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MODELING OF FUTURE REFRIGERANTS IN A VAPOUR COMPRESSION CYCLE

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Abstract. the refrigeration plant on a fishing vessel is one of the main contributors of the overall energy usage of the vessel. Any increase in efficiency of the refrigeration system will reduce the fuel consumption and can improve the overall efficiency of the vessel. The Montreal Protocol states that all environmental impacting refrigerants must be phased out. Therefore there is a need to find an environmentally friendly refrigerants that meets the global legislation requirements as well as high refrigeration efficiency. The present study investigates different refrigerants in a vapour compression refrigeration plant for efficiency and operational cost with special consideration on environmental impact. With the aid of simulations, the Coefficient of Performance (COP) for different refrigerants were determined. The results showed that carbon dioxide (R-744) and ammonia (R-717) have the highest calculated performances and therefore carbon dioxide can be recommended as a future refrigerant. On the other side, the hydrocarbons have the lowest COPs of 2.67, 3.01 and 2.98 for methane (R-50), ethane (R-170) and propane (R-290) respectively. Overall, the hydrocarbons have 24.72%, 10.63% and 11.74% less performance compared to R-134a. The safety consideration for the use of ammonia (R-717) and carbon dioxide (R-744) showed that carbon dioxide is the preferred future refrigerant. For new built refrigeration systems, carbon dioxide is recommended for its low global warming potential.

Key words: refrigeration system, PRO\II, future refrigerant, vapour compression cycle

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1 INTRODUCTION

Refrigeration system in a fishing vessel such as a trawler or long liner is a second largest contributor to the overall energy consumption of that vessel with the largest being the propulsion system. Therefore, any increase in the efficiency of the system will reduce the fuel consumption and can improve the overall efficiency of the vessel. The refrigeration system must be able to ensure that all marine life caught are stored in proper operating conditions (varies on the type of fish in terms of temperature) which will allow the meat to be preserved and ultimately increase the market value. For this reason, it is essential that the system runs as economical as possible without compromising the overall performance. Further, with tighter regulations on the environmental impact of refrigerants [1], there is a need for a non-polluting refrigerant which a high efficiency. However, there are various types of refrigeration systems existing in the marine industry. Some of the variations of the refrigerant systems include: single stage and multistage compression cycles, primary and secondary refrigerants and cascade systems. In this study, a single stage vapour compression cycle is considered.

2 LITERATURE REVIEW

Seafood industry shows the important of improving the refrigeration efficiency to reduce the amount of fish wasted caused by poor refrigeration systems. The two common refrigeration systems, the use and history of refrigerants as well as energy reduction methods are discussed next.

2.1 Seafood industry

Seafood industry represents 6% of the total protein demand worldwide and the importance of seafood will vary from country to country [2]. For some countries, fish is a major food source where in others fish is more of a luxury. As the human population increases, the world catch of fish must also increase to fulfill the demand. The current world catch is $7x10^7$ tonnes of fish. However, not all of this is used for human consumption. $1x10^7$ tonnes is wasted and another $2x10^7$ goes towards the production of fishmeal. However, the world catch may not be able to increase to a higher level without causing local and global depletion. Hence the improvement of efficiency in refrigeration systems will allow the catch to be properly stored and chilled, thus there will be a decrease in amount of fish that is wasted [2].

2.2 Refrigeration systems

The purpose of a refrigeration plant is to transfer the heat from one source into another. This task is completed by passing air through an evaporator containing chilled refrigeration liquid, (called a refrigerant), running through the system [3]. The size and type of the refrigeration plant is based on the need of that particular fishing vessel [4]. A small trawler may only require a small fish hold of a single species and therefore only a single temperature setting is required, whereas a larger trawler may require different temperatures for different fish species [5]. For an example, one fish hold may require the fish to be frozen whereas another fish hold may only require the fish to be chilled [4]. For example, when dealing with many tuna species the temperature required is much lower than that of other fish holds [4].

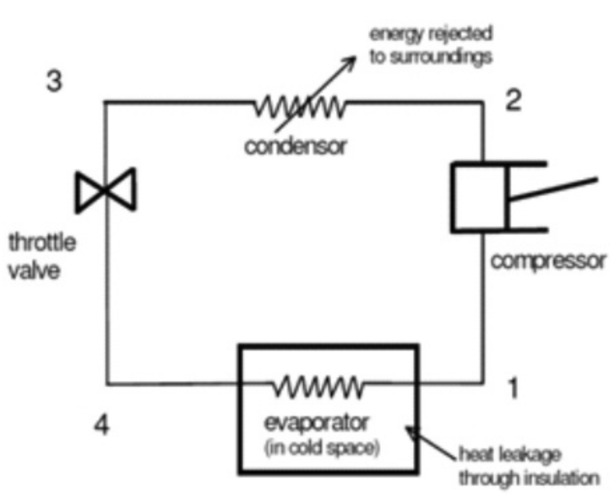

Figure 1 Schematically presented principle of a compression refrigeration system [6]

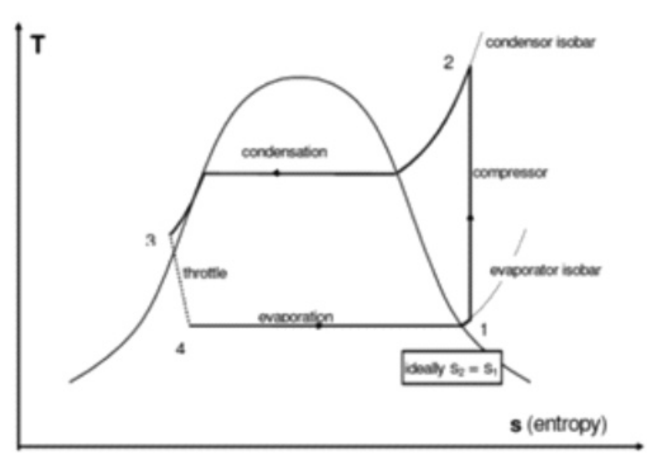

Figure 2 T-s Diagram for an ideal Vapour Compression Cycle [9]

The main areas for future improvements for refrigeration systems can be divided into two main categories; economic and environmental. The economic analysis is evaluating the cost of running the system which leads into finding the practical size of the system. The running cost is a major concern for refrigeration systems due to the potential large losses in efficiency [6]. This issue is addressed in the simulation models. The second category is based on the environmental concerns such as ozone layer depletion, global warming and fisheries depletion [1, 2, 7]. The main factors addressed are the global warming and the ozone layer effect of the refrigerants used. Fishing depletion can be reduced by ensuring that there is no wasted meat due to an ineffective system which is to be covered in the simulation models [5]. There are two main types of refrigeration plants that exist in the industry as described below [2].

2.2.1 Vapour compression refrigeration system

The compression refrigeration system is the most commonly found system in the marine sector [8]. The system uses a compressor and a condenser to force the refrigerant (the medium) to condense and dissipate heat [6]. A refrigeration system can vary from a simple design to a complex design based on its purpose such as a single stage compression system and multistage compression system.

A simple vapour compression refrigeration cycle consists of four major components, each having its own process and function as shown in Figure 1. The processes of the simple refrigeration cycle in relationship to temperature and entropy is shown in Figure 2. It can be seen that between points 1 and 2, there is a region of constant entropy (isentropic process).

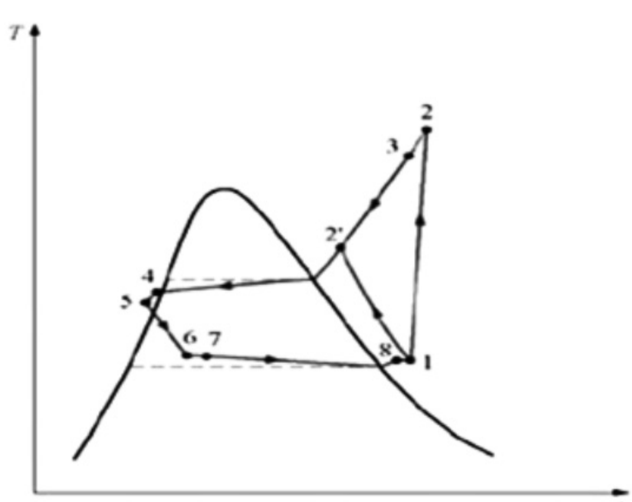

Figure 3 T-s Diagram for a real vapour compression cycle [10]

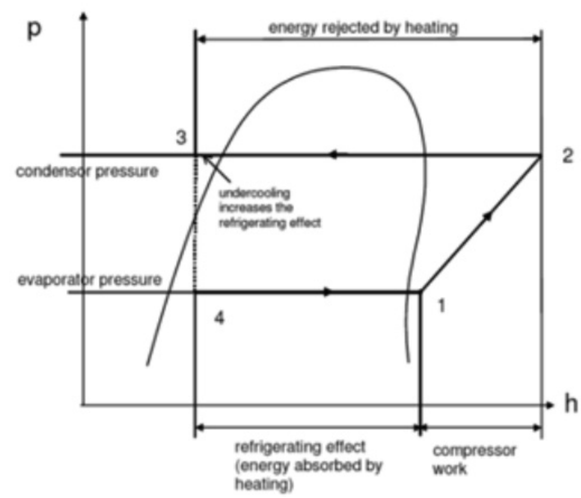

Figure 4 P-h Diagram for the Vapour Compression Cycle [9]

However, this is for an ideal refrigeration system. In a real refrigeration system, the entropy is not constant between points 1 and 2 and heat losses will occur throughout the system. Figure 3 shows a more realistic temperature and entropy diagram for a vapour compression cycle. Figure 4 shows the process of a simple refrigeration cycle in terms of pressure and enthalpy. Processes 2-3 and 4-1 can be seen to be at constant pressure for the condenser and evaporator. These pressures can also be called delivery and suction pressures respectively.

2.2.2 Absorption refrigeration system

The single effect absorption refrigeration system is the most commonly used design due to its simplicity [11]. Providing that the heat exchange has a large external heating source, the use of absorption refrigeration systems in fishing vessels has become a viable choice [12]. A single effect absorption refrigeration system is shown in Figure 5.

Unlike the compressor refrigeration system, the absorption refrigeration system replaces the mechanically driven compressor with a heat generator, liquid pump and an absorber. The generator can be used in conjunction with a heat exchanger to utilize the recovered heat from the prime mover's exhaust gases [14]. In theory, the efficiency can be improved by 60% by using a waste heat exchanger to improve the overall efficiency of the system [15].

2.3 Refrigerants

Many refrigerants are used in all refrigeration cycles as the medium which transfers the latent heat energy throughout the system [9]. The two most common re-

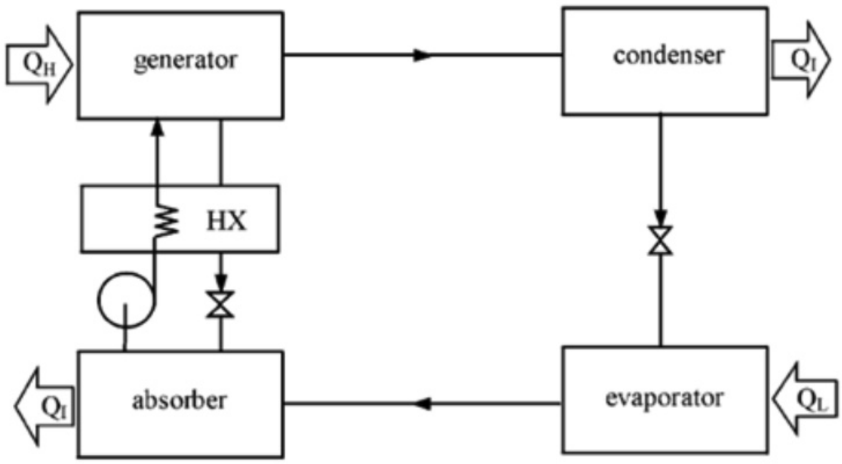

Figure 5 Single effect absorption refrigeration system [13]

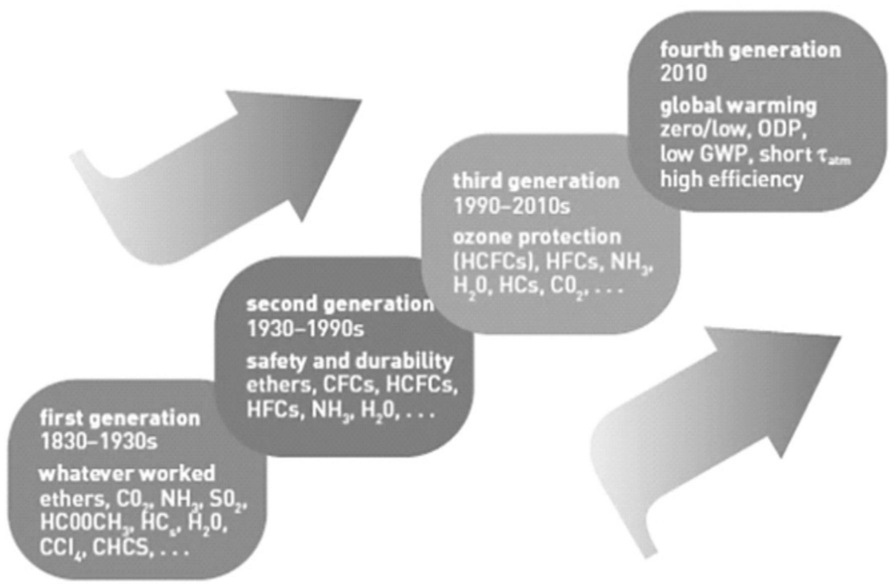

Figure 6 Generations of Refrigerants from 1830 to 2010 [19]

frigerants used in the fishing industry are chlorodifluoromethane (R-22) and 1,1,1,2-Tetrafluoroethane (R-134a) [1]. However, R-22 is required to be replaced due to the *Montreal Protocol.* The *Montreal Protocol* states that chlorofluorocarbons (CFC) and hydrogen chlorofluorocarbons (HCFC) are to be phased out by 1995 and 2020 respectively for developed countries [16]. Hydrofluorocarbons (HFCs) do not pose a threat to the ozone layer and therefore no further depletion [17]. An overview of the *Montreal Protocol* is shown in Table 1.

Hydrofluorocarbons (HFC) such as R-134a, at this stage does not need to be replaced although does have a global warming potential. Potentially R-134a may need to be replaced in later years if global warming is proven. On-going studies are being conducted to find replacement refrigerants that are environmentally harmless as well as safety considerations such as toxicity and flammability. The main two factors that determine the environmental impact of refrigerants are Global Warming Potential (GWP) and Ozone Depletion Potential (ODP).

Global Warming Potential (GWP) is a relative comparison of vapours compared to that of carbon dioxide (CO_2) in terms of greenhouse gases across a time interval commonly 100 years. Carbon dioxide is used as the reference point as it is regarded as the highest contribution to greenhouse gases. However, the topic of global warming is highly controversial. A low GWP is preferred but not required for refrigerants. Ozone Depleting Potential (ODP) is an index comparison of the refrigerants potential to destroy the ozone layer.

Table 1 Summary of Montreal Protocol control measures in Australia [16]

Ozone depleting substances	Control Method
Chlorofluorocarbons (CFCs)	Phased out end of 1995
Halons	Phased out end of 1993
CCl_4(Carbon tetrachloride)	Phased out end of 1995
CH_3CCl_3 (Methyl chloroform)	Phased out end of 1995
Hydrochlorofluorocarbons (HCFCs)	Freeze from beginning of 1996 35% reduction by 2004 75% reduction by 2010 90% reduction by 2015 Total phase out by 2020
Hydrobromofluorocarbons (HBFCs)	Phased out end of 1995
Bromochloromethane (CH_2BrCl)	Phase out by 2002

Table 2 Short list of ODP and GWP of common refrigerants [18]

ASHRAE Number	Chemical Formula	Chemical Name	Ozone Depletion Potential (*ODP*)	Global Warming Potential (*GWP*)
R-12	CCl_2F_2	Dichlorodifluoromethane	1.0	1890
R-22	$CHClF_2$	Chlorodifluoromethane	0.05	1790
R-134a	$C_2H_2F_4$	1,1,1,2-Tetrafluoroethane	0	1370
R-50	CH_4	Methane	0	23
R-170	C_2H_6	Ethane	0	~20
R-290	C_3H_8	Propane	0	~20
R-717	NH_3	Ammonia	0	<1
R-744	CO_2	Carbon Dioxide	0	1

The reference point ODP is R11, as it is considered to have the largest effect on the depletion of the ozone layer. Any refrigerant replacements are required to have a zero/low ODP [16] to satisfy the *Montreal Protocol*. A short comparison between the ODP and GWP for different refrigerants is shown in Table 2.

2.4 Evolution of refrigerants

Throughout the years, there have been various concerns to the environmental impact of the refrigerants. Each generation of refrigerants has been an improvement over the previous generation in terms of efficiency and safety. The evolution of refrigerants is shown in Figure 6.

For the first generation refrigerants, no environmental concerns were addressed. If the refrigerant worked, then it was used for that system. The refrigerants were nearly all flammable, toxic and high reactive which lead to accidents on a common basis [19]. Some of the first generation refrigerants included carbon dioxide (R-744), ammonia (R-717), sulphur dioxide (R-764) and water (R-718).

The second generation refrigerants addressed the issue of safety and durability with the a shift to the fluorochemicals (CFC, HCFC and HFC) [20]. Commercial production of R-11 and R-12 started in the early 1930s which became the standard refrigerants for most refrigeration needs with R-717 still preferred for large scaled plants [20]. However, with an increase of awareness, the ozone layer was considered to be depleting which started the production of the third generation refrigerants [21].

The third generation refrigerants concentrated on the removal of ozone-depleting substances (ODSs) with the creation of the *Montreal Protocol* [19, 21]. With chlorofluorocarbons (CFC) to be phased out by 1995, a replacement for Dichlorodifluoromethane (R-12) was required. 1,1,1,2-Tetrafluoroethane (R-134a) was created in 1995 with a similar performance to R-12 with zero ODP [22].

The fourth generation refrigerants look into ways of having the highest efficiency with little to no Global Warming Potential [12]. The interest in a “natural refrigerant” had grown to replace HFCs (R-134a) due to the global warming potential [16]. Possible “natural refrigerants” are ammonia (NH_3), carbon dioxide (CO_2), hydrocarbons (HC) and water (H_20).

Studies were conducted previously to compare different refrigerants in similar size refrigeration systems as there are some refrigerants that can be used as a

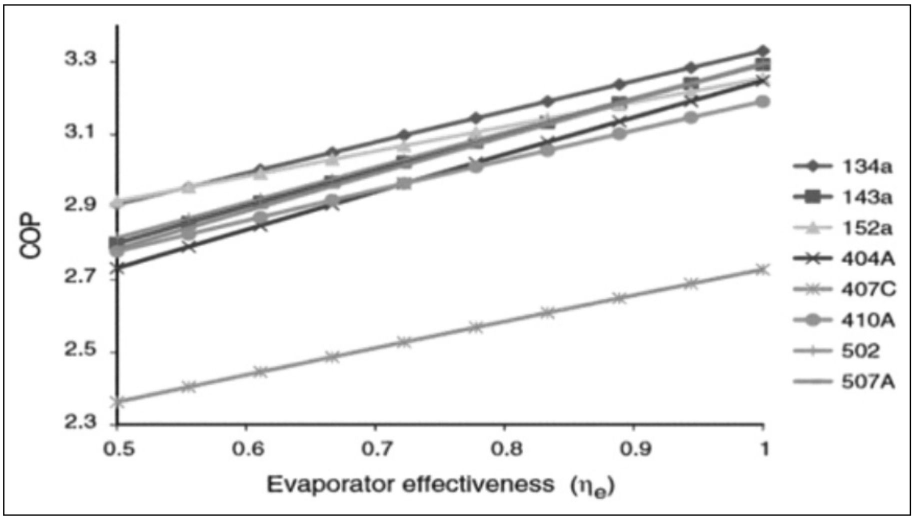

Figure 7 Evaporator effectiveness versus COP [23]

"drop in replacement." This means that the original refrigerant can be drained and replaced with a newer refrigerant without changing the system. However, for most studies conducted, there are limited investigations into comparing non-organic and organic refrigerants [4]. A study conducted by Reddy (2012) compared similar third and fourth generation refrigerants in a similar sized air conditioning system. The system used in this particular study is a simple single staged vapour compression cycle and the refrigerants used are shown in Table 3.

The performance of the refrigerants was compared with the evaporator effectiveness as shown in Figure 7. The effectiveness of the evaporator varied between 0.5 and 1.0 and the COP of the refrigerant improved as the effectiveness increases. 1,1,1,2-tetrafluoroethane (R134a) was found to be the most effective refrigerant whereas 407c, a mixture of difluoromethane (R32), pentafluoroethane (R125) and 1,1,1,2-tetrafluoroethane (R134a) had a poor performance.

3 METHODOLOGY

This section provides an overview of the methodology used in the construction of the simulation models created using *Simsci PRO/II 9.0* software. Furthermore, the testing conditions and selected refrigerants are defined and discussed.

3.1 Simulation models

The simulation model was created using *Simsci PRO/II 9.0* which allowed investigation of refrigeration systems by changing the refrigerant used as well as the system characteristics. The advantage of using a simulation program is the amount of variations and alterations that can be conducted with ease.

The refrigeration system used for this simulation was the vapour compression cycle shown in Figure 8. The model is set up with two simple heat exchangers to represent the evaporator and condenser. The evaporator (E2) is set to 1 degree kelvin rise above dew point

Table 3 Refrigerant properties [23]

ASHRAE Number	Chemical formula	Molecular Mass	NBP (°C)	Tc (°C)	Pc (MPa)	ASHARAE Safety Code
R-134a	CH2FCF3	102.03	-26.1	101.1	4.06	A1
R-143a	CH3CF3	84.04	-47.2	72.9	3.78	A2
R-152a	CH3CHF2	66.05	-24	113.3	4.52	A2
R-404a	R-25/143a/134a	97.6	-46.6	72.1	3.74	A1
R-407c	R-32/125/134a	86.2	-43.8	87.3	4.63	A1
R-410a	R-32/125	72.58	-60.9	72.5	4.95	A1
R-502	R-22/115	111.63	-45.3	80.7	4.02	A1
R-507a	R-125/143a	98.86	-47.1	70.9	3.79	A1

NBP – Normal boiling point (°C), Tc – Critical temperature (°C), Pc – Critical pressure (MPa)

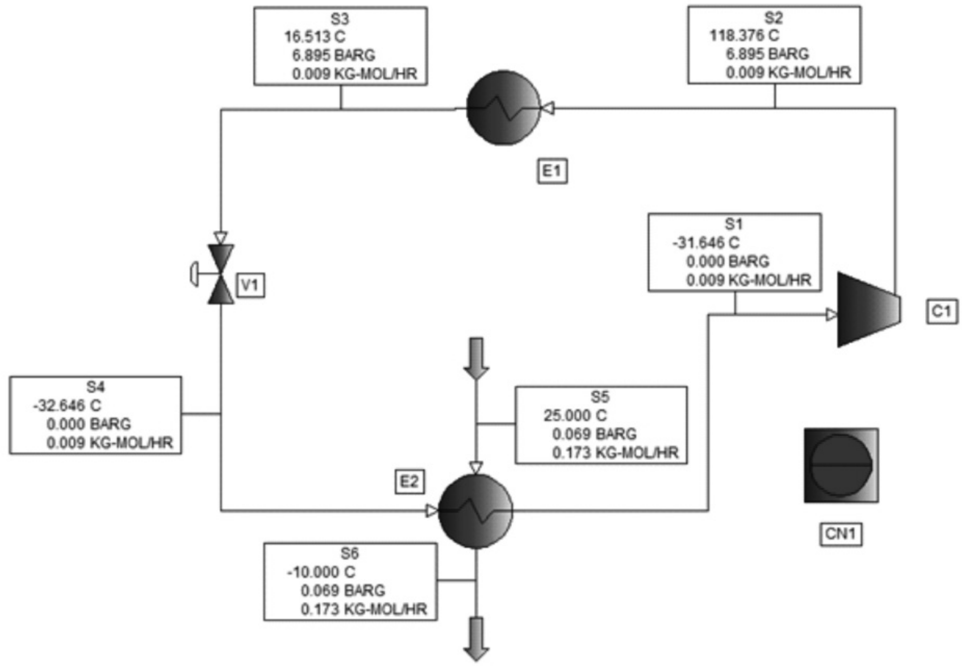

Figure 8 Simulation model – vapour compression cycle

to ensure that the refrigerant was in vapour phase at the outlet. Similarly, the condenser (E1) is set to 1 degree kelvin drop below bubble point to ensure that the refrigerant was in liquid phase. The compressor (C1) has been set to have an exit pressure of 689.5 kPa-g while the throttle valve (V1) has an exit pressure of 0 kPa-g. The streams (S1 to S4) contain the refrigerant while stream (S5 and S6) contain air.

Two controllers are used in the simulation program. The first controller sets the order of the component calculations based on initial conditions set at stream 1 (S1). The second controller varies flow rate of the refrigerant until the duty value of the evaporator was reached. The duty valve of an evaporator is also known the cooling load. This is used for the sizing of the evaporator for a refrigeration system as well as calculating the coefficient of performance of the system. The selected system is for operating temperatures from -40°C to 0°C. Therefore the refrigerants used for this system must have an exit temperature below -20°C after the throttle valve. The selected refrigerants used include both a mixture of non-organic and organic refrigerants for a comparison in performance. The following refrigerants have been selected:

- Commonly Used
  - R-12
  - R-22
  - R-134a
- Future Refrigerants
  - CH4 (R-50)
  - C2H6 (R-170)
  - C3H8 (R-290)
  - NH_3 (R-717)
  - $C0_2$ (R-744)

The following assumptions have been made:

- No external heat losses (through pipes)
- Mass flow rate is consistence at all locations
- Compressor, condenser and evaporator efficiencies are set to 100%

3.2 Single temperature system

The aim of this test objection is to find the optimum COP for the delivery and suction pressures of 689.5 kPa-g and 0 kPa-g respectively. The room size has not been determined as the simulation program is a steady-state simulator and therefore no time estimate can be taken. The mass flow rate of air is set to 1 kg/hr. This allows scaling to be taken place as flow rate between the refrigerant and air is proportional at a 1.1 ratio.

3.3 Scaled system

The scaled system is derived from the single temperature system. However, the duty valve is calculated from the total product load and hence the system is scaled proportionally. The duty required to cool 1 tonne of tuna from 25°C to three different room temperatures (-25°C, -20°C and -15°C) can be obtain using the total product load. The total product load is the sum of sensible heat and latent heat of freezing [25].

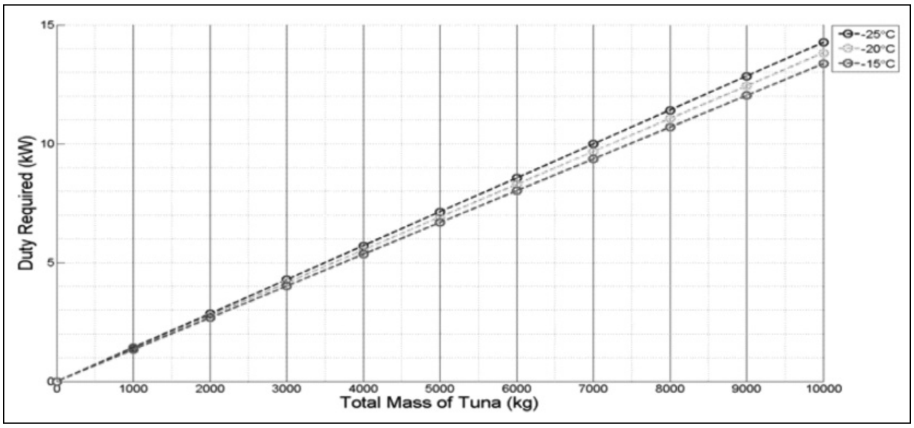

Figure 9 Total duty required

The duty required by the evaporator and mass of tuna is shown in Figure 9. As the mass of tuna increases, the required duty is proportionally increased. Similar, as the set temperature is reduced, the required duty also increases. The values for duty are shown in Table 4.

Table 4 Evaporator duty required

Mass of tuna (kg)	Evaporator duty required (kW)		
	-25°C	-20°C	-15°C
1000	1.43	1.38	1.34
2000	2.85	2.76	2.67
3000	4.28	4.14	4.01
4000	5.71	5.53	5.35
5000	7.13	6.91	6.68
6000	8.56	8.29	8.02
7000	9.98	9.67	9.35
8000	11.41	11.05	10.69
9000	12.84	12.43	12.03
10000	14.26	13.81	13.36

4 RESULTS AND DISCUSSION

In this section the Coefficients of Performance (COP) for different refrigerants are compared as well as economic, environmental and general safety matters are provided.

The coefficient of performance of refrigeration (COP) for all tested refrigerants was recorded and shown in Table 5. The highest recorded COP are 3.84 and 3.46 for ammonia (R717) and carbon dioxide (R744) respectively. The lowest COP recorded is 2.67 for methane (R50). 1,1,1,2-tetrafluoroethane (R134a) performance is much greater than that of the selected hydrocarbons, methane (R50), ethane (R170) and propane (R290), with percentage differences of 24.72%, 10.63% and 11.74% respectively.

The mass flow rates of each refrigerant required to reduce the temperature of air from 25°C to the temperature set point varies greatly between the refrigerants as shown in Table 6. The mass flow rate of air remains constant at 1 (kg/hr) allowing a direct comparison between the sizes of the refrigeration plant at the same required evaporator duty. Dichlorodifluoromethane (R-12) requires the highest mass flow rate at 0.452 kg/hr whereas ammonia (R-717) only requires 0.043 kg/hr (percentage difference of 90.49% reduction). Comparing the flow rates to the refrigeration affect, this relation is apparent. A high refrigeration effect will yield a low mass flow rate of the refrigerant required (smaller system). Furthermore, the compressor power required is also greater for that of R-12 compared to R-717.

Ammonia (R-717), carbon dioxide (R-744), 1,1,1,2-tetrafluoroethane (R-134a) and chlorodifluoromethane (R-22) have shown to have high COP_{REFRIG} whereas the hydrocarbons, methane (R-50), ethane (R-170) and propane (R-290), and dichlorodifluoromethane (R-12) have a poor performance in comparison. Dichlorodifluoromethane (R-12) has been phased out in Australia and a total phase out of chlorodifluoromethane (R-22) is to be completed by 2020. Possible options for a replacement for R134a are carbon dioxide (R-744) and ammonia (R-717).

4.1 Running cost

Using the required duty values calculated for 1 tonne of tuna stored at -25°C, the total input power of the compressor is determined as well as the running cost of the system. The running cost of 0.30 ($/kW-hr) is assumed. The true running cost is based on the setup of the fishing vessel with the generator brake specific fuel consumption (BSFC) and percentage of generator loading which will vary on trawler to trawler.

The running cost has been compared to that of 1,1,1,2-tetrafluoroethane (R-134a) as shown in Table

Table 5 Coefficients of Performance (COP) for different refrigerants

ASHRAE Number	Specific Enthalpy (kJ/kg)				Adiabatic Compression (kJ/kg)	Refrigeration Effect (kJ/kg)	COP_{REF}
	h1	h2	h3	h4			
R-12	142.47	179.26	31.53	31.53	36.79	110.94	3.02
R-22	193.76	245.70	20.62	20.62	51.93	173.14	3.33
R-50	-154.95	-3.71	-559.37	-559.37	151.24	404.42	2.67
R-134a	187.51	230.88	43.03	43.03	43.37	144.47	3.33
R-170	234.90	358.47	-136.43	-136.43	123.57	371.33	3.01
R-290	332.51	429.20	44.06	44.06	96.70	288.45	2.98
R-717	1260.03	1566.23	82.89	82.89	306.20	1177.14	3.84
R-744	217.19	309.54	-102.44	-102.44	92.35	319.63	3.46

Table 6 Mass flow rate of refrigerants

ASHRAE Number	Refrigerant Mass Flow Rate (kg/hr) for 1 (kg/hr) of air					
	T = -25°C	T = -20°C	T= -15°C	T = -10°C	T = -5°C	T = 0°C
R-12	0.452	0.407	0.362	0.316	0.271	0.226
R-22	0.290	0.261	0.232	0.203	0.174	0.145
R-50	0.124	0.112	0.099	0.087	0.074	0.062
R-134a	0.347	0.312	0.278	0.243	0.208	0.174
R-170	0.135	0.122	0.108	0.095	0.081	0.068
R-290	0.174	0.156	0.139	0.122	0.104	0.087
R-717	0.043	0.038	0.034	0.030	0.026	0.021
R-744	0.157	0.141	0.126	0.110	0.094	0.078

Table 7 Running cost

ASHRAE Number	Mass Flow Rate Refrigerant (kg/hr)	Input Power (kW)	Assumed Cost ($/kW-hr)	Running Cost ($)				Difference (%)
				hour	day	month	year	
R-12	231.43	2.365	0.30	0.71	17	511	6130	10.47
R-22	148.29	2.139	0.30	0.64	15	462	5545	-0.08
R-50	63.49	2.667	0.30	0.80	19	576	6913	24.58
R-134a	177.72	2.141	0.30	0.64	15	462	5549	-
R-170	69.14	2.373	0.30	0.71	17	513	6151	10.85
R-290	89.01	2.391	0.30	0.72	17	516	6197	11.67
R-717	21.81	1.855	0.30	0.56	13	401	4809	-13.34
R-744	80.33	2.061	0.30	0.62	15	445	5341	-3.75

7. The most cost effective option is shown to be ammonia (R-717) and carbon dioxide (R-744) compared to R-134a with a reduction in running cost by -13.34 and -3.75%. Methane (R-50), ethane (R-170) and propane (R-290) will increase the running cost by 24.48%, 10.85% and 11.67% respectful and is not recommended as a replacement for R134a.

Although ammonia has the highest COP and the lowest running cost, it is not recommended for this system due to the toxicity of the gas. Refrigeration systems can leak and care must be taken when dealing with toxic refrigerants. Leakage of ammonia gas to into the frozen products via the evaporator can potentially cause harm to the consumers. However, ammonia has a unique odour that can easily be detected. Furthermore, carbon dioxide is an odourless gas which is difficult to detect although can be harmful depending on the concentration.

5 CONCLUSION

The *Montreal Protocol* has phased out the commonly used refrigerants in the marine industry such as R-12 and R-22. Replacement refrigerants included R-134a and R-717 with future research into natural refrigerants. With the use of PRO/II, a simulation program, a vapour compression cycle was constructed to test varies refrigerants to calculate the coefficient of performance for refrigeration. A second investigation was conducted to find a cost effective option for the replacement of R-134a due its global warming potential. A final consideration to safety was also conducted.

The highest performances for refrigeration were recorded at 3.84 and 3.46 for ammonia (R-717) and carbon dioxide (R-744) respectively.

1,1,1,2-tetrafluoroethane (R-134a) performance is recorded at 3.33 showing that two suitable cost effective replacements for R-134a are ammonia and carbon dioxide to improve running costs as well as a large reduction in global warming potential. As the initial cost of upgrading the system from one refrigerant to another has not been considered, only the running costs were compared. The safety consideration for the use of ammonia (R-717) and carbon dioxide (R-744) showed that carbon dioxide is the preferred refrigerant with a compromise on performance due to toxicity levels. The hydrocarbons have the lowest recorded performances at 2.67, 3.01 and 2.98 for methane (R-50), ethane (R-170) and propane (R-290), with percentage differences of 24.72%, 10.63% and 11.74% compared to R-134a respectively. Ethane and propane can be used for as replacement for R-134a at a reduced performance (higher running costs) as well as methane at a much larger reduction in performance. However, this is not recommended as it is not cost effective.

For new built refrigeration systems, carbon dioxide is recommended to be used to ensure a high performance and low global warming potential. Future work is recommended for future investigation into different refrigeration systems such as absorption refrigeration systems, multistage compression cycles, cascade systems etc. Initial cost estimates should be calculated for an overall cost effectiveness of replacing the refrigerants with rate of return.

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