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Theoretical Investigation of Refrigeration System for Rapid Cooling Applications

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***Abstract**: Nearly half of the vaccines in developing countries go to waste every year due to temperature spoilage, according to the World Health Organization. Current transportation and storage methods in remote regions depend on ice packs that last just a few days. In order to maintain the optimal temperature range for vaccine preservation, this has become restriction to people to use refrigerator for medical purpose which is to deliver special medicine to village. Because of the above stated problem, this paper introduces a design of a meso-scale refrigerator. The system of refrigerator used is the ideal vapor-compression refrigeration cycle and the components of the system are a condenser, a compressor, a capillary tube and an evaporator. The design of prototype refrigerator more focus on designing length of condenser, evaporator and capillary tube. From the p-h diagram, the data will be calculated using ideal gas equation and energy balance equation to find mass flow rate and the length.*

***Keywords**: Vaccines, meso-scale refrigerator, vapor-compression refrigeration cycle, component design, p-h diagram.*

I. Introduction

A refrigerator is a cooling appliance comprising a thermally insulated compartment and a mechanism to transfer heat from it to the external environment, cooling the contents to a temperature below ambient. Refrigerators are extensively used to store foods which deteriorate at ambient temperatures; spoilage from bacterial growth and other processes is much slower at low temperatures.

Before the invention of the refrigerator, icehouses were used to provide cold storage for most of the year. After that, the first known artificial refrigeration was demonstrated by William Cullen at the University of Glasgow, Scotland in 1748. In 1805, Oliver Evans designed refrigerator based on a closed cycle of compressed ether, represented the first effort to use simple vapor instead of vaporizing a liquid. After that, in 1857, James Harrison introduced vapor-compression refrigeration to the brewing and meat packing industries [1].

II. Basic Theory

The design for contemporary refrigerator is based on two basic laws of physics: first, that heat flows from warmer material to cooler materials and never the reverse; second, when decreasing the pressure of a gas also decreases its temperature. The refrigeration systems typically include a compressor, a condenser, an expansion valve (capillary tube), and an evaporator. All components are interconnected to form a fluid circuit. Cooling is accomplished through evaporation of a liquid refrigerant under reduced temperature and pressure [1].

The raw material in refrigerators today consists of several basic components: the exterior cabinet and door, the inner cabinet or liner, the insulation inserted between the two, the cooling system, the refrigerant, and the fixtures. The cabinet and door are made of aluminum or steel sheet metal that is sometimes prepainted. The inner cabinet is made of sheet metal, like the outer cabinet, or of plastic. The insulation that fills the gap between the inner and outer cabinets consists of fiberglass or polyfoam. The components of the cooling system (compressor, condenser, coils, and fins) are made of aluminum, copper, or an alloy [2].

Refrigerators available in market have been designed in various sizes and different applications but its limited for indoor usage since it is large and powered by electricity. So, this paper focuses on designing of a small refrigerator. Refrigerator can be used to deliver the special medicines to villages by doctors. Beside that it can be an useful application in outdoor activities such as picnic and sport.

III. Design

The design of the vapour compression system shall consist of a system having 200 W cooling capacity. The other major components include an air cooled condenser, a water cooled evaporator and a capillary tube as an expansion device. Also the refrigerant considered for the design purpose is R-134a.

A. *Design of Evaporator*

In an evaporator, the refrigerant boils or evaporates and in doing so absorbs heat from the substance being refrigerated. The name evaporator refers to the evaporation process occurring in the heat exchanger. The shell-and-coil type evaporators are very efficient and require minimum floor space and headspace. As the name implies, a shell-and-coil evaporator consists of a shell and a coil arranged spirally in the shell. The shell diameters range from 150 mm to 1.5 m. The coil length may be between 1.5 m to 6 m [2]. Heat transfer rate at evaporator or refrigeration capacity, Qe is given by:

$$Q_E = m\,(h_1 - h_4) \qquad (1)$$

Where, m is the refrigerant mass flow rate in kg/s, h_1 and h_4 are the specific enthalpies (kJ/kg) at the exit and inlet to the evaporator, respectively. $(h_1 - h_4)$ is known as specific refrigeration effect or simply refrigeration effect, which is equal to the heat transferred at the evaporator per kilogram of refrigerant [2].

B. Design of Compressor

A compressor is the most important and often the costliest component of any vapour compression refrigeration system (VCRS). The function of a compressor in a VCRS is to continuously draw the refrigerant vapour from the evaporator, so that a low pressure and low temperature can be maintained in the evaporator at which the refrigerant can boil extracting heat from the refrigerated space. The compressor then has to raise the pressure of the refrigerant to a level at which it can condense by rejecting heat to the cooling medium in the condenser.

Rolling piston or fixed vane type compressors are used in small refrigeration systems (up to 2 kW capacity) such as domestic refrigerators [2]. In this type of compressors, the rotating shaft of the roller has its axis of rotation that matches with the centerline of the cylinder, however, it is eccentric with respect to the roller. This eccentricity of the shaft with respect to the roller creates suction and compression of the refrigerant. A single vane or blade is positioned in the non-rotating cylindrical block. The rotating motion of the roller causes a reciprocating motion of the single vane [2].

The leakage is controlled through hydrodynamic sealing and matching between the mating components. The effectiveness of the sealing depends on the clearance, compressor speed, surface finish and oil viscosity. Close tolerances and good surface finishing is required to minimize internal leakage. Unlike in reciprocating compressors, the small clearance volume filled with high-pressure refrigerant does not expand, but simply mixes with the suction refrigerant in the suction space. As a result, the volumetric efficiency does not reduce drastically with increasing pressure ratio, indicating small re-expansion losses [1]. The compressor runs smoothly and is relatively quiet as the refrigerant flow is continuous. Power input to the compressor or work of compression WC is given by:

$$W_C = m\,(h_2 - h_1) \qquad (2)$$

Where, h_2 and h_1 are the specific enthalpies (kJ/kg) at the exit and inlet to the compressor, respectively. $(h_2 - h_1)$ is known as specific work of compression, which is equal to the work input to the compressor per kilogram of refrigerant [2].

C. Design of Condenser

Condenser is an important component of any refrigeration system. In a typical refrigerant condenser, the refrigerant enters the condenser in a superheated state. It is first de-superheated and then condensed by rejecting heat to an external medium [1]. The refrigerant may leave the condenser as a saturated or a sub-cooled liquid, depending upon the temperature of the external medium and design of the condenser. At present for simplicity, it is assumed that the refrigerant used is a pure refrigerant and the condenser pressure remains constant during the condensation process.

An air cooled condenser has been considered in the present design. As the name implies, in air-cooled condensers air is the external fluid, i.e., the refrigerant rejects heat to air flowing over the condenser [1]. Air-cooled condensers can be further classified into natural convection type or forced convection type. In natural convection type, heat transfer from the condenser is by buoyancy induced natural convection and radiation. Since the flow rate of air is small and the radiation heat transfer is also not very high, the combined heat transfer coefficient in these condensers is small [1]. In forced convection type condensers, the circulation of air over the condenser surface is maintained by using a fan or a blower. Heat transfer rate at condenser, QC is given by:

$$Q_C = m\,(h_2 - h_3) \qquad (3)$$

Where, h_3 and h_2 are the specific enthalpies (kJ/kg) at the exit and inlet to the condenser, respectively [1].

D. Design of Capillary Tube

A capillary tube is a long, narrow tube of constant diameter. The word “capillary” is a misnomer since surface tension is not important in refrigeration application of capillary tubes. Typical tube diameters of refrigerant capillary tubes range from 0.5 mm to 3 mm and the length ranges from 1.0 m to 6 m [1].

The pressure reduction in a capillary tube occurs due to the following two factors:

- The refrigerant has to overcome the frictional resistance offered by tube walls. This leads to some pressure drop, and
- The liquid refrigerant flashes (evaporates) into mixture of liquid and vapour as its pressure reduces. The density of vapour is less than that of the liquid. Hence, the average density of refrigerant decreases as it flows in the tube. The mass flow rate and tube diameter (hence area) being constant, the velocity of refrigerant increases since, $m = \rho VA$. The increase in velocity or acceleration of the refrigerant also requires pressure drop [1].

For the isenthalpic expansion process, the kinetic energy change a cross the expansion device could be considerable, however, if we take the control volume, well downstream of the expansion device, then the kinetic energy gets dissipated due to viscous effects, and

$$h_3 = h_4 \quad (4)$$

The exit condition of the expansion device lies in the two-phase region, hence applying the definition of quality (or dryness fraction), we can write:

$$h_4 = (1 - x_4)\, h_{f,e} + (x_4 * h_{g,e)} = h_f + (x4 * h_{fg}) \quad (5)$$

IV. Results

The results for the original evaporator, the overall heat transfer coefficient is 281.98 W/m^{2}K.

Table I Water Cooled Evaporator Results

Sr. No.	Parameter	Inlet State	Exit State
1	Temperature(degree C)	0	45
2	Pressure(bar)	2.928	11.597
3	Enthalpy(kJ/kg)	263.712	263.712
4	Capacity(W)	200	
5	Tube Diameter(mm)	10.37	
6	Tube Thickness(mm)	0.514	
7	Length(m)	1.95	

Table II Rotary Compressor Results

Sr. No.	Parameter	Inlet State	Exit State
1	Temperature(degree C)	0	49.597
2	Pressure(bar)	2.928	11.597
3	Enthalpy(kJ/kg)	397.203	425.635
4	Capacity(W)	43	
5	Displacement(cc)	1.83	
6	Compressor Speed(rpm)	4500	
7	Height(mm)	2.456	
8	L/D	100	
9	Volumetric Efficiency	75.144 %	

Table III Plate-Fin-And-Tube Type Air Cooled Condenser Results

Sr. No.	Parameter	Inlet State	Exit State
1	Temperature(degree C)	49.597	45
2	Pressure(bar)	11.597	11.597
3	Enthalpy(kJ/kg)	425.635	263.712
4	Capacity(W)	243	
5	Tube Diameter(mm)	11.26	
6	Tube Thickness(mm)	0.254	
7	Length(m)	1.4	

Table IV Capillary Tube Result

Sr. No.	Parameter	Inlet State	Exit State
1	Temperature(degree C)	45	0
2	Pressure(bar)	11.597	2.928
3	Enthalpy(kJ/kg)	263.712	263.712
4	Tube Diameter(mm)	1	
5	Length of tube(m)	1.36	

V. Conclusion

The development of compact refrigeration systems presents innumerous challenges and demands technological competence in various fields of engineering. In this article, a complete refrigeration system was designed for maintaining vaccines at low temperature which can benefit this characteristic in order to increase its life. With this objective, a new compressor was built, whose main feature is the fact of being extremely slim, enabling the development of a refrigeration system which is also slim. In addition to the compressor, the compact heat exchangers present elevated energy dissipation power for the small space used. Different refrigeration techniques can be applied for the same purpose, nevertheless the search for a compact system, lightweight and of high energy efficiency generates a highly valuable attribute in many applications which is portability. This same refrigeration system can be a part of portable applications for a broad range of purposes, which today vapor compression refrigeration usage is limited.

It is seen that the study of Phelan [5] may be compared with the present study in terms of the sizes of the cycle. However, it should be noted that the study of Phelan [5] is an experimental study. Therefore, the present study may be thought as a milestone in the literature where a meso-scale refrigerator with all of the components is designed theoretically. In conclusion, a meso refrigerator has been successfully designed within the scope of this paper. The results actually indicate that it is possible to construct and test such a cycle.

Table V Comparison of Present Study with Literature

Sr. No.	Parameter	Chow [3]	Heydari [4]	Phelan [5]	Chriac and Chriac [6]	Present Study
1	Heat Load (W)	32	-	100-300	100	200
2	Te (^{0}C)	12	20	5	10	0
3	Tc (^{0}C)	-	60	55	55	45
4	Flow Rate (g/s)	16.3	-	0.827-2.47	-	1.498
5	Refrigerant	R-134a	R-134a	R-134a	R-134a	R-134a
6	COP	3.34	3.0	3.0	4.5	4.7
7	Compressor Type	Centrifugal	Piston	Scroll	Scroll	Rotary

VI. Future Work

For different application areas, the cycle may be analyzed for different temperatures, pressures and for different refrigerants. Different types of compressors may be designed for the cycle, such as, screw, centrifugal or scroll compressors. In the present study, a steady-state analysis of the refrigeration cycle has been performed. The transient response of the cycle may also be investigated. The designed cycle would be constructed and tested during the operation to verify the design procedure adopted from the literature. Finally, the design procedure may be improved by a variable speed compressor to cope with the variation of the refrigeration load due to different modes of operation.

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