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Experimental Study on Ice Slurry Generations with Sodium Chloride Solution-based Concentrations and Flow-rates

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Ruhama Sidqy[1], Agus Sujarianto Pamitran[1,*]

[1] Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, kampus UI Depok 16424, Indonesia

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ABSTRACT

This study was aimed at observing the effects of factors such as flow rates and concentrations on the rate of temperature reduction, the degree of supercooling, and ice fractions. The study was conducted with various flow rates amounting to 6.2, 7.9, 9.5, and 11.2 L/min, and various concentrations amounting to 3%, 4%, and 5% using NaCl solution. Ice slurry generators were expected to produce high ice fraction with minimum energy consumption. In the cooling process, the solution temperature dropped below the freezing point of pure water until it hit the minimum value called the degree of supercooling. The flow rate of 7.9 L / min and the concentration of 3% is the most optimum value among the other variations for the purpose of the highest temperature reduction speed and the lowest degree of supercooling. The most optimum flow rate among the other variations to produce the highest ice fraction in the fastest time is also 7.9 L / min.

Keywords:
Ice slurry; sodium chloride; concentrations; flow rates

1. Introduction

Ice slurry has a high energy storage density due to the latent heat of its ice crystal fusion. Moreover, it has a fast cooling rate due to the immense heat transfer surface area created by its numerous particles. The slurry maintains a constant low-temperature level during the cooling process and provides a higher heat transfer coefficient than that of water or of other single-phase liquids. These ice slurry features make it taken advantage of in various applications [1]. Ice slurry has better transport properties in the tube and heat exchangers. The pump’s energy consumption to transport the ice slurry is only about one-eight of the energy consumption necessary in a traditional single-phase secondary refrigerant system. Therefore, ice slurry is believed to be a very promising secondary refrigerant in the future [2]. The slurry ice technology has shown more profitable advantages when developed in the manufacturing process of chilled aquatic species products than that of traditional flake ice [3].

* *Corresponding author.*
E-mail address: pamitran@eng.ui.ac.id

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Sodium chloride, ethanol, ethylene glycol, and propylene glycol are the four most commonly-used freezing point depressants in the industry [1]. In this study, sodium chloride was used because it is an environmentally friendly phase change material (PCM) and non-toxic secondary refrigerant with high latent heat and high thermal conductivity [4]. There are many methods to generate ice slurry [5]; the mechanical scraping method is one of them. At present, most of the ice slurries produced by a mechanical scraper-type generator have an average particle size ranging from 100 μm to 200 μm [6]. The weakness of this method is that an ice layer will form on the cooling surface of the heat exchanger and must be removed by scraping. Because of the strong adhesion between the ice layer and the cooling surface, this scraping method requires a large amount of energy consumption and costs [7]. Therefore, further research is needed to reduce energy consumption and costs for ice slurry generation.

Current studies on ice slurry can be categorized into three groups: (1) system design and optimization for the generation, (2) the flow and heat transfer characters, and (3) the mechanisms and kinetics of its formation. Mohamad *et al.,* [8] concluded that inorganic salt hydrated with graphene nanoplatelets (GNP) was acceptable for low thermal energy storage application. Brooks *et al.,* [9] investigated another method to produce ice slurry where brine is supercooled by 4-6 K in a helically coiled heat exchanger (HCHX). Bédécarrats *et al.,* [10] studied the feasibility of a stable supercooled ice slurry generator. Ben *et al.,* [11] characterized the effects of various parameters (the flow rate, blade rotation speed, the distance between blades and wall, and product concentration) on the heat transfer for two products (water-ethanol mixture and aqueous sucrose solution) experimentally. Liu *et al.,* [12] studied the effects of sodium chloride concentration, scraping speed, and solution flow rates on the performance of ice slurry production. Kousksou *et al.,* [6] built a physical model to study the non-isothermal freezing kinetic in an ice slurry system. Chégnimonhan *et al.,* [13] studied the ice slurry crystallization process using kinetic tools integrated with the glide temperature for the mixtures without any equilibrium assumption.

Whatever the field of applications related to solidification, the central interest is the rate at which solidification occurs [14]. The process of solidification is dependent on temperature. Therefore, this study aims to investigate variations in the temperature of the ice slurry solution over time and the effect of flow rates on the rate of temperature reduction. Another problem is related to energy consumption that is affected by supercooling, which is further cooling below the freezing point. Supercooling can lead to higher energy consumption [15]. In addition, the longer the time needed to reach the degree of supercooling, the greater the energy consumed by the generator. Therefore, another purpose of this research is to study the effect of flow rates and concentration of the solution on the degree of supercooling and the time needed to achieve the degree of supercooling. Finally, the ice slurry generator is also expected to be able to produce ice with a high fraction. Therefore, the effect of flow rates on the ice fraction produced will also be studied.

2. Methodology

The system used to produce ice slurry in this study, as shown in Figure 1, consisted of a vapor compression refrigeration system, a circulation system of a NaCl solution with a centrifugal pump, and a mechanical scraped-surface cylindrical-type heat exchanger. The refrigeration system consisted of a condenser, compressor, filter, and throttle valve. This system was designed to observe the effect of the flow rate and concentration of the solutions on the temperature decrease, degree of supercooling, and growth of the ice fraction. Each experiment was conducted at a 25°C room temperature and a 0.1 MPa pressure; the mass of NaCl solution circulating through the system was

10 kg. Each parameter is obtained from the measurement results for a maximum of three measurements.

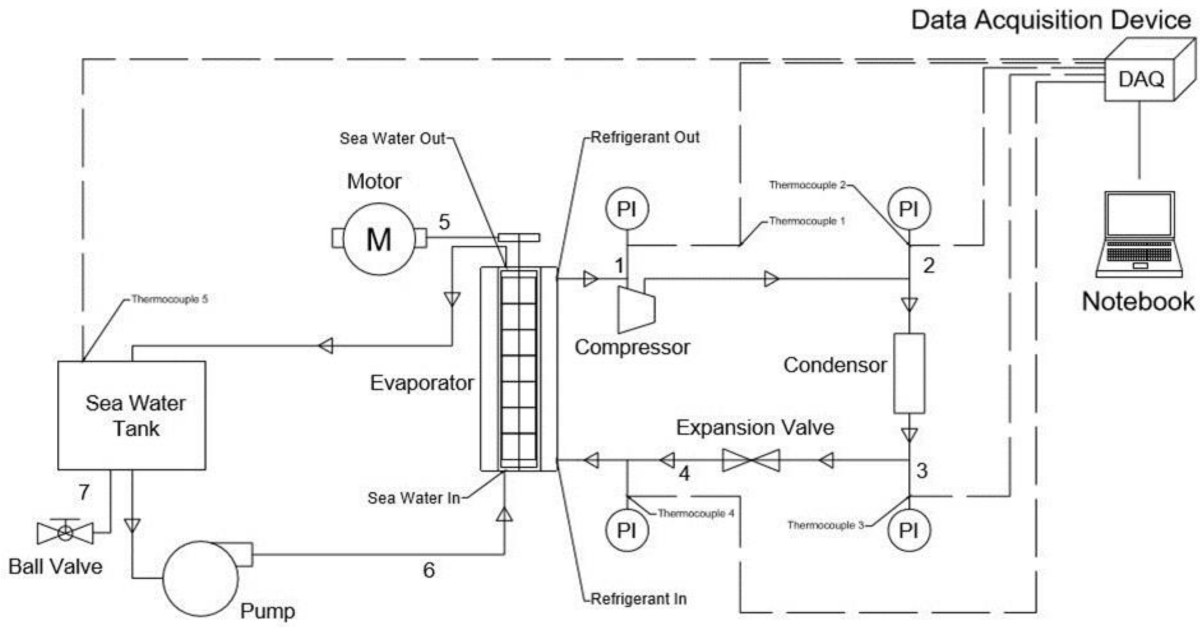

Fig. 1. The schematic diagram of an ice slurry producing device

The salt used in this study was cooking salt commonly traded in Indonesia in order that the ice slurry was produced from materials easily obtained and did not have harmful effects when applied as a food cooling medium, especially seafood. This iodized salt contained KJO_3 compounds with a 30/80-part-per-million-(ppm) level. The NaCl concentrations were 3%, 4%, and 5%. The concentration chosen was not too high because it can increase the degree of supercooling [4], which can ultimately increase energy consumption. The flow rates were 6.2, 7.9, 9.5, and 11.2 L/min. These flow rates were chosen because if it is too low, it will be difficult to pump the solution because some of it has become solid, and its viscosity has increased [16], otherwise, if the flow rates were too high then the possibility of leakage in the evaporator will increase.

The main component of the ice slurry production system was the evaporator, as Figure 2 showed us. The evaporator consisted of two cylinders of stainless steel 316. The diameter of the inner cylinder was 10 cm, and the diameter of the outer cylinder was 15 cm. The length of both cylinders was 33.75 cm. The total length of the evaporator, including the scraper shaft, was 50 cm. The distance between the scraper and the inner cylinder wall was about 3 mm, while the gap between the inner and outer cylinders was 5 mm. The NaCl solution circulated through the inner cylinder, while the refrigerant circulated between the two cylinders, both of which flew in the same directions. A gland packing was used to prevent the leakage of the solution covering the gap in the scraper shaft hole.

Each experiment was carried out with the same refrigeration system, namely a vapor compression system with propane (R 290) used as a refrigerant since R 290 produced a higher cooling speed than R -22 [17]. The refrigeration system comprised of a compressor, condenser, filter, and fan was a condensing unit commonly used as air conditioners in a building, has a 2.60-kW cooling capacity, a 3.5-A-to-3.3-A electric current, and a 0.76kW-to-0.79-kW electrical power input. The indoor cooling condition (DB / WB) was 27 / 19^{o}C, and the outdoor (DB / WB) was 35 / 24^{o}C, and the refrigerant standard that was used was R22. The refrigerant pressure on the evaporator inlet and the condenser exit was measured with a pressure gauge, and the measurement results were shown in Figure 3. The pressure at the evaporator was measured with a pressure gauge, which had a 10-bar maximum scale with a ±0.1 bar accuracy, while the pressure on the condenser was measured with a pressure gauge, which had a 30-bar maximum scale with a ±0.5 bar accuracy. Figure 3 showed us that the pressure at the beginning of the evaporator entry was 0.5 bar; then, it went up to a constant value amounting to about 1.6 bar. The pressure at the condenser exit was first 9.0 bar; then, it went up to a constant value amounting to around 9.8 bar.

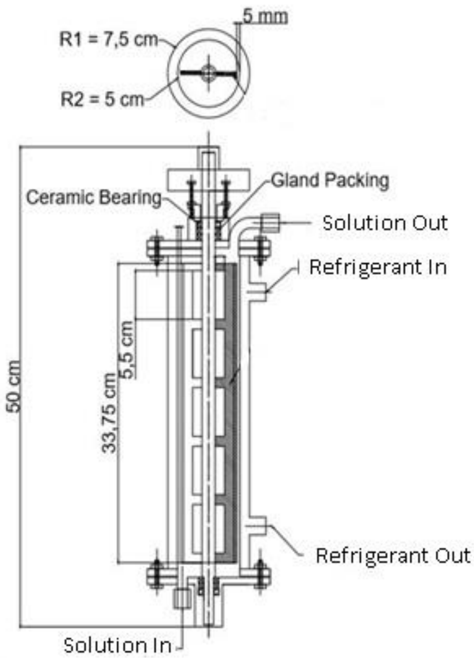

Fig. 2. Schematic plot of the evaporator

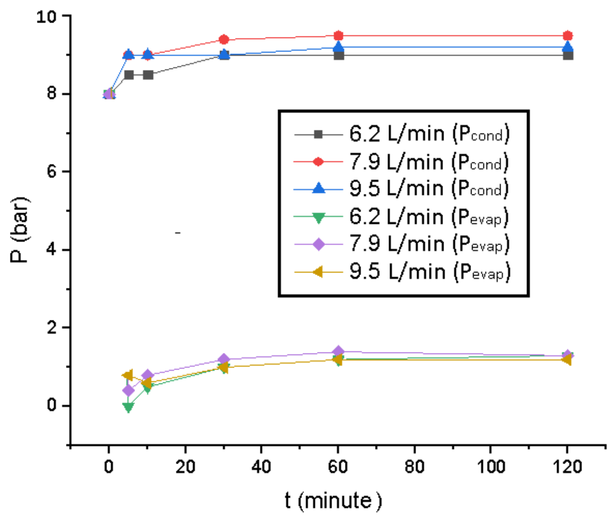

Fig. 3. A Variety of refrigerant pressure over time

Magnetic drive pump was employed to circulate NaCl solutions in the system. This pump had a 37-to-40-L/min maximum capacity, and the maximum pressure height was 4 - 5.8 m. The electric power during the operation was 65 W, 3 phases. Various flow rates could be adjusted by varying the rotational speed of the motor at the pump. The rotation speed of the pump motor was regulated with an inverter since we could vary its frequency values. By using a flowmeter with a ±0.5 L/min accuracy, we measured the flow rate against the frequency in order that we could obtain a linear relation between them.

The ice storage tank was built from a closed plastic tub and was coated with an insulator with an about-1-cm thickness. The NaCl concentration in the solution was measured with a refractometer. Its scale provided a direct reading of the specific gravity and concentration of salt in the water. The measurement ranged from 0 to 10%, with the smallest scale range amounting to 0.2%. The solution temperature in the ice storage tank was measured with a one-wire digital thermocouple, the measurement of which ranged from -10°C to +85°C with a $\pm$0.5°C accuracy. Before measured, the value on the thermocouple scale was first adjusted with the scale on the mercury thermometer. The electric power was measured with a multimeter with a $\pm$0.05 W accuracy. The volume fraction of the ice was visually measured with measuring with a $\pm$0.5 ml accuracy. The ice slurry samples taken with a measuring cup would be divided into two parts, namely the floating ice and water below. If the height of the floating ice column is h_I, and the height of the water column is h_W, then the ice volume fraction, c_I, can be obtained from Eq. (1).

$$c_I = \frac{h_I}{h_I + h_W}. \tag{1}$$

3. Results
3.1 Effects of the Flow Rates on the Temperature Reduction

Three basic stages of crystallization encompassed all types of ice slurry generators, including a solution, supersaturation, nucleation, and ice crystal growth [18]. Supersaturation is a situation in which the solution was not in equilibrium, and between the solution phase and the solid crystalline phase, there is a disparity in the chemical potential. The moment at which ice begins to form is known as the nucleation. For ice formation, the term nucleation implies a starting point, or a nucleus [14]. With the addition of solvent molecules from the supersaturated solution, nuclei grew into crystals during the growth process. In aqueous solution, ice growth depends on three factors, including the movement of water molecules to ice/liquid interface, the accommodations of these molecules on the ice layer, and the release of the heat of crystallization [19]. Crystal growth and its control are some of the issues that remain challenging tasks for engineers [20].

Figures 4-6 shows graphs of temperature reduction over time in the cooling process of NaCl solutions with their concentrations amounting to 3%, 4%, and 5%, respectively. Each graph was derived from three experiments conducted with different flow rates and the same 450-rpm scraper rotational speed. We could see that the temperature of the solution dropped below the freezing point of pure water until it hit the minimum value called the degree of supercooling. After surpassing the degree of supercooling, the temperature tended to be constant. At a 3% concentration, the temperature tended to go up slightly after surpassing the degree of supercooling. This result corresponded to the graph of the results of the experiments conducted by Liu [14], as shown in Figure 7 [14]. We could see that in both of them, the initial fluid temperatures dropped to the degree of supercooling, followed by a mild recovery. Because of the additive solution that served as an anti-freeze depressant, the total temperature and freezing point of the solution were lower than that of the pure water, which corresponded to the figure.

The flow rate did not seem to affect the rate of temperature decrease; this might be due to the tangential velocity resulting from the high scraper rotational speed, especially at the end compared to the axial speed, so the effects of the axial speed associated with the discharge could be neglected [9], except for the solutions with a 3% concentration, where the higher the flow rate was, the slower the rate of temperature decrease would be. That high flow rate could make the contact time between the solution and the evaporator wall shorter, so this could reduce the effectiveness of the contact, which in turn could reduce the rate of heat transfer from the solution to the refrigerant.

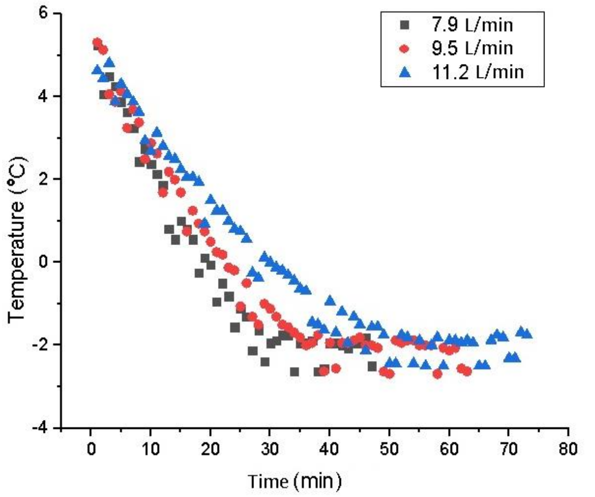

Fig. 4. Temperature reduction graph for variations in flow rates at 3% concentration

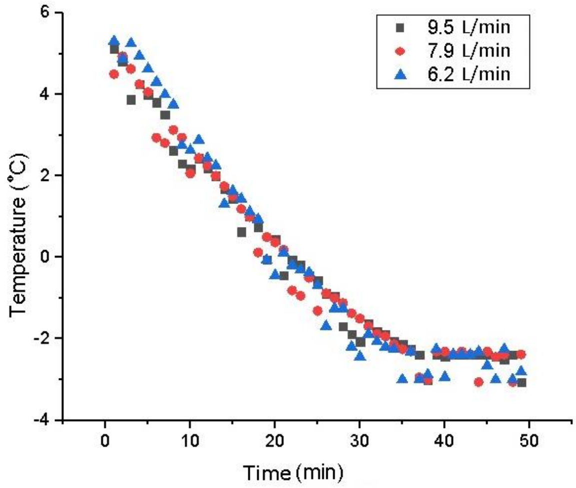

Fig. 5. Temperature reduction graph for variations in flow rates at 4% concentration

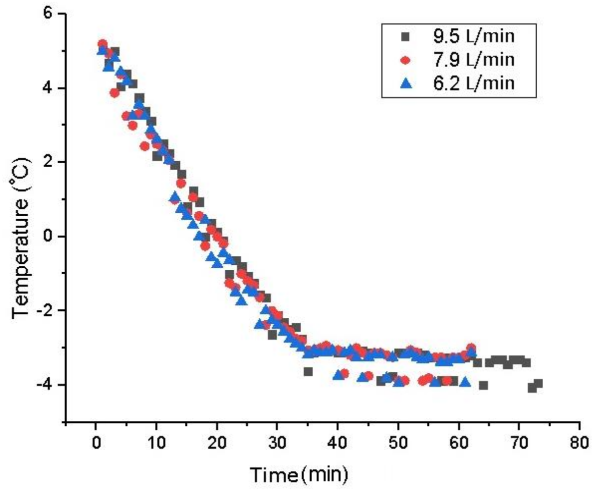

Fig. 6. Temperature reduction graph for variations in flow rates at 5% concentration

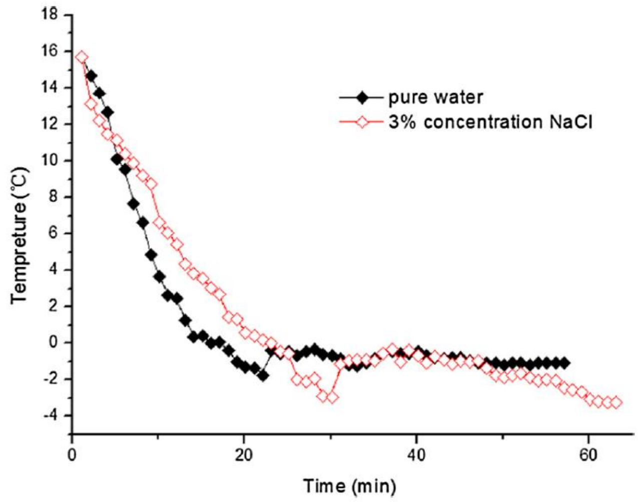

Fig. 7. Temperature variation of water and sodium chloride solution during the cooling process

3.2 Effects of the Concentration on the Degree of Supercooling

At the freezing temperature, T_f, most of the materials did not crystallize. The freezing temperature was equal to the melting point (liquid-solid equilibrium) at a lower temperature [14]. The nucleation phenomenon occurred once the liquid or solution exceeded the minimum temperature level, called the degree of supercooling. The latent heat released from the solid ice into the liquid in this segment was more than the energy extracted from the systems. Matsumoto *et al.,* [15] found that the supercooling degree could be actively regulated by varying the surfactant concentrations of the mixture, then hypothetically, the concentration of NaCl solution could affect the degree of supercooling. Figure 8 shows various degrees of supercooling to salinity for different flow rate values.

We could see that the higher the salinity was, the higher the degree of supercooling would be. We could explain this result using from Liu's [4] research stating that due to the increased additive, the effects of water electrolysis were more powerful, so it required more energy to isolate the water from the additives. Moreover, the degree of supercooling affected the formation time of ice, too, as shown in Figure 9. The higher the concentration was, the longer the time would be needed to reach the supercooling temperature. Furthermore, the flow rate had an effect, although not too significant, on the impact of concentration. The explanation was since the higher the degree of supercooling was, the more heat it had to release to lower the temperature, so the longer the time needed for ice formation was, the longer the ice production process would take and the higher the electrical energy consumption would be. What's more, the supercooling resulted in a decreased output coefficient (COP) in the ice forming process due to a drop in the evaporation temperature of the refrigerant and blockage of the ice slurry stream in a pipeline, thus making a supercooling control necessary [16].

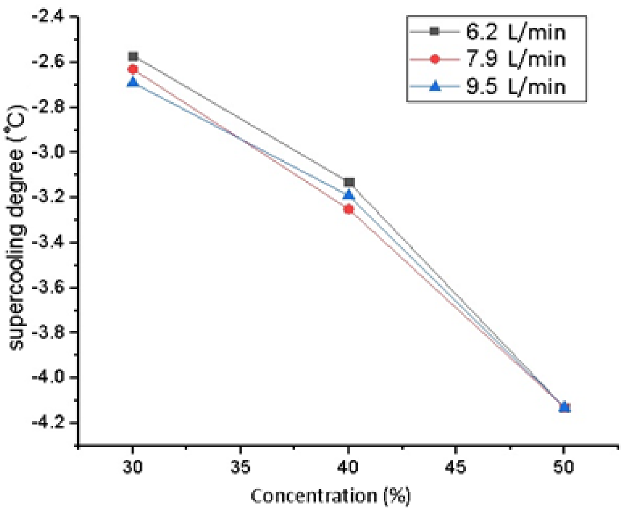

Fig. 8. Effect of the concentration on the degree of supercooling

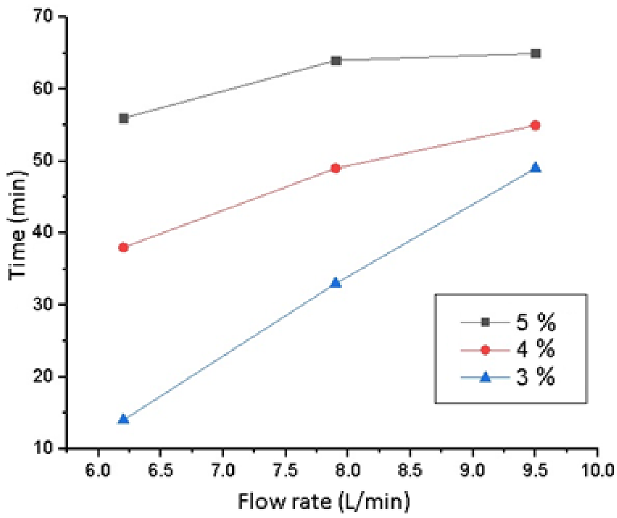

Fig. 9. Times required to hit the degree of supercooling

3.3 Effects of the Flow Rate on the Ice Fraction

The nucleation process began at the state of supercooling. After the state of supercooling, the temperature tended to go up slightly; then, it leveled up to a constant value indicating a high cooling speed in the formation and development of small ice crystals. Figure 10 shows the variation of the ice fraction over time for various concentrations and flow rates. We could see that at a 3% concentration, the higher the flow rate was, the slower the ice fraction would be. We could explain this result using previous studies showing that the higher the discharge was, the slower the temperature reduction would be, and the longer the time would be needed to hit the degree of supercooling.

Figure 10 showed us that the flow rate affected the increase in the ice fraction, i.e., the lower the flow rate was, the higher the ice fraction increase would be. This result was consistent with the previous ones stating that the lower the flow rate was, the shorter the time would be needed to hit the degree of supercooling, thus accelerating the ice formation. Moreover, we could see that the effects of the flow discharge were increasingly visible when the value was low indicated by the distant position of the graph between 7.9 L/min and 9.5 L/min, while the graphs positioned at 9.5 L/min and 11.2 L/min appeared to be close to each other.

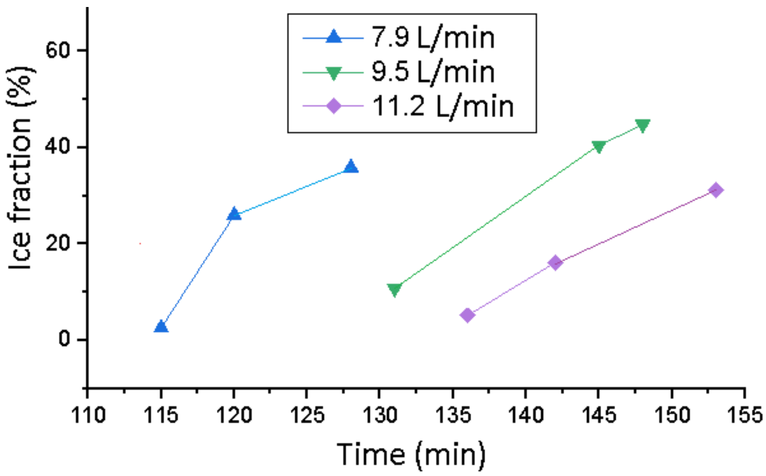

Fig. 10. Increase in the ice fraction to various flow rates at 3% concentration

4. Conclusions

This paper presented the results of a study on the ice slurry generator system in the form of the impacts of some factors such as the flow rate and the concentration on temperature reduction, the degree of subcooling, and the resulted ice fraction. It is found that for the solutions with a 3% concentration, the higher the flow rate was, the slower the rate of temperature decrease would be. The higher the concentration of the solution was, the higher the degree of supercooling would be, and the longer the time would be needed to reach the supercooling temperature. Furthermore, the flow rate also affected the increase in the ice fraction, i.e., the lower the flow rate was, the higher the ice fraction increase would be. Therefore, a flow rate of 7.9 L / min and a concentration of 3% is the most optimum value among the other variations for the purpose of the highest temperature reduction speed and the lowest degree of supercooling. The most optimum flow rate among the other variations to produce the highest ice fraction in the fastest time is also 7.9 L / min.

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