Modelling a simple-vapour compression refrigeration cycle for Fish-Storage boxes

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Abstract. In this paper, a computerized modelling of a simple single-stage vapour compression refrigeration cycle has been carried out. The aim is to find a cycle performance that is suitable for fish preservation applications. The simulation was completed using the CoolPack software on two different refrigerants and analysed at various condensation temperatures. As a fixed variable, a specific compressor power has been chosen for all cases in meeting the evaporation temperature designed. The results of this study inform the comparison of cycle performance including heat rejection rate, cooling capacity, COP, and pressure-enthalpy diagram. The main conclusion is that both types of refrigerant that are simulated can produce high COP which is useful for handling the cooling load that is later available. The report on this study will be used further to design a fish-storage box.

1. Introduction

Fish is one of the foods that are very easily damaged. Various types of bacteria can break down the nutritional components of fish into rotten and rancid compounds. Damage to fish quality can occur due to collisions during fishing, transportation, and preparation before processing. Symptoms of damage are marked by bruising (because it is crushed or pressed), torn, and cut. This damage is quite influential on the appearance and acceptance of consumers [1]. The way to extend the storage period of fresh fish is to use a refrigerator or freezer, which can inhibit bacterial activity. Storage in the refrigerator is very limited in number and storage period. While in the freezer, the fish can be preserved for quite a long time. However, this two equipment cannot be applied directly to a fishing boat while at sea due to the unavailability of electricity on the fishing boat. Difficulties in storing fish are usually experienced by fishermen when they return from fishing to the location of the fish sale. The solution that has been carried out by fishermen up to now is to use ice blocks which are put into fish boxes [2]. However, the use of ice blocks is less effective and efficient and often results in losses for fishermen if they do not get fish at sea.

The development of mini-scale refrigeration systems began to appear in the last ten years. Direct current (DC) electricity technology is an attractive choice in the application of wider portable refrigeration systems. Based on literature studies, several studies have been found in the design and development of mini-scale refrigeration systems in various sizes and purposes. The first, Wu and Du [3] conducted a design and experimental study of a mini-scale vapour compression refrigeration (VCR) systems to cool electronic equipment. The VCR was built with a compressor, a capillary pipe, a
condenser, a cold plate, and a control circuit with a system dimension of 300 x 230 x 70 (mm), and has a cooling capacity of 200W. The compressor is operated by a 24V DC unit whose speed can be controlled by adjusting the input voltage. The result is that through a heat load of 200W, the temperature of the cold plate can be maintained in the range of 60 °C for hours with a system efficiency that varies between 23% to 31%. Secondly, a practical miniature vapour compression refrigerator has been developed by Yuan et al. [4]. The dimensions are 190 x 190 x 100 (mm) with a weight of 2.75 kg. This refrigerator is powered by a mini rotary compressor and a small electronic expansion valve (EXV) that operates with pulse width modulation (PWM). Also, a micro-finned mini-channel evaporator is made with vacuum bonding technology and a micro-channel aluminium condenser with parallel flow. The experiments were carried out to evaluate the performance of the refrigerator, especially on the effects of EXV and cooling performance. The results show that the system can operate smoothly and reliably with a cooling capacity of 260W. This value is equivalent to cooling one person with a medium heat load, where the highest ambient temperature and the temperature of cold water entering from the evaporator are 50 °C and 24 °C, respectively. Under these operating conditions, the COP of the refrigerator can reach 1.62 with a reversible efficiency of 0.324. Furthermore, a similar study was also carried out by Poachaiyapoom et al. [5] who developed a mini-scale vapour compression refrigeration system to cool electronic devices. The prototype was built with a compressor, an evaporator, a capillary, and a condenser, and adopted refrigerant R134a. The evaporator contains 106 rectangular micro-channels with a depth of 450 μm, width of 150 μm, a wall thickness of 150 μm, and a length of 20 mm. Experimental conditions including compressor speeds are set in the range of 3000 to 6000 RPM with thermal energy of 100W, 150W and 200W. The results showed that by increasing the compressor speed, the surface temperature of the heater could be reduced, but the coefficient of performance (COP) also dropped. The highest COP value obtained is 9.069 at the compressor speed of 3000 RPM and thermal energy of 200 W, which produces a heating surface temperature of 73.3 °C. This mini-scale vapour compression refrigeration system can be used to cool electronics under the right conditions, especially with 200W heat energy and compressor speed 3000 RPM. The proposed prototype is not suitable for cooling electronics at thermal energy of 100W and 150 W because the surface temperature of the heater is less than 40 °C.

Before further designing, the initial work of this study is to model a simple vapour compression refrigeration cycle to find suitable cycle parameters applied to a fish storage box. This modelling also refers to several similar studies, such as Senawi and Mahmod [6], which conducted a study of computer simulations of a simple single-stage vapour compression refrigeration system using the Cleland regression equation with refrigerant R134a. The output of this simulation is the effect of refrigeration, the work input from the compressor, the performance coefficient (COP), and the vapour flow rate on the suction side of the compressor per kilowatt of refrigeration. Besides, there is also a study of a novel numerical vapour compression refrigeration system conducted by Zsembinszki et al. [7]. The modelling starts from the three input parameters, specifically at ambient air temperature, cooled room temperature, and the degree of superheat. The simulation calculation algorithm is based on iterative loops used to determine the operating point of the refrigeration system. The experimental setup uses a walk-in freezer unit as a model development and validation. And the most recent is a study conducted by Ambarita et al. [8] concerning the investigation of an optimal temperature of a single-stage vapour compression refrigeration cycle in an Air Conditioning unit. The modelling was carried out using Aspen Plus software on three selected refrigerants. The results show that the optimal temperature is obtained in an optimal and ideal refrigeration cycle.

Based on overall the studies reported above, it is informed that the vapour compression refrigeration system will continue to develop for various purposes, especially in the application of DC electrical systems to support portable and practical refrigeration products with reliable performance. The focus of this study is to model a simple vapour compression refrigeration cycle with two different refrigerants. The results will inform the comparison of cycle performance including heat rejection rate, cooling capacity, COP, and pressure-enthalpy diagram. A follow up of this work in the future is to design a DC-powered fish-storage box to be applied in a fishing boat.
2. Methods

In this study, CoolPack software is used to model the vapour compression refrigeration cycle as shown in Figure 1. CoolPack software is a combination of several simulation models for refrigeration system applications, each of which has a specific purpose such as analysing cycles, determining the size of the main components, analysing energy, and optimizing. The CoolPack software is free licensed software that can be used by anyone freely [9].

![Figure 1. Dimension of a simple single-stage refrigeration system displayed by CoolPack software.](image)

A schematic of a simple refrigeration system and a pressure-enthalpy diagram of a vapour compression refrigeration cycle are shown in Figure 2. In this figure, it can be seen that the refrigeration system has four main elements, namely a compressor, a condenser, an expansion valve, and an evaporator. Through the support of a pressure-enthalpy diagram, a significant quantity of the vapour compression refrigeration cycle can be determined. These quantities are compressor power, heat rejection rate, cooling capacity, and performance coefficient [10]. Compressor power per unit mass of the refrigerant is calculated by the following equation:

\[ W_c = \dot{m}_r (h_2 - h_1) \]  

(1)

Where \( W_c \) is the compression power in units of kJ/s, \( \dot{m}_r \) is the mass flow rate of the refrigerant in kg/s, and \( h \) is the enthalpy according to the subscript in Figure 2, in units of kJ/kg.

![Figure 2. Schematic of the system and pressure-enthalpy diagrams.](image)
The second quantity, the heat rejection rate, $Q_c$ (kW), can be calculated by the following equation:

$$Q_c = \dot{m}_r (h_2 - h_3)$$ (2)

Third, the cooling capacity of the system, $Q_e$ (kW), can be calculated by the following equation:

$$Q_e = \dot{m}_r (h_1 - h_4)$$ (3)

And finally, the coefficient of performance (COP) which is calculated by the following equation:

$$COP = \frac{Q_e}{W_c}$$ (4)

### Table 1. Variations of condensation temperature.

| Refrigerant | Evaporation temperature (°C) | Condensation temperature (°C) |
|-------------|-------------------------------|-------------------------------|
| R134a       | -10                           | 34                            | 36                            | 38                            | 40                            | 42                            | 44                            |
| R600a       | -10                           | 34                            | 36                            | 38                            | 40                            | 42                            | 44                            |

### 3. Results and Discussion

The modelling has been carried out on six variations of condensation temperature (Table 1). The types of refrigerants used in the system are R134a and R600a. Its physical properties are determined through the refrigeration utility features that are available in the CoolPack software. Evaporation temperature is set constant at -10 °C. Compressor power is assumed to be constant at 0.125 kJ/s, which offers to the availability of components on the market. This modelling is assumed to be in steady state. All over the resistance, pressure loss, and energy differences in the system are ignored.

In the modelling process, the software will inform the value of the results of cycle calculations that are useful in selecting the right performance to be applied to a simple refrigeration system. Twelve cycle models have been analysed, and the overall values have been summarized in Table 2.

### Table 2. Performance of the system.

| Condensation temperature (°C) | Heat rejection rate (kJ/s) | Cooling capacity (kJ/s) | COP     |
|-------------------------------|----------------------------|-------------------------|---------|
|                               | R134a | R600a | R134a | R600a | R134a | R600a | R134a | R600a |
| 34                            | 0.723 | 0.735 | 0.598 | 0.610 | 4.78  | 4.88  |
| 36                            | 0.689 | 0.701 | 0.564 | 0.576 | 4.51  | 4.61  |
| 38                            | 0.657 | 0.670 | 0.532 | 0.545 | 4.26  | 4.36  |
| 40                            | 0.628 | 0.641 | 0.503 | 0.516 | 4.03  | 4.13  |
| 42                            | 0.601 | 0.614 | 0.476 | 0.489 | 3.81  | 3.91  |
| 44                            | 0.576 | 0.589 | 0.451 | 0.464 | 3.61  | 3.71  |

#### 3.1. Cooling capacity

Based on the summary results presented in Table 2, it can be observed the comparison of the cooling capacity at the specified condenser temperatures. Figure 3 (a) presents the cooling capacity variants of R143a and R600a. The line with the cross mark is the cooling capacity value of the refrigerant R134a, and the line with the triangle mark represents the cooling capacity of the refrigerant R600a. In the figure, the same cooling capacity tendency is shown for both cycles, where the highest value is obtained by refrigerant R600a. In this case, the increase in cooling capacity is influenced by the characteristics of the refrigerant used.
3.2. Coefficient of Performance
Similar to cooling capacity, COP also shows the same tendency as shown in Figure 3 (b). The refrigerant R600a produces a higher COP than R134a for the specified condensation temperatures and compressor power. On average, COP values increase by 10% if the system uses R600a. This means there is energy savings in the system that provides good benefits. If it refers to research that has been done by Hastak et al. [11], it was found that modifying a household refrigerator using refrigerant R600a turned out to increase COP by 26%. This information will certainly support and strengthen the results of modelling the refrigeration cycle that has been done.

3.3. Pressure-Enthalpy Diagrams
In the CoolPack software, many tools can be used to design a refrigeration system starting from refrigerant selection, dimensioning, and evaluation of the system. In this study, only two tools are used to model the system, namely the refrigeration utility that is useful for obtaining cycle performance, and the cycle analysis tool used to present the pressure-enthalpy diagram of the analysed cycle. Figure 4 shows a pressure-enthalpy diagram represented by refrigerant R134a at a condensation temperature of 44 °C. In this figure, it can be seen the values of the system performance and the presentation of the temperature values for each point.
4. Conclusion
Modelling of a simple vapour compression refrigeration cycle has been observed. Numerical simulations have been carried out to determine the system performance by using refrigerants R134a and R600a at the specified condensation temperatures and compressor power. The results of this reported study will be used further to design a fish-storage box that is applied to fishing boats. The high COP value of the refrigerant R600a will be advantageous for handling the cooling load of the fish during the storage period and is a good potential for energy savings. The main conclusion of this study is that both types of refrigerants that are simulated can produce good cycle performance with a COP range of 3 to 5. Besides, it is important to know that R600a is an environmentally friendly alternative refrigerant that can help reduce the ozone depletion potential and global warming.

5. References

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