surface type of ice slurry generator. One is that the scraper is prone to wear and even broke due to the continuous contact with ice crystals on the wall. Another pitfall of it involves ice blockage, i.e. ice accumulating in large amounts within a given period due to changes in one or more parameters in the ice slurry generation machine at a certain time, which affected the generation process and converted the generation effect and engender malfunction of the generator.

According to the operation principle of scraper for fluidizing ice by rotary scraping method, the cross-section of scraper can be shaped into a zigzag to facilitate the traditional ice slurry generation machine, as shown in figure 2.

![Cross section of scraper](image)

Figure 2. The improved scraped-surface type of ice slurry generator.

6. Summary

(1) Ice slurry, as a new type of fast and efficient ice storage medium, has enjoyed extensive popularity. It is applied in multiple fields. In contrast, the scraped-surface method holds certain virtues and predominates in practice. In this paper, research status on ice slurry generation with scraped-surface method is analyzed.

(2) The rotary scraped-surface type of ice slurry generator designed in this paper can extend area of thrust surface between scraper and ice, effectively reducing the wear of scraper. It also has stronger
ice-breaking ability, which can still work in case of ice blockage, improving the energy efficiency and solving the ice blockage problem.

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