Design of refrigeration system using refrigerant R134a for macro compartment

M F H Rani¹, Z M Razlan¹, A B Shahriman¹, C K Yong¹, A Harun², M S M Hashim¹, M K Faizi¹, I Ibrahim¹, N S Kamarrudin¹, M A M Saad¹, I Zunaidi¹, W K Wan¹ and H Desa¹

¹School of Mechatronic Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.
²School of Microelectronic Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.
zuradzman@unimap.edu.my

Abstract. The main objective of this study is to analyse and design an optimum cooling system for macro compartment. Current product of the refrigerator is not specified for single function and not compact in size. Hence, a refrigeration system using refrigerant R134a is aimed to provide instant cooling in a macro compartment with sizing about 150 \times 150 \times 250 mm. The macro compartment is purposely designed to fit a bottle or drink can, which is then cooled to a desired drinking temperature of about 8°C within a period of 1 minute. The study is not only concerned with analysing of heat load of the macro compartment containing drink can, but also focused on determining suitable heat exchanger volume for both evaporator and condenser, calculating compressor displacement value and computing suitable resistance value of the expansion valve. Method of optimization is used to obtain the best solution of the problem. Mollier diagram is necessary in the process of developing the refrigeration system. Selection of blower is made properly to allow air circulation and to increase the flow rate for higher heat transfer rate. Property data are taken precisely from thermodynamic property tables. As the main four components, namely condenser, compressor, evaporator and expansion valve are fully developed, the refrigeration system is complete.

1. Introduction
Due to the warm weather, especially in Malaysia, it had become a common practice to go for a cold drink under the hot weather. Thus, cold drinks are preferable by people and the demand for them never ceases since this is a good way to cool the body temperature down [1]. Therefore, there are people starting to commercialize them and looking for a better solution to prepare cold drinks in shortest time either designing new approaches in chilling [2] or developing high efficiency cycle in refrigeration [3]. However, the refrigerator, chiller and freezer available at electrical shops are in standard size, not having much variation, usually in big size and designed to perform combined tasks. Their volume and cooling capacity are the reason why those refrigerators are not suitable to provide an immediate cooling to a size of drink bottle or can for people. For normal cases, once a drink can is placed into the freezer, the cooling process may take up about 15 to 20 minutes, in order to lower the temperature of the drink to the desired temperature, which is about 8°C for good tasting [4]. An alternative that people are still practicing is to go to a nearby shop or vending machine to purchase. However, this is
still inconvenient for consumers to go out only to get a bottle or can of cold drink. At present, there are some mini fridges available with storage capacity of approximately 0.3 m$^3$ to 0.5 m$^3$ or in other words, it could store up to 12 bottles or drink cans and able to provide cooling in a few minutes to reach the desired temperature of cold drink. In this research, developing a macro compartment refrigeration system of size about of 150 × 150 × 250 mm is concerned, which will be able to cool a single bottle or drink can in only 1 minute as illustrated in Figure 2.

2. Refrigeration cycle analysis
The pressure – enthalpy diagram is analysed by selecting a particular region of the Mollier diagram of refrigerant R134a as shown in Figure 1. Basically, point 1 to 2 represent the compressor work input, point 2 to 3 represent heat dissipation from the condenser to the surroundings, while point 3 to 4 is the expansion process by capillary tube. Evaporator (point 4 to 1) works vice versa to the compressor, which extracts heat from the surrounding into the cycle [4].

![Figure 1. Pressure – enthalpy diagram.](image)

3. Refrigerant landscape for HVAC industry
R134a has been very successfully used in screw chillers where short pipe lengths minimise costs associated with larger tubing. R134a also finds a niche where extra high condensing temperatures are needed in many transport applications [4]. By applying working principle of air conditioning, refrigerant R134a is chosen to be working fluid in removing heat from a bottle or drink can. According to Montreal Protocol [5], this refrigerant has replaced former refrigerant R22 in the refrigeration industry as it is potential for ozone layer depletion. Hydrofluorocarbons, HFCs such as R134a have no ozone depletion potential (ODP) but they do have global warming potential (GWP), which affects the environment if the refrigerant escapes to the atmosphere. A catastrophic chiller failure leading to a refrigerant leak may cause HFC refrigerant to escape into the atmosphere, yet, such occurrences are generally very low.

There is a claim that lower GWP has been always better, but a lower GWP could come with trade-offs. The lower GWP refrigerants, i.e., R32 and R152a have lower efficiency than the refrigerants we are using today, which is not preferable for the HVAC market. For chillers, apart from electricity generation to run the equipment, the refrigerant containment is also critical. There is no direct impact on global warming from refrigerants as long as they are contained and not released into the atmosphere. Selecting a chiller with an A1 refrigerant solely on the basis of GWP could be a losing proposition. If the refrigerant is less efficient than R134a or R410A, the chiller could lose efficiency and contribute more to global warming through higher energy usage leading to increased carbon emissions. Thus, Class A refrigerants, i.e., R134a and R410a are a safer and smarter choice for refrigeration purpose as they offer the lowest ASHRAE toxicity classification (“A”) [6].
4. Methodology

4.1. Identification of heat load produced by a drink can

A drink can is assumed to be at room temperature initially before it is placed into the macro cooling compartment for cooling process to take place. Several drinks are selected to determine the heat load produced by a drink can. Based on ASHRAE Handbook: Refrigeration [7], specific heat capacity for selected beverages are considered in calculating the cooling capacity for the macro compartment. As summarized in Table 1, the heat load of the selected beverages is then calculated when being cooled from 30°C to 8°C. Since water possesses higher heat load among them, it is selected as reference for cooling capacity value in the entire process of refrigeration analysis [8]. The cooling capacity required for the evaporator must be higher in order to overcome the heat load. Hence, a safety factor of 10% is added as the cooling capacity of the evaporator.

| Beverage     | Specific heat above freezing (kJ/kg. K) | Heat load, Q (kJ) |
|--------------|----------------------------------------|------------------|
| Cola         | 1.760                                  | 15.84            |
| Cream soda   | 1.790                                  | 16.11            |
| Orange juice | 1.730                                  | 15.57            |
| Water        | 4.187                                  | 62.81            |

4.2. Compressor displacement volume evaluation

Compressor displacement value could be obtained by evaluating the mass flow rate, \( m \) and volumetric flow rate, \( V_{th} \) of refrigerant R134a [9]. Based on the schematic of Mollier diagram in Figure 3, enthalpy difference compressor and evaporator (point 1 and 4), \( \Delta h \) is crucial in determining both values.

4.3. Analysis on heat exchanger volume (evaporator and condenser)

The volume of the heat exchanger could be calculated by using the same method and formula for both evaporator and condenser [9]. However, their volume and designs will be varied due to differences in parameters such as temperature, pressure and enthalpy. Usually, the condenser has 1.5 times larger size than the evaporator. Selection of blower is considered too to enhance the heat transfer rate.

4.4. Analysis on suitable resistance value for expansion valve

For the purpose of optimization, suitable resistance value for expansion valve must be analysed to reduce the pressure in the refrigeration system especially between condenser and evaporator [9]. As
shown in Figure 3, the pressure difference between condenser and evaporator (point 3 and 4), \( \Delta P \) is regulated by temperature sensor and pressure sensor in the expansion valve. The expansion device regulates the mass flow rate of refrigerant and removes pressure from the liquid refrigerant to allow expansion from liquid to vapour in the evaporator. Table 2 summarizes essential equations that were utilized during refrigeration system analysis for macro compartment by using refrigerant R134a.

**Table 2. Equations involve in refrigeration system analysis for macro compartment.**

| Parameter and equation | Nomenclature |
|------------------------|--------------|
| Heat load             | \( Q = m c_p [T_i - T(t)] \) |
| Required heat transfer rate | \( \dot{Q}_{\text{load}} = \frac{Q}{t} \) |
| Suggested cooling capacity | \( \dot{Q}_{\text{cooling}} = \dot{Q}_{\text{load}} + 10\% \) |
| Compressor displacement volume | \( V = \frac{60 V_{\text{th}}}{\eta_m N} \) |
| Overall heat transfer coefficient | \( \frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_o} \) |
| Condenser heat transfer surface area | \( A_{s. \text{cond}} = 1.5 \times A_{s. \text{evap}} \) |
| Pressure difference between condenser and evaporator | \( \Delta P = P_3 - P_4 \) |

**5. Result and discussion**

5.1. **Cooling capacity required for refrigeration system in macro compartment**

Based on the heat load of water as shown in Table 1, at least 1046.75 W amount of heat transfer rate must be established in the macro compartment. By considering 10% of safety factor, about 1150 W of cooling capacity is suggested to implement a refrigeration system in macro compartment. The cooling capacity will decide the value of compressor displacement volume, design of the heat exchanger volume and the resistance value of the expansion valve.

5.2. **Compressor displacement volume**

Based on Figure 6, heat transfer occurs between air and refrigerant, where refrigerant increases in temperature when gaining heat from the air while air decreases in temperature due to heat loss. 0°C of refrigerant is set in the inlet of evaporator in order to obtain a desired outlet temperature of air around 8°C. By considering suggested cooling capacity, \( \dot{Q}_{\text{cooling}} \) as well as enthalpy value at the inlet and outlet of the evaporator (\( h_i \) and \( h_o \)), an amount of 295 cc/stroke of pumping power is required to allow 0.0076 kg/s of mass flow rate of refrigerant in the cooling system of macro compartment.
5.3. Design of heat exchanger volume (evaporator and condenser)

Overall heat transfer coefficient in macro compartment is found to be 32.31 W/m² K, which covers a total surface area of 0.0588 m² of heat transfer at evaporator and 0.0882 m² of heat transfer at condenser respectively. For desired heat transfer to take place, at least 2.9475 m length of copper tube must be designed at evaporator while a minimum length of 4.4212 m at the condenser. By designing the mean diameter of a coil spring to be 0.07 m, the evaporator is designed to have 14 number of turns with a height of approximately 0.18 m as shown in Figure 4. On the other hand, as shown in Figure 5, two layers of copper tube are required at condenser since the length of copper tube at condenser is longer compared to evaporator.

By designing the copper tube with 20 number of turns, its length is reduced to 0.11 m. Full designs of heat exchanger for internal flow are shown in Figure 8 (a) and Figure 8 (b) while the illustration of drink bottle in the evaporator is illustrated in Figure 8 (c). For external flow, as shown in Figure 8 (e), a compact fan [10] with maximum 0.0067 m³/s air flow volume is selected to improve the heat transfer rate that covers 0.0144 m² area of the evaporator. Due to severe loss, such as friction, the air flow rate discharged from the fan is assumed to have 80% efficiency, which supply 0.00536 m³/s of air flow rate only into the evaporator.

![Figure 4](image1.png)  ![Figure 5](image2.png)

**Figure 4.** Copper coil design at evaporator.  **Figure 5.** Copper tube design at condenser.

5.4. Resistance value of expansion valve

Since the condenser is placed outdoors, the condenser coil is contacting with the outdoor ambient air, which is not constant in temperature all the time. Thus, any changes to the outdoor temperature will affect the pressure at the condenser, thereby influence the overall refrigeration cycle. As illustrated in Figure 7, the expansion valve must contain a pressure difference, ΔP of 1.0251 MPa between condenser and evaporator in order to optimize the overall refrigeration cycle.

![Figure 6](image3.png)  ![Figure 7](image4.png)

**Figure 6.** Heat exchange at evaporator.  **Figure 7.** Pressure difference between condenser and evaporator.
Besides of redesigning the evaporator by spring helical shape as illustrated in Figure 8 (d), the rate of heat transfer also could be improved by adding shaker or rotator mechanism at the platform where the drink can is placed. An artificial induced convection current circulation is created once the can is shaken or rotated. This situation will help the drink can to achieve equilibrium heat transfer and cool the drink can faster at all corners. If this method is proven to be successful, the macro compartment will take shorter time to cool down the drink bottle or drink can.

The heat load of drink can determines the cooling capacity of the refrigeration system. As higher heat load is accumulated, higher cooling capacity is required for the refrigeration system to be designed. The heat load produced by drink bottle or drink can in macro compartment was calculated to be 62.805 kJ, where the water becomes the reference drink. The mass flow rate of the refrigerant depends on the cooling capacity and enthalpy difference. By obeying the 1st law of thermodynamic (law of conservation energy), the mass flow rate of the refrigerant R134a needs to be calculated precisely since it is kept constant throughout the system. The evaporator coil was designed with spring condenser and evaporator.

Figure 8. (a) Design of evaporator with fin, (b) Design of condenser with fin, (c) Illustration of drink bottle in evaporator, (d) Alternative design of evaporator, (e) DC axial fan series 420 J.
helical shape to fit the geometry of drink bottle or drink can. The diameter of cooling coil of evaporator was determined to be 0.07 m with 14 turns and height approximately 0.18 m. The wire diameter of copper tube used for both evaporator and condenser is 6.35 mm. Meanwhile, the copper tube used for condenser was designed to be double layers, with 20 turns alternately and a length of 0.11 m for better heat transfer to the outdoor ambient air. Fins were added to allow mix flow of the heat exchangers for effective heat transfer. The pressure difference between the inlet and outlet of expansion valve was determined to be 1.0251 MPa. All design parameters of refrigeration system by using refrigerant R134a for macro compartment are summarized in Table 3.

| Parameter                                           | Value                          |
|-----------------------------------------------------|-------------------------------|
| Required heat transfer rate, \( Q_{\text{load}} \)  | 1046.75 W                     |
| Suggested cooling capacity, \( Q_{\text{cooling}} \) | 1150 W                        |
| Mass flow rate of refrigerant, \( \dot{m}_{\text{ref}} \) | 0.0076 kg/s                   |
| Volumetric flow rate of refrigerant, \( \dot{V}_{\text{th}} \) | 4.187                         |
| Compressor displacement volume (Pumping power), \( V_c \) | 295 cc/stroke                 |
| Cross sectional area of flow passing through copper tube, \( A_c \) | \( 1.77 \times 10^{-5} \) m\(^2\) |
| Reynolds number                                      | 76256                         |
| Nusselt number                                       | 311                           |
| Heat transfer coefficient inside copper tube, \( h_i \) | 808.27 W/m\(^2\). K          |
| Heat transfer coefficient outside copper tube, \( h_o \) | 30.32 W/m\(^2\). K           |
| Overall heat transfer coefficient, \( U \)          | 32.31 W/m\(^2\). K           |
| Mass flow rate of air, \( \dot{m}_{\text{air}} \)   | 0.0082 kg/s                   |
| Minimum heat capacity ratio, \( C_{\text{min}} \)   | 8.2574 W/K                    |
| Number of transfer units, NTU                        | 0.23                          |
| Total surface area for heat transfer at evaporator, \( A_{s,\text{evap}} \) | 0.0588 m\(^2\)               |
| Minimum length of copper tube at evaporator, \( L_{\text{evap}} \) | 2.9475 m                     |
| Number of turns of copper tube at evaporator, \( N_{\text{evap}} \) | 14 turns                     |
| Suggested height of copper coil at evaporator, \( H_{\text{coil}} \) | 18 cm                        |
| Total surface area for heat transfer at condenser, \( A_{s,\text{cond}} \) | 0.0882 m\(^2\)               |
| Minimum length of copper tube at condenser, \( L_{\text{cond}} \) | 4.4212 m                     |
| Number of turns of copper tube at condenser, \( N_{\text{cond}} \) | 20 turns                     |
| Pressure difference between point 3 and 4, \( \Delta P \) | 1.0251 MPa                    |

6. Conclusion
An optimum refrigeration system for macro compartment that fits a single drink bottle or drink can is possible to be developed in compact approach. The heat load of drink can and cooling capacity of macro compartment determine the design of the four main components in refrigeration cycle, i.e., compressor, condenser, expansion valve and evaporator. The compressor converts the liquid refrigerant into refrigerant vapour by regulating the refrigerant’s pressure. As heat exchanger, evaporator and condenser allow heat transfer to occur between refrigerant and air. Thus, a suitable volume of heat exchanger is important to optimize the efficiency of the heat transfer process. In the macro compartment, the evaporator coil is designed with spring helical shape to fit the geometry of drink bottle or drink can. The condenser coil is designed with double layer to maximize the heat transfer rate to the outdoor ambient air to provide effective cooling to the refrigerant. The expansion device decreases the pressure of the liquid refrigerant to allow expansion from liquid to vapour in the evaporator.

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