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Possibilities of ice slurry systems onboard fishing vessels

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ABSTRACT

Rapid handling of seafood at low temperatures are important for the quality and shelf life of the catch. There are several different methods onboard fishing vessels, including no chilling, ice storage, refrigerated sea water (RSW) and ice slurry chilling. A refrigeration system is needed for the chilling methods and it is either located on land (when ice is brought on the ship) or installed on the ship. The main working fluid in fishing vessels globally is still R22, but there are efforts for providing systems with natural refrigerants, even if this should be done at a much faster rate. Most of the new systems on fishing vessels in Norway have either R717 or R744. The use of slurry systems has been investigated in this study. A few vendors have been contacted and an overview of the status of ice slurry system is given. It can be concluded that storing seafood with ice slurry gives longer shelf life, but is not used widely in the industry, mainly because of limited capacities and high costs. Not many of the ice slurry systems are operated with natural refrigerants either. There is clearly a potential for development, but for now there is no interest from the market and no incentives for that.

Keywords: Marine refrigeration, ice slurry, RSW, seafood quality, CO_2, NH_3

1. INTRODUCTION

Globally, many fishing vessels don't have sufficient cooling of the fish, which leads to enzymatic and bacteriological degradation of fish, lower product quality and discards (Jessen et al., 2014). As a substitute for proper chilling, different chemical substances for preventing degradation are in use (different acids, formalin etc.) with some unwanted side effects both on product quality and health of the personnel (Rahman et al., 2016). Among those that have refrigeration systems, many still use synthetic refrigerants with climate and environmental issues. It is therefore necessary to show that there are good, efficient and economically viable alternatives with natural refrigerants. Proper on-board conservation of fish by refrigeration can increase quality and shelf life, and thus reduce food loss, and efficient design and operation of refrigeration systems employing natural refrigerants can reduce use of fossil fuels and high-GWP leakages, thus reducing emissions.

Vingelsgård et al. (2022) made steady state theoretical evaluations on a fish chilling system with additional ice, compared with data measured from a RSW system onboard a fishing vessel (Svendsen et al., 2021). The results showed that for a case with a large catch (66 % of a 529 m^3 tank) of fish, it is possible to reduce the cool-down period from 6.36 hours to 2.79 hours by using slurry with an ice concentration of 20%, compared to standard RSW. The study also looked at maintenance cooling during return trip and it was found that with an ice slurry system it could be possible to run the system on full load for 1.4 h instead of part load for 17.5 h. That would result in lower energy demand and lower CO_2 emissions, since the refrigeration system onboard runs on diesel engines.

Many vessels have no systems for cooling of the catch onboard, but could have advantages of a small, efficient system. Literature does not clearly state what the alternatives are and how to evaluate them. The intention of this study was to give an overview of existing ice slurry systems and if there is a potential for increased use of them. This can be relevant both for fishing vessels with and without existing cooling systems.

2. ONBOARD CHILLING OF FISH

2.1. Cooling of fish onboard – different alternatives

Although some smaller fishing vessels does not have cooling of the catch, it is recommended to have some form of cooling, either with ice or onboard refrigeration system.

Chilling fish with ice brought from shore is a better option compared to no cooling. Adding ice to the bottom and top of boxes with fish will help to reduce the temperature down towards 0 °C, given that a correct ratio of fish:ice is used. In terms of chilling rate this method is quite slow (compared to RSW and slurry) since the contact between fish and ice is reduced. Adding ice in tanks and topping up with water (CSW) increases the chilling rate. Typical procedure is to fill tanks with 1/3 of ice, top with water and then load the fish on board. Excess water will spill as fish are stowed. For both cases it is necessary to calculate and estimate the correct amount of ice needed, which in short is dependent on expected temperatures, catch size, duration of fishing trip and type of storage. An alternative is to have an on-board ice production, which allows the fisher to produce ice on demand.

Refrigerated seawater (RSW) is a well-established practice and is widely in use for larger vessels, particularly those fishing pelagic fish. For smaller vessels however the main challenge is access to smaller-sized RSW systems. These systems require a refrigeration system, usually employing R717 for commercially available systems, albeit R744 could be a better option for compact systems (due to size requirements), in addition to RSW tanks connected with piping for circulation of seawater. The chilling rate is quite fast if using an adequate ratio of fish and water (towards -2 °C), but not quite as rapid as slurry systems. Another benefit with RSW is that it allows the fisher to keep the fish alive (live capture).

With respect to chilling rate, **ice slurry** is the most efficient option to chill fish, which is important with respect to shelf life and quality attributes. These systems would require a refrigeration system connected to an ice slurry generator, storage tank for the produced slurry and possible a mixing device (separate or as part of storage tank) to keep the slurry at the correct ice:water ratio. An example is shown in Figure 1. The slurry itself can be produced by either fresh or sea water, and salts can be added to lower the slurry temperature. Compared to flake ice, slurry is small/microscopic ice crystals which can better fill gaps between fish and thus enhance the heat flow, which leads to high chilling rates. Furthermore, opposed to water, the purpose of using slurry is to take advantage of the latent heat stored in the ice crystals, and this can be controlled by producing slurry with a specific ice fraction (or concentration). Concentrations up to 60% are possible while still being pumpable, but pressure drop increases in pipes at higher concentrations, and in worst case, leads to clogging of pipes. For small vessels that don't have an on-board refrigeration system, nor place for it, another option is to bring slurry from land, store in mixing tank and distribute to fish tanks/boxes by a simple pumping system.

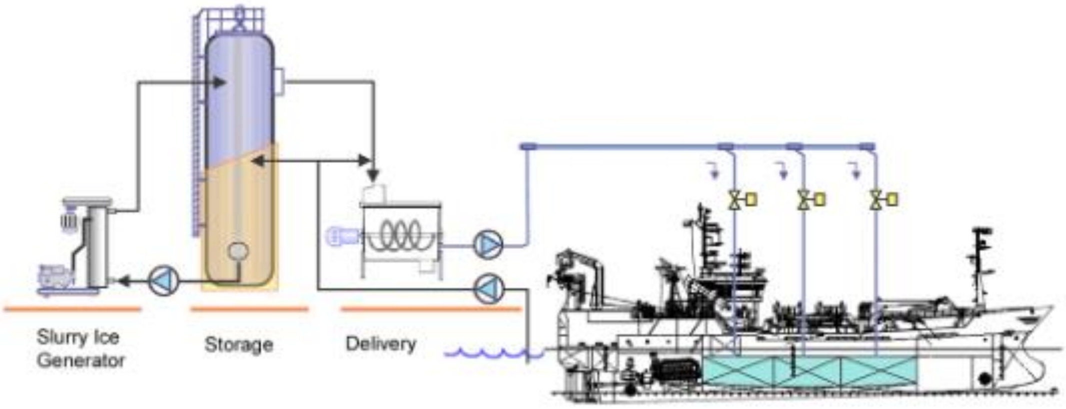

Figure 1: A low salinity ice slurry system used onboard a Japanese purse seiner. From (Kauffeld et al., 2010)

2.2. Characteristics of small Norwegian fishing vessels

For 2021, almost 80% of the 5633 Norwegian fishing vessels were 11 meters or less in length (Fiskeridirektoratet, 2021a) and accounted for a total of 11% (~80 000 tonnes) of cod landings, mostly by netfishing or linefishing (Fiskeridirektoratet, 2021b). Of these landings, only 5% were reported to be conserved by ice while the rest were reported as fresh (no preservation). Even though these figures are self-reported and might be inaccurate, they are in line with findings from other projects and surveys done on this group of small vessels. Considering the use of ice slurry as means of conservation across all vessel types, it holds a very small share compared to the more traditional methods. As can be seen in Figure 2, less than 0.5% of landed volume is reported to be chilled with slurry for the last two decades (in Norway), amounting to 2000-8000 tonnes.

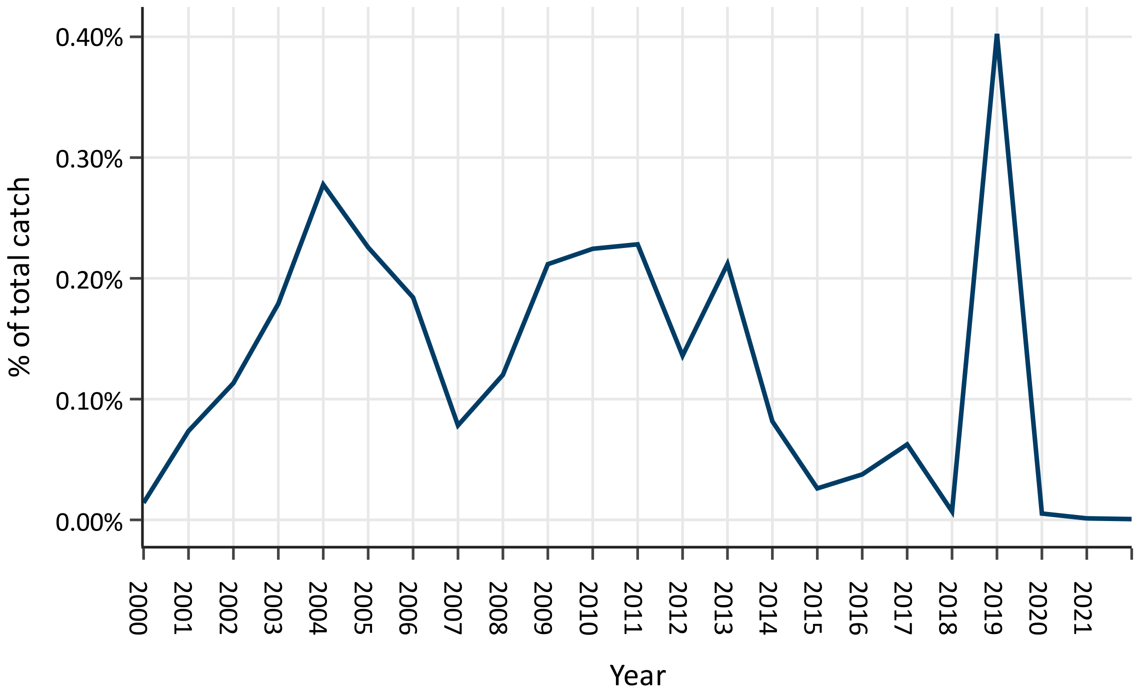

Figure 2: Use of slurry among Norwegian fishing vessels 2000-2021

An important criterion for design of a chilling system is the operational profile of the vessel. It is difficult to define a general profile for this group of vessels as it constitutes of many different vessel types with different fishing gear, type of species they're fishing, number of fishing days in a year and distance from home harbour to fishing grounds. However, looking into catch data can reveal some general trends and figures for this group. Figure 3 shows number of landings and the total annual catch volume (for 2021) for every vessel with a maximum length of 11 m.

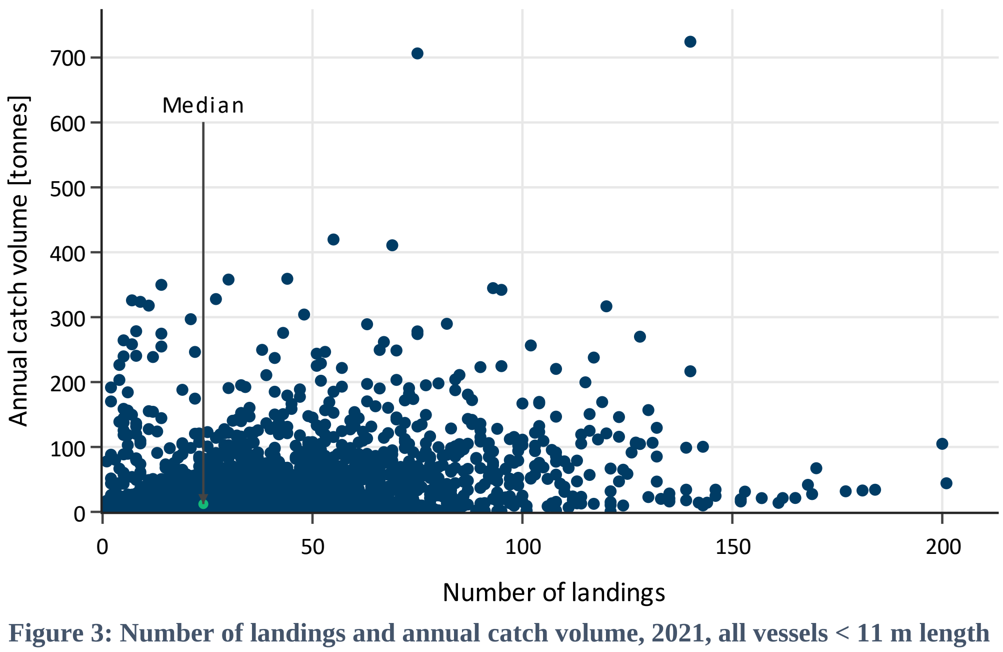

Figure 3: Number of landings and annual catch volume, 2021, all vessels < 11 m length

If we make the reasonable assumption that each fishing trip is less than 24 hrs, number of landings would then equal how many active days a year each vessel has. Going by this data, the median days at sea for these vessels are 24, but as one can see it ranges from very few to 200 days for the most active ones. Total catch also has a large variation, from very few kilograms to above 400 tonnes annually, while the median is 12 tonnes annually. The median catch size is then half a tonne for each landing for these vessels, albeit with a large variation.

If we use this piece of data as a springing point to perform dimensioning for a chilling system, and we consider cod, the amount of energy that needs to be removed from one kg to cool from 10 °C to 0 °C is 38 kJ. This translates into a cooling demand of 5.3 kWh for a 500 kg catch, and in addition comes the heat losses from the storage bins/tanks for the period. These losses are dependent several factors which may vary amongst the different vessels in this group, like type of storage, size of fish being caught, length of trip and local ambient temperatures. However, going by the 'rule of thumb' of using 1 kg ice for 1 kg of fish given by (Shawyer and Medina Pizzali, 2003), this translates into a capacity:demand of 333:38 kJ/kg, which, again, for 500 kgs turns into 46.3 kWh.

2.3. Refrigeration systems with natural refrigerants

It has been known for several years that leakage of some refrigerants affect the global climate and there are different strategies to prevent this. However, the use of those refrigerants is still widely spread, and the transition to natural refrigerants is slow. The international maritime organization (IMO) regularly publishes a report about greenhouse gas emissions from the shipping industry, including a section with information on estimates of refrigerant leakage. Annual estimated loss of refrigerants from the fishing fleet are shown in Figure 4 (GWP data available in Table 1). Although the latest report (IMO, 2021) says that the use of R-22 is on decline because there is a shift from R-22 to R-134a, the numbers show an increased release to the atmosphere from 2012 to 2018. The report does not say anything about refrigeration systems with natural refrigerants. It is maybe not included since the most common natural refrigerants does not have GHG emissions. However, ammonia as refrigerant is mentioned in the second IMO report, from 2009 (IMO, 2009) and ammonia systems should be mentioned as a low GWP option. It was assumed that the total number of R717 systems were much lower than the other, which was also stated by Larminat (2018). The number of R717 systems might have increased globally since then, Widell et al. (2016) reported that most new refrigeration systems onboard fishing vessels in Norway was with ammonia, but it is likely a slow process until all high-GWP systems are converted.

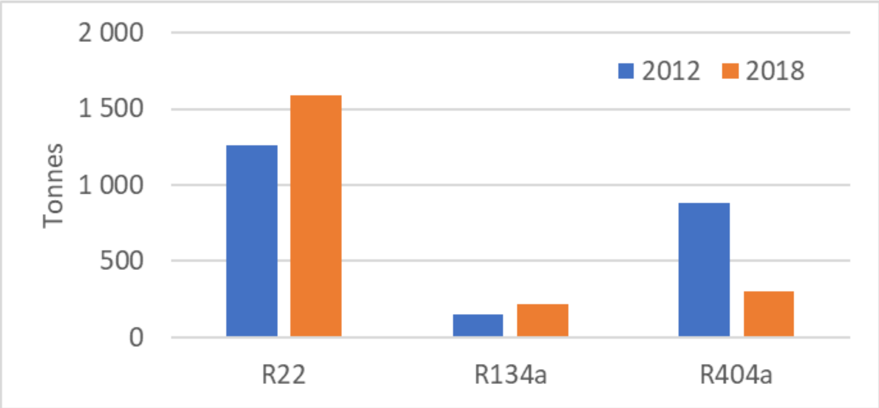

Figure 4: Annual estimated loss of refrigerants from the fishing fleet (IMO, 2021, 2014)

The alternatives to the refrigerants with high GWP are either the low-GWP HFCs (the "HFOs") or the natural refrigerants. The reason the HFOs have low GWP are that they decomposes quickly, after only a few days, and GWP is mainly calculated on a 100 year basis. However, the decomposition products are not harmless and does not disappear easily. For example, they are a major source of PFAS (Per- or Poly-Fluoro-Alkyl Substances) pollution and research shows they are extremely persistent and can be found in drinking water. Restrictions have been proposed to limit the increase of concentration of these substances. (Barbo et al., 2023; Hafner and Ciconkov, 2021; Herzke et al., 2022; Jones et al., 2022).

Table 1. Global warming potential (GWP) for some selected synthetic refrigerants, calculated for a 100- and a 20-year range. (ATMOsphere, 2021; Smith et al., 2021)

	R22	R134a	R404A	R449A
GWP_{100}	1960	1530	4200	1400
GWP_{20}	5690	4140	6600	3100

There is no reason to continue with substances that have such environmental issues, but we should instead suggest natural refrigerant solutions in all new refrigeration systems. Hafner and Ciconkov (2021) stated that although there is no single working fluid that can be applied for all the different applications, a suitable natural working fluid can be found for all situations, for each unit. R717 and R744 are the best solution for freezing applications for food processing (temperatures between -50 °C and 5 °C). R717 is the main refrigerant for fishing vessels, but Söylemez et al. (2022) also showed the possibilities of R744. The benefits of R744 are compact systems and has low risk of affecting human health and food products in the case of a leakage. It is therefore relevant for ice slurry systems for seafood chilling.

3. EXISTING ONBOARD SLURRY SYSTEMS

There are several suppliers of flow ice and ice slurry systems for fishing vessels and information from three of them have been included in this paper, based on feedback in meetings and the available information on the company's web pages. (Borhai and Goldstein, 2022; Nedal, 2023; Vikse, 2023)

3.1. System description

As described in section 2.1, ice slurry is small/microscopic ice crystals mixed with water, typically produced from filtered sea water. The slurry is produced in a slurry generator, not to be confused with crushed ice mixed with sea water, which has larger and sharper ice particles. The systems have typically lower cooling capacities than RSW-systems and are used for slightly different purposes (see section 3.3). Some of the systems are easy to transport and are plug-and-play which can reduce the risk of malfunction, but also gives good flexibility. Figure 5 shows two examples of ice slurry systems.

Figure 5: Left: Ice slurry system in a transportable container *(Vikse, 2023)*. Right: Mobile unit that can deliver to different plants and harvesting sites *(Deepchill, 2023)*.

3.2. Refrigerants

The smaller systems that are provided by the vendors in this study are mainly provided with synthetic refrigerants, R448A or R449A. The global warming potential for them is 1396 and they are a substitute for R404A (GWP 3922). When asking if there could be an alternative natural refrigerant for these systems, the answer has been that the system is built for these refrigerants, and it would be too costly to change to for example R744. There is also no demand in the market for a change. For larger slurry systems one vendor provides the option of either using R717 or R744, the system is then custom made and not plug-and-play.

3.3. Market

The main seafood products chilled with ice slurry is farmed salmon, shrimps and crabs and for by-catch on pelagic vessels. In the salmon industry it is typically used for chilling of weak fish, which are in the risk of dying because of de-lousing or other handling processes. It is economically beneficial to slaughter that fish as it is otherwise a risk that it will die and has to be treated as waste instead. This also reduces the food loss in the salmon industry. Another potential source of waste is by-catch on pelagic fishing vessels. They catch large amounts of for example herring and mackerel, but may also catch small amounts of white fish (cod, haddock).

The quality of that fish is preserved if stored with ice slurry and can be sold for a good price. Shrimps stored on ice slurry can keep their quality for more days than stored on ice, which will allow the vessel to go on longer trips. Figure 6 shows these two alternatives. It has been mentioned that the shelf life of shrimps is extended with several days, if stored in ice slurry compared to flake ice (Vikse, 2023).

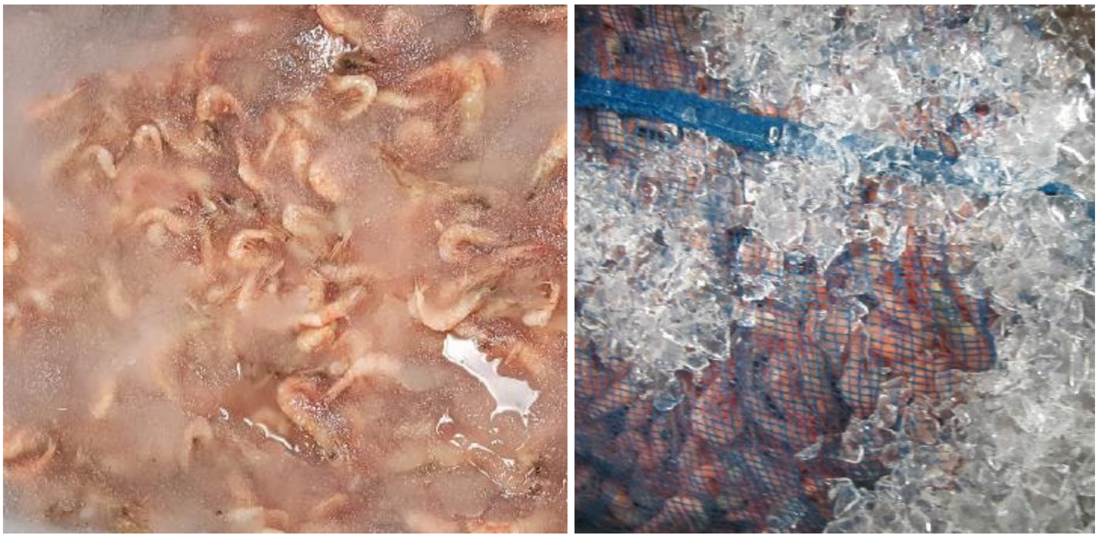

Figure 6: Left: Shrimps stored in ice slurry. Right: Shrimps stored in flake ice. ***(King and Thompson, 2018)***

3.4. Quality aspects

Ice slurry systems can preserve fish at temperatures below zero degree. The main advantage of ice slurry is a rapid cooling rate, gentle handling due to microscopic ice particles, longer shelf life due to lower storage temperature than crushed ice and a cleaner handling because of the pumpability of the slurry.

The product quality parameters (e.g. microbial conditions, water binding capacity, texture) have been shown to be better when using slurry systems compared to traditional ice storage. This has been shown for several fish species such as European hake (Losada et al., 2004), farmed turbot (Campos et al., 2006), farmed perch (Lan et al., 2021), horse mackerel (Losada et al., 2005), farmed salmon (Chan et al., 2020; Erikson et al., 2011) and cod (Eliasson et al., 2021). Digre et al (2011b) investigated the effects on quality for rested and stressed farmed cod chilled with slurry (superchilled) and traditional ice storage. They found that chilling in slurry was more rapid compared to ice, and also that after 14 days of storage the potential advantages of superchilling with slurry became prominent with respect to microbiological activity, freshness and K-values. However, negative aspects such as development of cloudy eyes and salt uptake was also observed. No advantages for superchilling in slurry was observed before 14 days of storage, which is in line with other studies.

3.5. Advantages

There are several advantages of using ice slurry systems for chilling of seafood. It is easy to transport and distribute, since it is pumpable. It has also very small ice particles, which allows it to have great contact with the seafood. It is a latent heat storage methods, which makes it more dense than RSW, which is a sensible storage heat method. This also allows rapid chilling. The water in the slurry keeps the surface of the seafood wet and can also to some extent have a cleaning function.

3.6. Barriers

There are also barriers for increased use of slurry systems. Based on the communication with the vendors it is clear that different systems are used for different purposes and it is for example not likely that ice slurry system will be used instead of RSW systems on large trawlers. The capacity of a ice slurry system is normally much smaller than a typically RSW system. It is also common to do as traditionally have been done and it is not easy to provide a new type of system in an existing market. End users buying a new system will go for what they already are familiar with and what success stories others have shared. Costs of a system can also be a barrier, but it all depends on what the purpose is and if installing the system gives higher income. A fish with higher quality may be sold to a higher price, but not always.

4. CONCLUSIONS AND FURTHER WORK

An often-heard argument for not taking active measures in chilling of the fish is that the fishing trips are short, and that the ambient temperature (during high-season) is anyhow quite low. Barriers for those investigating the possibility of onboard chilling equipment besides the cost, is available space. The vessels are small, and the available area is usually already utilized for various equipment and fishing gear, and anything added would possibly reduce the amount of fish storage. Bringing ice or slurry from shore can be challenging due to manual handling, availability, and easy ways to transfer ice/slurry to the vessel.

For the case of installing chilling systems onboard small vessels, there is a need for development on equipment specifically targeting this group which manages for the barriers mentioned above. In short, the critical criteria for designing a system would be:

- Size: System should be compact with a small base area
- User-friendly: System should be easy to use, i.e. not require deep technical understanding of the fisher/operator but with an intuitive control panel, easy handling and method for distribution of chilling medium and not increase number of manual labour-intensive operations.
- Energy-efficient: Compared to the case of no cooling, installing a chilling system would inevitably incur increased energy use. The chilling system should operate energy-efficiently as to keep this as low as possible
- Emissions: The chilling system should employ refrigerants from within the natural group (R744, R717, HCs). Leakage on onboard systems is comparably higher than for on-land systems due to harsher environments, and thus the leakage should not contribute to increased emissions. Indirect emissions due to more energy use should be lowered by complying to the previous criteria of energy efficiency

To address the issue of investment cost, the system must above everything else provide sufficient cooling so that the quality of the fish is maintained (compared to no chilling, flake ice etc.). This in turn should be reflected in the prices the fisher gets for their landings, and if not already implemented, mechanisms for enabling price differentiations based on quality should be established (regulatory).

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