Developing a Two Stage Cascade Compressor Arrangement for Ice Block Production

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***Abstract*-This paper presents the design, construction and evaluation of an ice making machine using a Two-stage Cascade Compression System as its main key element. Two compressors provide work inputs to the machine; one compressor for the refrigerating space and the other for the cascade system. The cascade compression system was used to cool down the temperature of the refrigerant to a desired temperature just before it enters the expansion zone. The refrigerant then enters the evaporating coils to extract more heat from the refrigerating space. The cascade system improves the system efficiency and the refrigerating capacity of the machine as well as reducing the time required for the formation of ice blocks. The machine was designed and fabricated with tests carried out on it to evaluate its performance.**

Keywords- Cascade; Refrigerating Space; Compressor; Heat Load; Coils

I. INTRODUCTION

Water exist in solid state as ice. Its solid phases include snowflakes, hail, icicles, glaciers, pack ice and entire polar ice caps. It is an important component of the global climate, and plays an important role in the water cycle. Furthermore, ice has numerous cultural applications, from ice cooling of drinks to winter sports and the art of ice sculpting. Phase transformation to ice normally occurs below 0 ℃ (273.15K, 32 ℉) at standard atmospheric pressure. Ice can also be formed directly from vapour as in frost.

Nowadays, ice is produced mechanically for domestic, leisure (for sports and recreation activities), commercial and industrial purposes [1]. Ice had to be harvested from its naturally occuring sites before the development of refrigeration systems. Poor supply of electricity and the warm climate in Nigeria today are responsible for the large demand for ice because of the need to locally refrigerate drinks. The development of an ice making machine based on a cascade compressor arrangement was borne out of this need [2, 3].

A cascade refrigeration system is commonly used in the industrial settings. It is made up of two or more seperated refrigerating cycles that are connected such that the evaporator of the top system serves as condenser for the other system. Both system do not need to use the same or the same type of refrigerant [4, 5]. Although the concepts of this design are not new, related documented works were either based on numerical simulations, incorporate technologies that are too advanced for the third world country or used unsuitable refrigerants [5-7].

The system designed will incorporate a refrigerating space/box, compressors, heat exchanges, expansion valves, and other common refrigerating accesories. Criteria such as size, capacity, power requirement, availability of materials and cost were considered for the selection of materials for construction. The performance of the constructed system was evaluated by comparison with that of a similar machine with single stage vapour compression of the same capacity.

II. METHODOLOGY

This aspect is based on the improvement of an ice making machine for commercial use by using simple and locally available materials. The cascade compressor arrangement would be the brain behind its whole working operations. Also here, the construction of the ice making machine was described in order to justify and investigate its working performance compare with other unit of relative capacity in terms of total work input and refrigerating space.

A. Description of Ice Making Machine

The machine was made in a compact form for ease of carrying out tests and investigations. The machine has a refrigerating space of *72 litres* with length, breadth and depth of *60cm, 40cm and 30cm* respectively, and is divided into three compartments. An approximate of *0-45 litres* of water was used to carry out the test, i.e. transforming *0-45 liters* of water to ice. The box was made up of material comprising of galvanized steel sheet and polyisocyanurate with the evaporator coil lined inside the box.

Two 1hp compressors were used to drive out the heat load in the box. The condensing unit is also mounted outside the box next to the compressors. The unit also comprise of a concentric tube counter flow heat exchanger, expansion valves and dryers.

The evaporator is a concentric tube counter flow heat exchanger. The expansion valve was designed and built from copper pipes; the refrigerating box was built from galvanized steel sheet metal and polyisocyanurate riveted together to form a rigid box. The compressors, dryers and the condenser are predesigned as they are readily available in the market.

The machine was designed in three forms and each unit was compared to one another. The most economically reasonable and viable design was selected from the lot after preliminary of tests and investigations were carried out on the units. This is summarized in Table 1.

TABLE 1 COMPARISON OF DIFFERENT REFRIGERATION SYSTEMS WITH REMARKS

Design	**Description**	**Compressor Size / Rating**	**Working Principle**	**Remark**
1	Using a compressor which is rated half of the required rating capacity.	One *1hp* compressor	Single stage vapour compression refrigeration cycle	Insufficient refrigerating capacity and increased work input to drive the total heat load.
2	Using a compressor with the required rated capacity to drive the heat load.	One *2hp* compressor	Single stage vapour compression refrigeration cycle	Reasonable work input and refrigerating capacity.
3	Using two compressors whose ratings when added together equals the rated capacity.	Two *1hp* compressor	Two stage vapour compression refrigeration cycle	Improved refrugerating capacity, decreased work and boundary temperature. Due to the reduced load on one of the compressors

B. Operation of the Machine

Fig. 1 shows the schematic diagram of a two-stage vapour compression refrigeration system. It consist of an evaporator, two compressors, a condenser, a concentric tube counter-flow heat exchanger and expansion valves. Refrigerating effect was obtained using system “B” that is, cycle 1234, in the cold region as heat is extracted by the vaporization of refrigerant in the evaporator. The refrigerant vapour state from the evaporator is compressed in the first compressor “B” to a high pressure at which saturation temperature is greater than that of the environment.

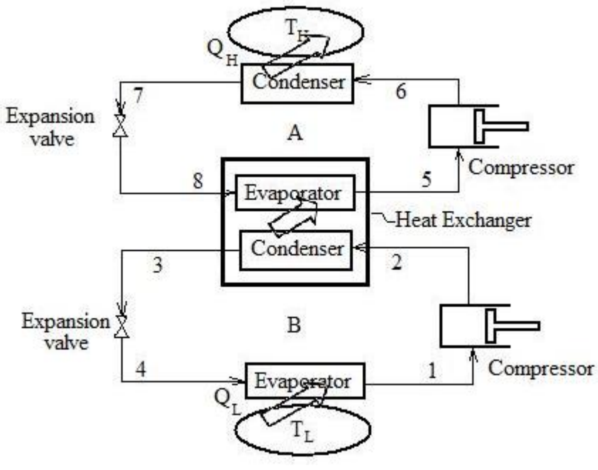

Fig. 1 Schematic diagram of a two stage cascade refrigerating system

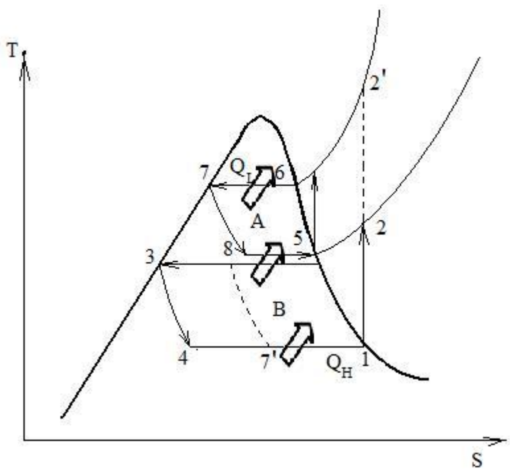

Fig. 2 T-S diagram for a two stage cascade refrigeration system

When the high pressure, high temperature refrigerant flows through the heat exchanger, condensation of the vapour into liquid takes place by heat rejection to another medium. This serves as the evaporator of system “A”, that is, cycle 5678. System “A” is another refrigerating cycle. It absorbs the heat discharged by the refrigerant in system “B”, then discharges the heat to the environment. To complete the cycle, the high pressure liquid was made to flow through an expansion valve in which the pressure and temperature of the refrigerant decrease. This low pressure and temperature refrigerant vapour evaporates in the evaporator taking away heat from the cold region. It must be noted that the systems operates in a closed cycle and requires input in form of mechanical work to the compressor in order to drive the refrigerant through the two systems.

As shown in Fig. 1, the condenser for the low temperature refrigerator is used as the evaporator for the high temperature refrigerator. System “B” removes heat from the refrigerating space while system “A” removes that heat from the refrigerant of system “B” discharges it to the environment. Cascading improves the coefficient of performance (COP) and the rate of refrigeration of the refrigeration system. The two cycles are connected through the heat exchanger in the middle, which serves as evaporator and condenser for both systems. As shown in Fig. 2, there is an increase in refrigeration capacity (area under 4-7’) and a decrease in compressor work (2-2’-6-5). The following relationship could be established:

$$m_A(h_5 - h_8) = m_B(h_2 - h_3) \tag{1}$$

$$COP_{R,cascade} = \frac{m_B(h_1 - h_4)}{m_A(h_6 - h_5) + m_B(h_2 - h_1)} \quad (2)$$

C. Justification for Use of Items, Materials and Components

The refrigerating box: This box provides a space or a closed system where water would be transformed into ice blocks.

Polyisocyanurate and galvanized steel sheet: Polyisocyanurate is a form of insulation used in refrigeration; it prevents external sources of heat from entering into the refrigerating space. Refrigerating insulations are always rated as a function of the thermal resistance (R-value) the material has. Polyisocyanurate with one-inch thickness has an R-value of 7 ft^2f/Btu, which is a measure of its thermal resistance, and the galvanized steel sheet provides rigidity to the walls of the refrigerating box.

Compressors: The compressor comes in different sizes, shapes and capacities. It compresses the refrigerant vapor from the evaporator to a high pressure in which its saturation temperature is greater than that of the surrounding ambient temperature.

Condensing unit: The condenser's main function is to return the state of the high pressure, high temperature vapour refrigerant back into the liquid stage by heat rejection to the environment.

Concentric heat exchanger: Using the two-stage cascade compressor arrangement, the heat exchanger is used to absorb heat from one cycle and to reject it into another. Concentric single pass counter flow heat exchanger is selected because of its higher capacity of transferring heat from two unmixed fluid, i.e. taking large quantity of heat from one fluid and transferring it to another within a very short distance.

Copper pipes and tubes: Copper is selected for its good heat conduction ability, ability to be bent and withstand hash environmental impacts.

Dryer: The dryer removes moistures from the refrigerant in the vapour stage just before it enters into the evaporators/concentric tube heat exchanger.

Expansion valve: The expansion valve otherwise known as the "throttle valve" is used to lower the pressure of the high pressure liquid refrigerant coming from the condenser as it enters the evaporator (lowering the pressure causes expansion of the liquid).

Working fluid: The working fluid also known as the refrigerant earlier referred to as either liquid or vapour is the heat transporting medium. The working fluid absorbs heat from the surrounding in the evaporator inside the refrigerating space and releases the heat via the condenser. In this case R22 is selected because of the compressor and its friendly nature to the environment.

III. DESIGN AND FABRICATION

The correct sizing of refrigeration units was determined by the following factors; mass of water to be cooled, minimum time required for cooling and, the nature of the refrigerating space; its size, insulation, and how it is to be operated. As much as one-half of the refrigeration capacity in refrigerating units is used to overcome heat gained through the insulator walls and doors, it is important to minimize these gains.

The box is made of galvanized sheet metal and polyisocyanurate insulator to prevent heat leakage in and out of the refrigerating space. With an outer dimension of *77 x 56 x 40cm* and internal dimensions of *60 x 40 x 30cm*, insulator is *7.6cm* and the total thickness of the galvanized steel sheet (both internal and external) is *1.3cm*. The refrigerating space is divided into three compartments, *12cm* apart, in order to allow for conductive flow of heat between water and the evaporating coils. All the three compartments have evaporating coils round them. The galvanized steel sheet and Polyisocyanurate are riveted together to give a rigid boxlike shape.

The lid is a slab of *62 x 42cm* with *2.5cm* insulation covered on all sides with galvanized steel sheet metal. It fits perfectly into the top of the box. An airtight seal between the lid and the box is an important part of the box's thermal efficiency; the design incorporates a flat straight gasket material placed at the channel on the top edge of the box which forms an airtight seal when the lid is closed. The evaporator coils are fitted round the side interior walls of the three compartments in the box in-between the galvanized steel sheet.

A. Estimation of Heat Load and Compressor Capacity

Heat leaks and splashes entering and leaving the refrigerating space comes from several sources. Transformation of "m" liters of water to ice using an R-21 insulator and a refrigerating space of *60 x 40 x 30cm*, and the temperature difference between the inner and the outer side of the box is: $45^oC-(-15^oC)$. Heat is conducted into the refrigerating space through the walls of the box, and the amount of heat flowing through these surfaces is a function of their thermal resistance (R-value), their area, and the temperature difference between one side and the other. The walls have an R-value of $21(ft^2f/Btu)$, since

Polyisocyanurate has an R-value of *7(ft^2f/Btu)* per inch and an area of *1.080m^2(11.625ft^2)*. The temperature difference between the inside and outside is *60^oC* (which is, *108^oF*). Thus, heat conducted is given by

$$HC(Btu) = \frac{Total\ Area\ (ft^2) * \Delta T(^oF)}{Rvalue(ft^2 F / Btu)} \tag{3}$$

$$= \frac{11.625 * 108}{21} = 59.79 Btu = 63.077 kJ$$

Heat energy from water is brought into the cooling space to be transformed to ice block, and it equals the heat load in water between *45^oC* to *0^oC*, the heat load at *0^oC* and the heat load between *0^oC* to *-15^oC*. Therefore,

$$FH = HLA + HLB + HLC \tag{4}$$

where HLA is heat load in water between *45^oC to 0^oC*; HLB is the heat load in the water as it transforms to ice; HLC is heat load in ice between *0^oC* and *-15^oC* and FH is field heat. For a given mass of water,

$$HLA = mc_w \Delta T_1 = m(h_H - h_L) \tag{5}$$

$$= m(4.87 * 45) = 219.15 m\,kJ$$

$$HLB = m * L = m * 334 = 334 m\,kJ \tag{6}$$

$$HLC = mc_l \Delta T_2 = m(2.108 * 15) = 31.62 m\,kJ \tag{7}$$

from Eq. (4),

$$Total\ \ field\ \ load,\, FH = m(219.15 + 334 + 31.62)$$
$$= 584.77 m\ kJ$$

where c_w is the specific heat capacity, *4.187kJ/kgK*, c_l is the specific heat capacity, *2.108kJ/kgK*, $\Delta T_1 = 45^o C - 0^o C = 45^o C$, $\Delta T_2 = 0^o C - 15^o C = 15^o C$ and specific latent heat of melting water, $L = 334 kJ / kg$.

The amount of heat contributed by this source is usually very difficult to determine accurately and is therefore dealt with collectively and estimated to equal 1 percent of the heat from the other two sources, thus the service load is given by:

$$\begin{aligned} SL &= (HC + FH) * 1\% \\ &= 5.85m + 0.63\ kJ \end{aligned} \tag{8}$$

and the total heat load is given by

$$\begin{aligned} Total\ \ heat\ \ load,\, THL &= SL + HC + FH \\ &= 590.62m + 63.71\ kJ \end{aligned} \tag{9}$$

using the *45litre* design capacity, mass of water converted to ice is *45kg*, thus THL is *26,641.61kJ*. Refrigeration systems are usually rated by how much heat it will remove or displace in a given unit time. The standard rating is ton and *1 ton* of refrigeration equals *288,000 Btu* per *24 hours*, or *12,000 Btu* per hour, or *3.517 kW*. The compressor capacity can be estimated using

$$Q_R = \frac{THL}{24 * 3600} = \frac{26641.61}{24 * 3600} = 0.31 kW \tag{10}$$

this is approximately *0.088ton* of refrigeration in a day, and the estimated compressor rating in horsepower is *0.41hp* which is approximated to *½hp*. Since we would be using the cascade compressor system which uses two compressors, we selected our compressors size in a way that a single compressor can drive out the entire heat load to transform water to ice.

B. Material Selection and Testing of Machine

Some series of test were carried out while varying the compressor sizes and volume of water, respective cooling rates of single stage compressor system and two stage compressor systems are recored. Likewise some challenges occured during testing, including electrical power problems, choking of dryers, determining the properties of the refrigerant at different stages and also determining the actual refrigerant needed in the systems.

While selecting some prime components, several properties (desired characteristics) of known materials that could serve the same purpose were considered and compared, so as to choose the best of them without any occurrence of failure in the future.

i. The refrigerating box

The inside and outside surface of the box are made of galvanized steel sheet.

Properties of the galvanized steel sheet are:

1. Its resistance to corrosion and a metallic-gray appearance;
2. Its high durability;
3. Its surface is also a hundred times smoother than uncoated steel.

ii. Refrigerant pipes and connectors

All pipes used are made of copper; copper is selected because of its desirable properties. Properties of copper pipes are:

1. Depending on the velocity of fluids flowing through the copper pipes, they may last for decades;
2. Copper pipes are less brittle which makes it easy to be bent into shapes which can withstand stress and environmental factors to some extent;
3. Copper has a very good thermal conductivity property.

iii. Insulator

Polyisocyanurate insulator was also chosen because of its ability to prevent heat from flowing through it. Fig. 3-5 shows the construction aspect of the work.

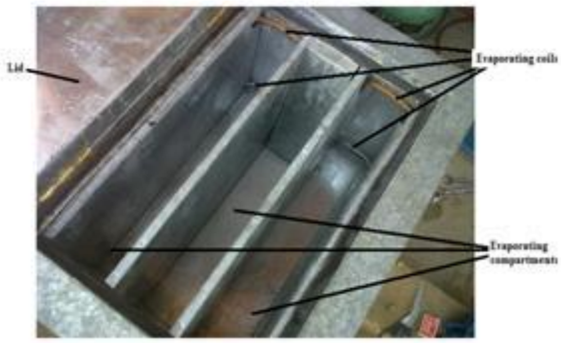

Fig. 3 The refrigerating box opened showing, the refrigerating space with compartments; the compartments houses the evaporating coils

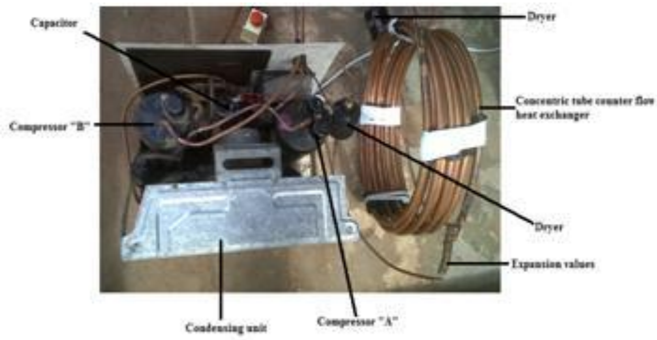

Fig. 4 The two compressors, condensing unit, the designed concentric tube counter flow heat exchanger and the two dryers

Fig. 5 Overall view of the machine as a whole

IV. RESULTS AND DISCUSSION

Evaluation refers to the examination and judgment of a system in terms of worth, quality of performance, degree of effectiveness, condition and so on. Evaluation is a continuous process which begins during the actual design and extends through the product use and logistic support phase until the system is retired. The purpose is to determine (through a combination of prediction, analysis and measurement) the true characteristics of the system and to ensure that it successfully fulfills its intended mission. Evaluation is carried out during the design to establish whether the output is in compliance with the initially specified requirements. If the output is in compliance, the fabrication stage begins; if not, corrective action would be required.

Various aspects of the design were reviewed on the basis of the specified requirement, and corrective action initiated in areas where non-responsiveness to this requirement was indicated. Changes made at this stage were relatively easy to incorporate and the costs were low. An overall test programme was established, which allows for the evaluation of hardware and its support elements on an evolutionary basis.

A. Test Programme

A tests programme constitute of a series of individual tests tailored to the needs of the machine, which include:

1. **Performance Test**: Test was accomplished to verify individual system performance characteristics, i.e. its reliability. Reliability is a measure of the capacity of a piece of equipment to operate without failure when put to service under the operating condition encountered.
2. **Environmental Qualification:** Temperature cycling, vibration, humidity, wind dust and sand, fungus and acoustic noise tests were conducted. These factors are oriented to what the equipment will be subjected to during operation, maintenance, transportation and handling, etc.
3. **Structure Tests:** Tests were conducted to determine material characteristics relative to stress, strain, fatigue, bending, torsion and general decomposition.
4. **Personnel Test and Evaluation:** Tests were also carried out to verify the relationship between people and equipment, the personnel skills required and training needed.

Further performance test was carried out while adjusting the compressor size, mass of water and the compression systems in order to evaluate their rate of ice formation or the time taken for a given mass of water with a given compression stage and compressor size to transform water to ice while assuming some other variables constant.

Fig. 6 shows the time taken for different mass of water, compression stage and compressor size to transform to solid ice. From the table it was observed that there was little variance between the estimated and the actual time taken for the machine to produce ice blocks when using one compressor of one horsepower rating but there was a variation of about one hour when two compressors with one horse power rating each were used. This observation could be as a result of some numerous factors like; impurities in water, changes in ambient temperature or line current to the compressor. Moreover, the cascaded arrangement with two compressors cut down the time of ice formation by 40%.

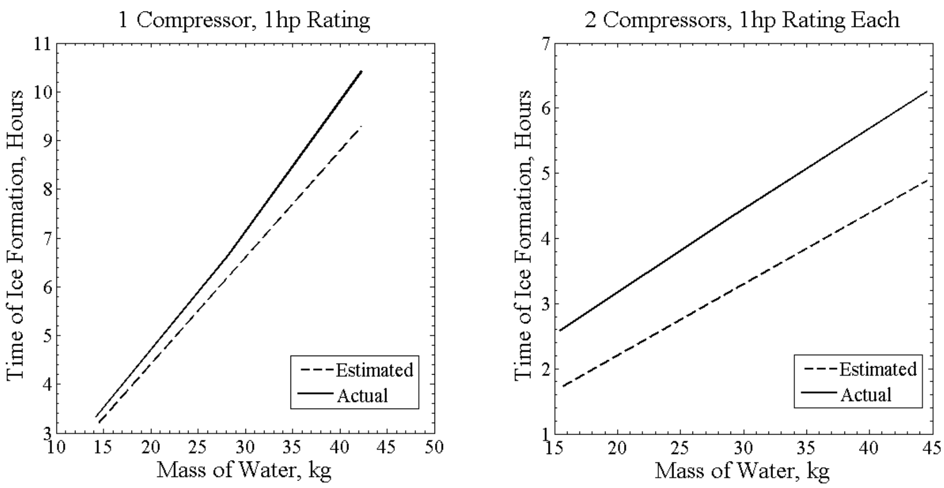

Fig. 6 Performance evaluation test, comparing the actual and estimated time taken for ice formation

V. CONCLUSION

The high efficiency observed during the various test of the ice making machine denotes high reliability and dependency of the machine. Its show clearly that the required time to transform water to ice in a fixed system is dependent on the mass or volume of water placed in the refrigerating space (between the evaporator coils). From all tests carried out, the designed machine reflects a high transformation capacity which is quite impressive compared with some other homemade ice making machines.

It is a design easy to assemble and disassemble; just that it requires technical knowhow of its working principles and activities. Regular maintenance would be required including cleaning of internal parts, refrigerating space and the body.

Furthermore damage and obstructing of various copper pipe lines should be avoided. The machine is relatively easy to use as its design is similar to the regular deep freezers used at homes.

The design was tested and evaluated against objectives which resulted in the following conclusion:

1. That the produced design could be adopted for small and large scale production of ice.
2. That the test results show that making the machine made from locally sourced materials is economically viable.
3. That further overall improvement could be achieved through system optimization.
4. That unit cost of production of the design will reduce in event of batch or mass production.

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