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Novel Hydronic Heat Exchanger for Ice Thawing Applications

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In progressive freeze concentration (PFC), a solution is phase-separated into solid ice and liquid concentrate fractions to achieve separation of certain compounds of interest by migrating all the compounds into the liquid phase, leaving the solid fraction free of any solutes. PFC is advantageous in water purification over conventional distillation by consuming considerably less energy during the phase change. However, the thawing of ice that follows usually requires more energy than PFC itself and this negates the energy efficiency benefits of PFC in the first place. Therefore, this paper introduces a novel method of using water as a heating medium (hydronic) to thaw ice that used only 7.9 % of the energy required for conventional electric resistance heating. A heat exchanger (HEX) using only room-temperature water was found to be able to thaw ice at a reasonable rate, higher efficiency and achieve overall heat transfer coefficient of 422 $W/m^2 \cdot °C$. Shape of HEX coil and temperature setting of the electric heater were investigated for responses like electrical energy consumption and ice thawing rate. The M-shaped HEX coil with three bends increased ice thawing rate and consumed less electrical energy compared to S-shaped HEX coil with only two bends due to rate of heat transfer improvement induced by turbulence inside curved sections of the HEX coil. Increasing the temperature setting of the electric heater increased ice thawing rate but maintained the same total electrical energy consumption. Room temperature water is an energy-efficient method to thaw ice compared to electric resistance heating.

1. Introduction

Water scarcity can lead to conflicts between nations (Gleick and Shimabuku, 2023). To improve water security, existing water resources should be protected and utilized efficiently. One important water source often overlooked is the use of rainwater for potable use. Though unpredictable, rainwater is often abundant and easy to harvest when available. To ensure safe human consumption, harvested rainwater should be treated to remove harmful pathogens and contaminants (How et al., 2023). While existing water treatment technologies are sufficient to render harvested rainwater safe, a novel technology known as progressive freeze concentration (PFC) has been used to purify rainwater (How et al., 2024).

PFC works by freezing an aqueous solution partially to achieve separation of solutes and purification of water. When temperature of solution is brought down to below the freezing point of water, ice crystals will start to form. Since ice is a crystalline solid, it has a specific form of crystal lattice. During the formation of the crystal lattice, all solutes are rejected and concentrated in the unfrozen liquid concentrate phase. Any aqueous solution can therefore be purified to various degrees by forming pure ice in PFC. This method is advantageous against other energy-intensive conventional water treatment techniques such as distillation as the latent heat of fusion (333.6 kJ/kg) is much lower than latent heat of vaporization (2,256.4 kJ/kg) (Haynes, 2013).

However, to get pure water from pure ice, heat energy is required to thaw the ice. This heat energy can be produced from electric resistance heating, burning of fossil fuels or simply leaving the ice out in the ambient. All these methods differ in the energy and time required. On one hand, electric heating can be quite fast but involves high cost of electricity, on the other hand, thawing ice naturally is free and easy but takes an exceedingly long time to complete.

Electric heating is a common heating method for heat transfer, and a hotplate is a common electrical appliance used in laboratories for heating purpose. It consists of a resistive heating element and a bimetallic switch to

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serve as both a control element to regulate the heating temperature and safety switch that turns off the hotplate if it is too hot. While hotplate is safer compared to heating with a stove due to the absence of an open flame, hotplate can be expensive to operate depending on the electricity tariff. Optimum heating temperature setting is important to minimize the use of electrical energy.

As electric heating can have certain limitations, this study is proposing to use alternative heating method using water as the heating medium (hydronic). A recent study (Hurley et al., 2024) tested the use of hot water in polyethylene pipe embedded in concrete to simulate de-icing of concrete block. In this paper, a heat exchanger (HEX) with copper as the material of construction and tap water as the heating medium were studied as an ice thawing alternative. Copper has the second highest thermal conductivities (390 W/m·°C) (Haynes, 2013) after silver, is commonly available in high purity and easy to work with. Though copper ions may leach into water when copper is used in plumbing, the concentration of copper in water is unlikely to exceed WHO guideline value and cause adverse health effects (WHO, 2022). For this work, copper was chosen due to its compatibility and corrosion resistance against water under normal conditions.

Important for drinking water applications, metallic copper surface also shows antimicrobial properties against pathogenic E. coli (Salah et al. 2021) and prevents biofilm formation (Gomes et al., 2020). Despite all these benefits of using copper to produce drinking water, the cost of copper is still more expensive compared to steel and aluminium by weight (Shearer, 2025) and judicious use of copper for HEX coil fabrication is important to prevent wastage and reduce cost. Therefore, the objective of this paper is to propose a novel and efficient method to thaw ice using room-temperature water as a heating medium (hydronic) in the tube side of a copper HEX. The effects of HEX coil shape and temperature setting of electric heating were also investigated in this work.

2. Materials and Methods

This study was divided into three sections: (1) the fabrication of HEX coils, (2) ice thawing experiments with different HEX coil shapes and (3) ice thawing experiments with different electric heating temperatures.

2.1 Materials

Two lengths of soft-drawn copper tubes (3/8" x 0.61 mm x 1 m) was bent into HEX coils with four passes (M-shaped) (Figure 1a) and three passes (S-shaped) (Figure 1b). Ice cubes were prepared using plastic ice cube tray with silicone bottom (23.4 cm x 8.4 cm x 2.1 cm) to ease ice cube removal and plastic lid to reduce sublimation loss of ice during freezing. Ice trays were filled with tap water and kept in a chest freezer (Sharp SJC155) overnight prior to thawing experiments. An electronic electricity meter (CAT II) was used to monitor power consumption of all electrical appliances during experiments.

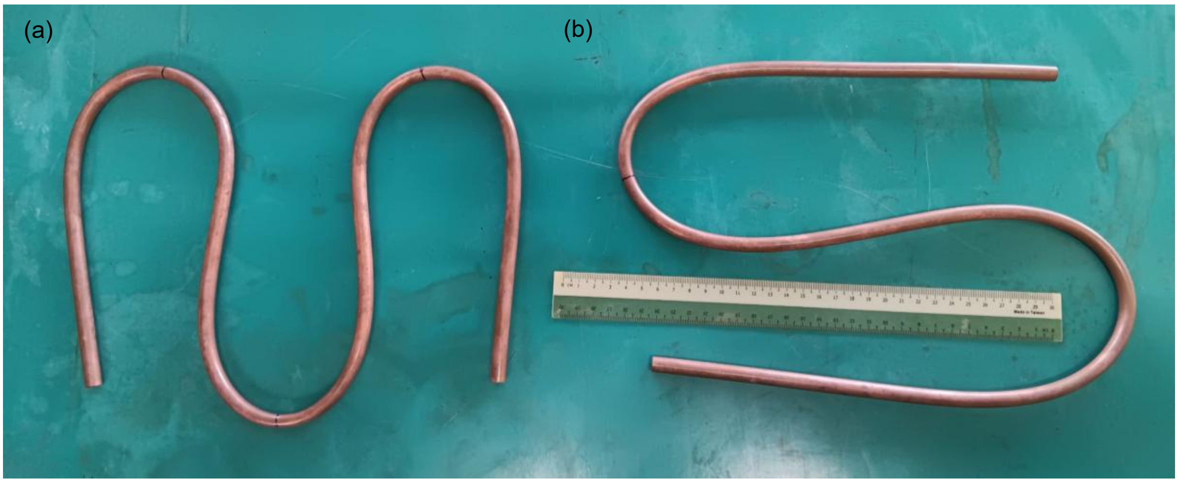

Figure 1: HEX coils with (a) M-shaped and (b) S-shaped designs

2.2 Effects of Novel Hydronic HEX Coil Shape

An ice thawing experiment was set up using novel HEX as shown in Figure 2. Approximately 900 g of ice cubes was placed on top of the M-shaped HEX coil in a plastic tank placed on top of a platform shaker (90 W). For the heat source, a circulation pump was placed inside a tank containing 5 L of room temperature tap water (27 ± 2

°C) to circulate the water through the HEX coil in an open loop manner. Platform shaker and circulation pump were then switched on to start the thawing of ice. Ice thawing was considered complete when no ice was visible. Time taken for ice to thaw completely was used to calculate ice thawing rate (Eq(1)) and energy consumption (Eq(2)) in each experimental run. Rate of heat transfer, Q was assumed to be equal to the rate of latent heat energy absorbed by ice thawing in Eq(3) (Ji et al., 2020). Coefficient of performance (COP) was calculated using Q and average input power in Eq(4). The experiments were repeated for the second set of configuration using the S-shaped HEX coil. All experiments were conducted in triplicates. Overall heat transfer coefficient based on the outside surface area (U_o) was calculated using Eq(5) (Özisik, 1985). Mean and standard deviation (s) were calculated using AVERAGE and STDEV.S functions in Microsoft Excel respectively.

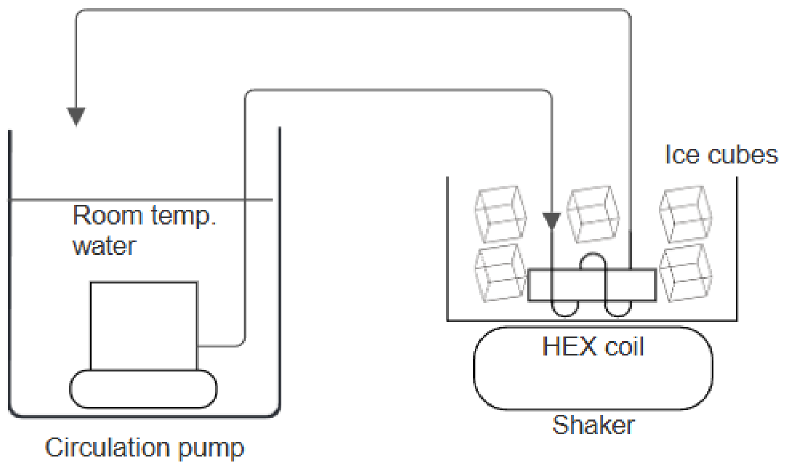

Figure 2: Experimental setup of novel hydronic HEX

$$Ice\ thawing\ rate\ (\frac{kg}{h}) = \frac{Mass\ of\ ice\ (kg)}{Time\ taken\ (h)} \tag{1}$$

$$Energy\ consumption\ (kJ) = Average\ input\ power\ (W) \times Time\ taken\ (h) \times \frac{3.6\ kJ}{Wh} \tag{2}$$

$$Q\ (W) = \ Ice\ thawing\ rate\ (\frac{kg}{h}) \times Latent\ heat\ of\ fusion\ of\ ice\ (\frac{kJ}{kg}) \times \frac{Wh}{3.6\ kJ} \tag{3}$$

$$COP = \frac{Q\ (W)}{Average\ input\ power\ (W)} \tag{4}$$

$$U_o\ (W/m^2 \cdot {}^{\circ}\mathrm{C}) = \frac{Q\ (W)}{Outside\ surface\ area\ of\ HEX\ (m^2) \times Temperature\ difference\ (K)} \tag{5}$$

2.3 Effects of Conventional Electric Heating Temperature Setting

An ice thawing experimental setup was assembled using conventional electric heating as shown in Figure 3. Approximately 900 g of ice cubes was placed in a glass beaker secured on top of a hotplate magnetic stirrer (Ingenieurbüro CAT M 6) with temperature setting of 450 °C. Platform shaker and hotplate were then switched on to start the thawing of ice. Ice thawing was considered complete when no ice was visible. Time taken for ice to thaw completely and cumulative energy consumption was used to calculate ice thawing rate and energy consumption, Eq(6) in each experimental run. All experiments were conducted in triplicates. A second set of experiments was repeated using temperature setting of 300 °C.

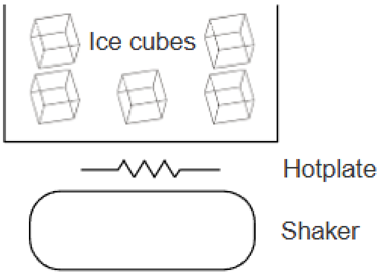

Figure 3: Experimental setup of conventional electric heating

$$Energy\ consumption\ (kJ) = Change\ in\ cumulative\ energy\ consumption\ (kWh) \times \frac{3600\ kJ}{kWh} \tag{6}$$

3. Results and Discussion

The effects of different HEX coil shapes and heating temperatures are presented and discussed in the first and second parts respectively. The last part discusses the overall heat transfer coefficient of the HEX coils.

3.1 Effects of Novel Hydronic HEX Coil Shape

The experimental results of the effects of HEX coil shape on ice thawing rate and total electrical energy consumption are shown in Table 1 for M-shaped HEX coil and Table 2 for S-shaped HEX coil. The average time taken for M-shaped HEX coil to thaw ice completely was shorter at 0.245 h or 14.7 min compared to S-shaped HEX coil of 0.262 h or 15.7 min. M-shaped HEX coil thawed ice faster by 7.0 % and consumed 9.5 % less energy compared to S-shaped HEX coil. Temperature of the tap water dropped to 23 ± 2 °C and dew formation was observed outside the tank at the end of the experiment.

A COP of 8.77 in M-shaped HEX coil meant that the setup transferred 8.77 unit of heat energy into thawing ice for every unit of electrical energy input to circulation pump and platform shaker. The M-shaped HEX coil had 13.9 % higher efficiency (COP) compared to S-shaped HEX coil due to the higher number of bends in the M-shaped HEX (three bends) compared to only two bends in the S-shaped HEX coil. Bends or coiled tubes can serve as a heat transfer enhancement device because the secondary flow produced by the curvature causes an increase in the heat transfer coefficient (Özisik, 1985). HEX coil with more bends induces more turbulence via secondary flows in the tube side and increases rate of heat transfer.

The value of U has been shown to be higher for curved pipe compared to straight pipe and increases with decreasing radius of curvature, i.e. tighter turn of coil shape (Yang and Chiang, 2002). This effect is more pronounced in turbulent flow compared to laminar flow. Ciofalo and Di Liberto (2015) described a dimensionless number, γ, that is the ratio between the length of straight section to the radius of curvature. Decreasing the value of γ, i.e. having shorter straight sections overall increased the value of U in serpentine pipe, where there are alternating sections of straights and bends that change sign periodically (sinusoidal-like).

Table 1: Experimental results of the M-shaped HEX coil

Run	Time taken (h)	Thawing rate (kg/h)	Energy consumption (kJ)	Q (W)	COP	U ($W/m^2\cdot °C$)
1	0.2550	3.53	36.35	327.1	8.26	404.9
2	0.2444	3.68	34.14	341.2	8.79	422.3
3	0.2356	3.82	32.39	354.1	9.27	438.3
Mean	0.2450	3.68	34.30	340.8	8.77	421.8
s	0.0097	0.15	1.98	13.5	0.51	16.7

Table 2: Experimental results of the S-shaped HEX coil

Run	Time taken (h)	Thawing rate (kg/h)	Energy consumption (kJ)	Q (W)	COP	U ($W/m^2\cdot °C$)
1	0.2533	3.55	36.02	329.2	8.33	407.5
2	0.2636	3.41	38.15	316.4	7.87	391.6
3	0.2697	3.34	39.52	309.2	7.60	382.8
Mean	0.2622	3.43	37.90	318.3	7.93	394.0
s	0.0083	0.11	1.76	10.1	0.37	12.5

3.2 Effects of Conventional Electric Heating Temperature Setting

Table 3 shows the experimental results of the effects of electric heating temperature setting on ice thawing rate and total electrical energy consumption. The average time taken for 450 ℃ temperature setting to thaw ice completely was shorter at 0.391 h or 23.5 min compared to 300 °C temperature setting of 0.790 h or 47.4 min. The 450 °C temperature setting thawed ice faster by 101.9 % but consumed the same amount of electrical energy compared to the 300 °C temperature setting.

This difference is because the rate of heat transfer is highly dependent on the temperature difference between the heat source (electric heating temperature) and the heat sink (ice thawing temperature) (Özisik, 1985). Since the melting point of ice is constant, the ice thawing rate is increased when heating temperature increases as the rate of heat transfer increases. While the hotplate needed to operate at a higher average power to maintain a higher temperature (450 °C), the hotplate also operated for a shorter period of time to thaw the ice completely. This shorter operating time consequently balanced out the higher average operating power, resulting in the same total electrical energy consumption for both 450 °C and 300 °C temperature settings.

Table 3: Experimental results of the effects of heating temperature setting

Run	Time taken (h)	Thawing rate (kg/h)	Energy consumption (kJ)	Run	Time taken (h)	Thawing rate (kg/h)	Energy consumption (kJ)
450(1)	0.3906	2.30	432	300(1)	0.8025	1.12	432
450(2)	0.3767	2.39	432	300(2)	0.7672	1.17	432
450(3)	0.4067	2.21	432	300(3)	0.7994	1.13	432
Mean	0.3913	2.30	432	Mean	0.7897	1.14	432
s	0.0150	0.09	0	s	0.0195	0.03	0

3.3 Overall Heat Transfer Coefficient

Figure 4 shows the comparison of thawing rate and energy consumption between HEX coil and electric heating. On average the ice thawing rate using HEX coil was 49 to 114 % faster and consumed only 7.9 to 8.8 % of the theoretical energy compared to using electric heating. This is equivalent to a theoretical COP of 11.4 to 12.6, which is between COP reported in the literature, which was between 4.17 (Chen et al., 2020) and 47.1 (Ozgener, 2012). This is due to the HEX coils acting as heat pumps to transfer sensible heat energy from room temperature water to thaw the ice while using just a little electrical energy for the circulation pump and shaker to improve overall heat transfer efficiency. Therefore, the HEX coils can achieve overall heat transfer coefficient of up to 422 $W/m^2\cdot°C$.

On the other hand, electric heating consumed electrical energy higher orders of magnitude compared to HEX coils because a lot of heat energy was required to heat up the heating element (hotplate) and the beaker from ambient temperature before effective heat transfer can occur from the heating element to the ice cubes. Radiative heat loss also occurred to a higher degree in electric heating due to the higher temperature difference between the hotplate and the surroundings.

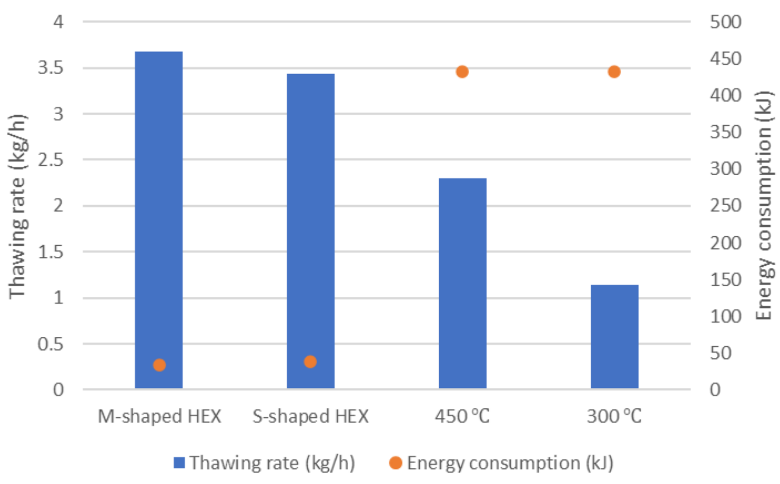

Figure 4: Comparison between HEX coil and electric heating

This works has shown that the M-shaped HEX coil can achieve ice thawing rate of 3.68 kg/h or 32,200 kg ice per year. The annual energy consumption using M-shaped coil is 341 kWh while 4,300 kWh of energy is required for electric heating at the same capacity. Based on the current domestic electricity tariff of RM0.218/kWh in Malaysia (TNB, 2025), the annual cost of using the M-shaped coil is RM74.34 whereas electric heating costs RM936.34 per year. An annual saving of RM862.00 or 92.1 % is achieved by using M-shaped HEX coil compared to electric heating.

4. Conclusions

Using copper HEX coil and room temperature water to thaw ice is an energy efficient and low-cost method. Different HEX coil shape and electric heating temperature setting can influence the rate of heat transfer, ice thawing rate and energy consumption. Increasing temperature setting of electric heating increased ice thawing rate but consumed the same total electrical energy consumption as lower temperature setting. The HEX coil with more bends (M-shaped) increased ice thawing rate and consumed less electrical energy compared to S-shaped HEX coil. Overall heat transfer coefficient of 422 $W/m^2 \cdot °C$ can be achieved by M-shaped HEX coil.

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