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Investigating the Opportunities for Environmentally Benign Options in the Refrigeration Industry of Uganda

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Authors' contributions

This work was carried out by collaboration between all authors. Author BP initiated the idea, assisted in its development and offered technical guidance during the study. Author TM developed the idea, selected the materials and methods for the study, participated in data collection and wrote the manuscript. Authors JBK and AS assisted in providing information sources, data collection and giving technical guidance during the study. All the authors read and approved the final manuscript.

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ABSTRACT

Using synthetic refrigerants has led to ozone depletion, global warming and the associated climate change. This study therefore aimed at investigating the application of environmentally friendly options in the refrigeration industry of Uganda with the main emphasis on refrigerants. A field study was done to assess the current status of refrigeration in Uganda as well as to obtain relevant

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information for the study using questionnaires, interviews, field measurements and observations. The required data included evaporation and condensing temperatures and pressure, refrigerant mass flow rate, system type, refrigerant type, etc. Using the above data as input, models of the available systems were developed using EES and their efficiencies determined; also, models were proposed for each sector in the industry using an appropriate natural refrigerant(s) and comparison of the efficiencies obtained with those of installed systems was made. EES also assisted in the performance of a parametric study on the system operating parameters. Results from the field survey showed that synthetic refrigerants dominate the industry and the systems installed are single stage vapor compression while those from modeling and simulation reveal that natural refrigerants offer a promising solution in the refrigeration industry of Uganda and should be adopted for energy, safety and environmental reasons. Nevertheless, it is recommended that rigorous testing of the systems with alternate refrigerants proposed be conducted to verify the results of the simulations before full adoption. Furthermore, performing an economic analysis would give better justification for adoption from an industrial point of view. However, the major challenges to be encountered in case of adoption are safety, system modifications especially in systems that are to use R744, lack of technical expertise to design, install, operate and service the systems as well as lack of government policy to spearhead the transition. Therefore for the transition to be realized there is need to come up with policy concerning the use of environmentally harmful refrigerants and also create awareness in the industry.

Keywords: Environmental friendliness; refrigeration; refrigerants; greenhouse; EES; Uganda.

ABBREVIATIONS

CFC: Chlorofluorocarbons; HCFC: Hydrochlorofluorocarbons; HFC: Hydrofluorocarbons; HC: Hydrocarbons; NEMA: National Environment Management Authority; MEMD: Ministry of Energy and Mineral Development; EES: Engineering Equation Solver; COP: Coefficient of Performance, EU: European Union; USA: United States of America; ODP: Ozone Depleting Potential; GWP: Global Warming Potential; ASHRAE: American Society of Heating, Refrigeration and Air Conditioning Engineers; IPCC: Intergovernmental Panel on Climate Change; IIR: International Institute of Refrigeration; UIA: Uganda Investment Authority; HVAC: Heating, Ventilating and Air Conditioning.

NOMENCLATURE

h = *specific enthalpy of the refrigerant [kJ/kg]*
$\dot{m}$ = *mass flow rate of refrigerant in the system components [kg/s]*
$\dot{m}_1$ = *mass flow rate of brine in the pump [kg/s]*
$\dot{m}_2$ = *mass flow rate of brine in low temperature circuit heat exchanger [kg/s]*
$\dot{m}_3$ = *mass flow rate of brine in chiller cabinet [kg/s]*
$\dot{m}_r = \frac{\dot{m}_H}{\dot{m}_L}$ = *mass flow ratio of refrigerant [-]*
P = *pressure [kPa]*
P_{ii} = *pressure ratio [-]*
$\dot{Q}$ = *heat flow in the system components [kW]*
T = *temperature [C]*
$\dot{W}$ = *power demand of the system components [kW]*
δT = *temperature difference in cascade heat exchanger [C]*

SUBSCRIPTS

c = *condenser*
cas = *cascade*
chiller = *medium temperature unit*
E = *evaporator*
freezer = *low temperature unit*
H = *high temperature*

HTC = *high temperature circuit*
is = *isentropic*
L = *low temperature*
LTC = *low temperature circuit*
m = *mechanical*
M = *medium temperature*
MTC = *medium temperature circuit*

1. INTRODUCTION

Refrigerating engineering is the technology associated with the creation and maintenance of temperatures lower than the surroundings. It is the art of pumping heat from one body of a low temperature to one of higher temperature. The main applications of refrigeration are in the handling, storage, preservation and supply of food products as well as climate control and air conditioning [1].

The transition to the use of environmentally friendly solutions in refrigeration applications is of high importance worldwide; the earliest refrigerants used were sulfur dioxide (R764), methyl chloride (R40), ammonia (R717), propane (R290) and iso butane (R600a), but these had drawbacks of flammability, toxicity, a strong smell as well as posing a challenge of leakage through the shaft seals of compressors [2,3]. CFC refrigerants were introduced to replace R764, R40 and R717; these became popular in the 1930s and dominated the domestic refrigerant market.

Later on, it was discovered that CFC had an ozone depleting effect which led to a shift from CFC to HCFC and then HFC with no ozone depleting potential [3]. However, there was strong advocacy for natural refrigerants, because the doubt about synthetic refrigerants was confirmed by the realization that emission of these substances contributes to at least 20% of the greenhouse gas emissions [4,5]. Today, with increasing pressure from legislators, business partners and consumers to push environmental issues up the agenda unlikely to subside anytime soon, companies are tasked to rethink established solutions and implement environmentally benign yet economically sensible technologies to seize their individual eco-advantage.

There are five substances generally recognized as natural refrigerants in modern refrigeration i.e. air (R729), water (R718), ammonia (R717), carbon dioxide (R744) and HC. R729 is used in a variety of gas cycles, with no change of phase and can achieve reasonably low temperatures, but the low theoretical efficiency of the Brayton cycle and the difficulty of getting close to that ideal have limited its use [6]. R718 has been used with large centrifugal and axial turbines in open systems but the low pressures, large swept volumes and an evaporation temperature limit of 0°C place several restrictions on its use and make it fundamentally unsuited to smaller air conditioning systems, industrial cooling and freezing applications. R717, R744 and HC have a broader range of applications and are used in more conventional systems [6-8].

While the environmental and technological benefits of natural refrigerants are being acknowledged in the refrigeration industry, only few studies have heard the industry's voice on their economic prospects. The most commonly used natural refrigerants today are R717, R744 and HC such as R290, R600a and R1270. Mixtures of R717 and dimethyl ether (R273) have been developed as well as various HC blends with optimized performance and safety properties [9,10]. R729 and R718 are also used to a lesser extent in absorption chillers and deep freezing applications; given their non-toxicity and non-flammability in addition to their unbeatable environmental credential in combination with widest availability, these two have shifted again to the focus of research and development activities today. The natural refrigerants no longer in use today are R764 and R40 [3,11].

In Uganda just like many other developing countries, it is difficult to characterize the refrigerating equipment used because data is extremely scanty and makes it difficult to provide an accurate picture of the overall situation. The main applications however are in cold storage and domestic refrigeration [12,13]. Unlike other countries; Uganda is privileged in that it largely requires neither heating nor cooling of buildings. This is because the country suffers no climatic extremes throughout the year, hence the need for heating and cooling is very rare. Thermal comfort is attained by taking advantage of natural ventilation and wearing appropriate clothing [14].

The use of synthetic refrigerants has led to the breakdown of stratospheric ozone molecules and global warming. A decrease in the ozone layer can significantly increase the incidence of skin cancer, eye damage, decreased crop yield and damage to forests and aquatic life. In addition, ozone depletion in the stratosphere can aggravate photochemical pollution. The global warming effect on the other hand causes an increase in global temperatures and associated catastrophic effects such as rising sea level, changes in the amount and pattern of precipitation, increase in the frequency and intensity of extreme weather events, fluctuations in agricultural yields as well as glacier retreat. This in Uganda is evidenced by change in climate that has led to unpredictable wet and dry seasons which significantly affect agricultural production and the economy at large since Uganda is an agricultural country.

As a result of global warming and global climate change, many business and industrial sectors as well as personal aspects of our lives have come under heavy scrutiny. There is immense pressure to find ways to decrease the impact of human activities on the environment. Although energy generation and use is the major contributor to carbon dioxide emissions in the earth's atmosphere, certain fluorinated gases that are used for refrigeration and other beneficial purposes have been found to have direct global warming potentials much higher than carbon dioxide if they are released into the atmosphere [15,16]. The benefits that refrigeration and air conditioning brings to our lives are highly desired hence need for an increased effort to find new methods to achieve cooling that does not depend on environmentally harmful substances. It is now paramount from a business perspective that companies avoid criticism for contributing to global warming and global climate change. Natural refrigerants reduce direct emissions from high potential global warming gases, save costs and future proof the refrigeration industry in Uganda from upcoming legislation.

The aim of this study was therefore to investigate the opportunities for the application of environmentally benign options in the refrigeration industry of Uganda with the main emphasis on refrigerants. However, it should be noted that if synthetic refrigerants are to be substituted or if their use is to be constrained to applications where there is no technically and economically viable alternative, then it is essential that the chemicals used in their stead fast satisfy some fundamental requirements i.e. should not be less energy efficient than the fluids that they can replace, must be proven safe for both the immediate neighborhood and the global environment, must be simple and cost effective to use, readily available and must not require any significantly new or unfamiliar technology [17].

2. MATERIALS, INSTRUMENTATION AND METHODS

2.1 Materials

The materials used in the study included; a questionnaire for collecting data, EES used to model and simulate the refrigeration systems and Microsoft Excel used for data analysis.

2.2 Instrumentation

2.2.1 Infrared digital thermometer

An AR 300 infrared digital thermometer was used to measure the evaporation and condensation temperatures. These two parameters served as input data during computer modeling of the systems. This instrument was chosen basing on its compactness, ruggedness and ease of use. In addition, its ability to safely measure surface temperatures of hot, hazardous or hard to reach objects as is the case with HVAC systems was crucial for its selection. The specifications for this thermometer are summarized in Table 1;

Table 1. Specifications of the infrared digital thermometer

Metric	Value
Temperature range	-32°C to 300°C(25.6°F to 572°F)
Accuracy	±1.5%
Resolution	0.1°C (0.1°F)
Range	Up to 8 m

2.2.2 Pressure gauge

A pressure gauge was used to measure the evaporation and condensing pressure. These two parameters also served as input data to the computer modeling process. The model PEM 202 LF was chosen since it is recommended for plumbing, air compressors, water tanks, pneumatic and HVAC systems. A summary of the manufacturer's specifications for this model is presented in Table 2;

2.2.3 Power meter

A power meter was used to measure the power requirement of the compressor. The measured values were used as input data during computer modeling. Model 3169-20 of a portable digital power meter was used for this purpose because of its versatility and availability. The specifications for this model are summarized in Table 3;

Table 2. Specifications for the pressure gauge

Metric	Value
Range	0-100 psi
Accuracy	±2.5%

Table 3. Specifications for power meter

Metric	Value
Range	750 W -900kW
Accuracy	±0.2%

2.3 Methods

2.3.1 Information sources

Information related to the study was collected from various sources such as the internet, relevant textbooks and brochures. The relevant authorities like NEMA, MEMD among others were consulted as well.

2.3.2 Ascertaining the current status of refrigeration in Uganda

A field survey was done to obtain data on operating parameters of the systems such as evaporation and condensing temperature, refrigerant mass flow and compressor power demand, the survey also helped to ascertain the current state of refrigeration in Uganda. The data was obtained through questionnaires interviews and field observations; the equipment and instrumentation used are summarized in Table 4. According to [18], the instrumentation in Table 4 and Fig. 1 is deemed appropriate for evaluating the performance of refrigeration systems;

Table 4. Summary of instrumentation used

Parameter	Symbol	Units	Instrumentation
Pressure	P	kPa	Pressure gauge
Compressor power	$\dot{W}$	kW	Power meter
Temperature	T	C	Thermometer
Mass flow rate	$\dot{m}$	kg/s	Mass flow meter

The instrumentation in Table 4 was used to collect relevant data for the computer modeling of the systems. The required data included; temperature and pressure at the suction and discharge line of the compressor, evaporation and condensing temperature and the mass flow rate of the refrigerant. However, as a result of failure to obtain the mass flow meter, it was necessary to know the enthalpy of refrigerant before and after the compression process. With knowledge of the compressor power demand, the mass flow rate of the refrigerant was then calculated. The sectors visited included fish, beer, soft drinks, dairy, supermarkets, hospitals, commercial and automobile air conditioning companies.

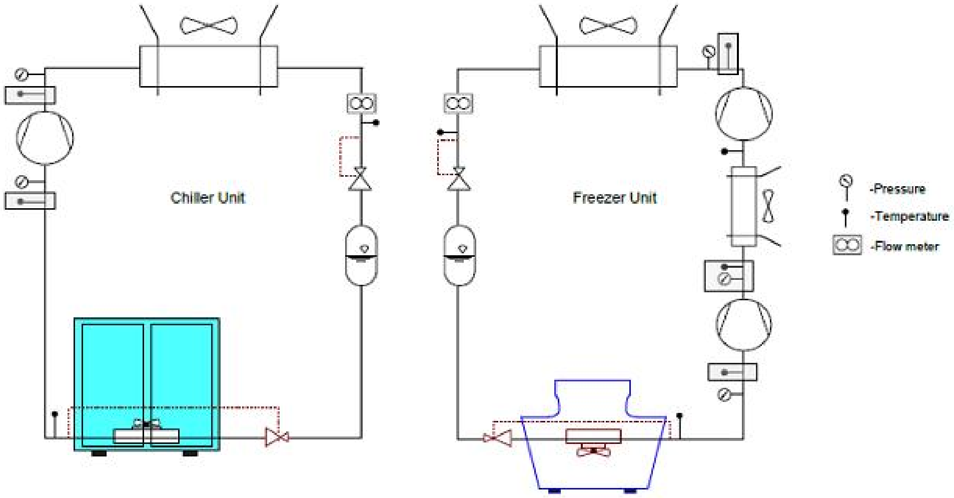

Fig. 1. Instrumentation used

2.3.3 Computer modeling and simulation

The application of new system solutions must be verified against existing technologies by theoretical analysis which is an essential step in defining potential advantages, disadvantages and limitations in each solution; therefore models were developed using EES. During the modeling process the following assumptions were taken;

i) There is no superheating and subcooling in the systems
ii) The isentropic efficiency (η_{is}) of the compressor and the mechanical efficiency (η_m) of the pump are 0.7 and 0.9 respectively.
iii) A throttling process takes place in the expansion device
iv) Changes in kinetic and potential energy are negligible
v) The cycle operates under steady state conditions
vi) There is negligible pressure and heat losses/gains between the piping and system components
vii) The temperature difference in the cascade condenser is 5°C

Assumption (i) had to be taken since obtaining the degree of superheating and subcooling required opening up of the systems in order to access the suction line and liquid line of the system and most companies were not comfortable with this. This assumption was further justified using literature [17,19,20]. The justification for assumption (ii) is that although the isentropic efficiency of the compressor varies with the pressure ratio, the value of 0.7 was used since this is the average value for most modern compressors used in the refrigeration industry nowadays [17]. Assumptions (iii), (iv), (v), (vi) and (vii) were also justified by literature [17,19-21].

EES was used to perform the modeling and simulation because of its versatility compared to other programs such as REFPROP and FORTRAN i.e. it can solve a set of algebraic equations, differential equations, equations with complex variables, can do optimization, provides linear and non-linear regression, generates plots, simplifies uncertainty analysis and provides animations. Secondly, EES automatically identifies and groups equations that must be solved simultaneously which greatly simplifies the problem for the user and ensures that the solver always operates at optimum efficiency. Furthermore, EES provides many built-in mathematical and thermophysical property functions useful in engineering calculations, allows the user to enter his/her own functional relationships and is compatible with other programs such as C^{++}, Pascal or FORTRAN.

Using data obtained during the field survey, computer models of the systems were developed using EES software and the system efficiencies determined using appropriate equations and assumptions. Calculations using computer modeling and simulation were made to compare and evaluate the performance of systems in the Ugandan conditions. Limitations and possibilities for the suggested environmentally friendly solutions have also been discussed. The thermophysical properties of the refrigerant were determined using EES which contains built-in property functions of many refrigerants.

2.3.3.1 Single stage vapor compression system

Taking into account the assumptions made, mass and energy balance for a single stage vapor compression system was done by using the general equations (1) and (2) respectively; specific equations for each system component are summarized in Table 5 with reference to Fig.2 while the COP of the system is calculated by equation (3). For two such systems serving as a chiller and freezer as is the case in Ugandan supermarkets, the overall COP was calculated using equation (4);

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \tag{1}$$

$$\dot{Q} - \dot{W} + \sum_{in} \dot{m}h - \sum_{out} \dot{m}h = 0 \tag{2}$$

$$COP = \frac{\dot{Q}_L}{\dot{W}} \tag{3}$$

$$COP = \frac{\dot{Q}_{L,freezer} + \dot{Q}_{L,chiller}}{\dot{W}_{freezer} + \dot{W}_{chiller}} \tag{4}$$

2.3.3.2 Multi stage vapor compression systems

Two temperature levels are required for supermarket refrigeration i.e. medium temperature for chilled foods and low temperature for frozen foods. Product temperatures of around +3°C and -18°C are typical; two stage or cascade systems are used for these low temperature applications [22-24]. On the other hand, biomedical refrigeration requires storage of biological specimens like stem cells, sperms, blood and organs at a storage temperature of around -80°C; for long term storage of biological materials, temperatures below -120°C are considered to safeguard against the effects of devitrification and crystallization [19]. A single stage vapor compression system can only achieve cooling of about -40°C and moreover the COP begins to drop under -35°C due to a large temperature lift between the evaporator and condenser; therefore, in order to reach a lower temperature, a cascade refrigeration system is utilized [19-21]. For a two stage vapor compression system, the equations (1) and (2) apply with reference to Fig. 3;

The Intermediate pressure between compression stages and the COP of the two stage vapor compression system were calculated using equation (5) and (6) respectively. The specific equations for each of the system components are summarized in Table 6;

$$P_M = \sqrt{P_H . P_L} \quad (5)$$

$$COP = \frac{\dot{Q}_L}{\dot{W}_L + \dot{W}_H} \quad (6)$$

A schematic diagram of a cascade refrigeration system for biomedical refrigeration is shown in Fig 4. This system comprises a high temperature circuit and a low temperature circuit thermally connected to each other through a cascade condenser which serves as an evaporator for the high temperature circuit and as a condenser for the low temperature circuit. The three important design parameters for a cascade refrigeration system are the evaporating temperature, condensing temperature and the temperature difference in the cascade condenser.

The thermodynamic analysis of a cascade refrigeration system was accomplished using the general equations (1) and (2) to perform a mass and energy balance on the system components with reference to Fig. 4. The COP of the system was calculated by equations (7)-(9);

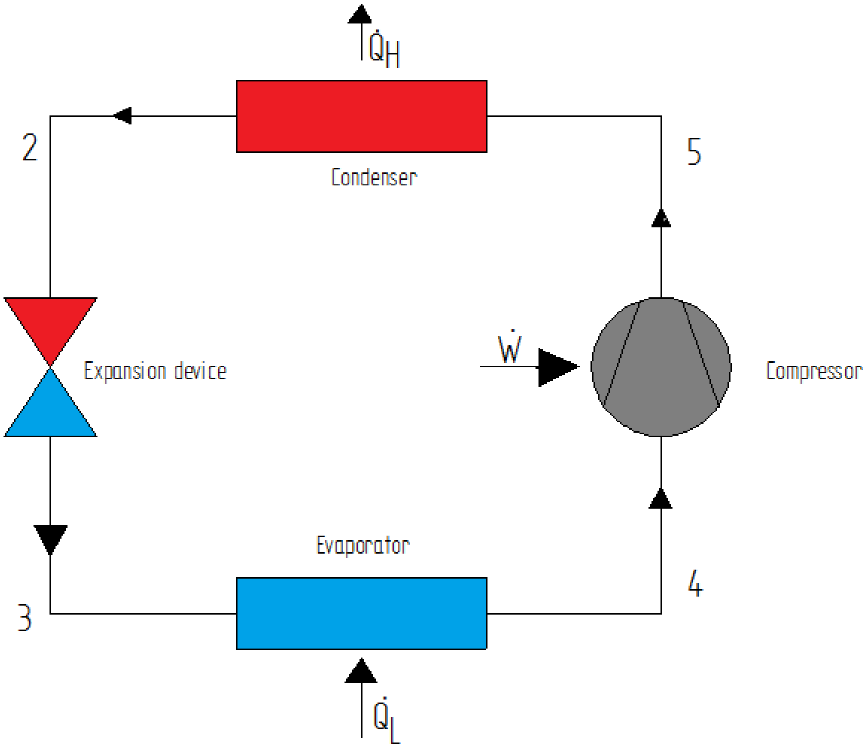

Fig. 2. Single stage vapor compression system

Table 5. Energy and mass balance for a single stage vapor compression system

Component	Mass flow (kg/s)	Enthalpy change (kJ/kg)	Energy flow (kW)
Compressor	$\dot{m}$	$h_5 - h_4$	$\dot{W} = \dot{m}(h_5 - h_4)/\eta_{is}$
Condenser	$\dot{m}$	$h_2 - h_5$	$\dot{Q}_H = \dot{m}(h_2 - h_5)$
Evaporator	$\dot{m}$	$h_4 - h_3$	$\dot{Q}_L = \dot{m}(h_4 - h_3)$
Expansion device	$\dot{m}$	$h_2 = h_3$	0

$$COP = \frac{COP_{LTC} + COP_{HTC}}{1 + COP_{LTC} + COP_{HTC}} \quad (7)$$

$$COP_{LTC} = \frac{\dot{Q}_L}{\dot{W}_L} \quad (8)$$

$$COP_{HTC} = \frac{\dot{Q}_{cas}}{\dot{W}_H} \quad (9)$$

The rate of heat transfer in the cascade condenser was determined from equation (10);

$$\dot{Q}_{cas} = \dot{m}_H(h_5 - h_8) = \dot{m}_L(h_2 - h_3) \quad (10)$$

The specific equations for each of the system components are summarized in Table 7;

The modified cascade refrigeration system for supermarket refrigeration with brine in the medium temperature circuit is shown in Fig. 5. The thermodynamic analysis of this cascade refrigeration system was done using the general equations (1) and (2) for mass and energy balance for each system component with reference to Fig. 5. Specific equations for each component are given in Table 8. The energy and mass balance in the brine loop was performed using equations (11) and (12) respectively;

$$\dot{Q}_{cas,HTC} = \dot{Q}_{cas,LTC} + \dot{W}_P + \dot{Q}_M \quad (11)$$

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 \quad (12)$$

The COP of the system is calculated using equations (13), (14) and (15);

$$COP_{LTC} = \frac{\dot{Q}_L}{\dot{W}_L + \frac{\dot{Q}_{cas,LTC}}{COP_{MTC}}} \quad (13)$$

$$COP_{MTC} = \frac{\dot{Q}_M}{\dot{W}_H + \dot{W}_P} \quad (14)$$

$$COP = \frac{\dot{Q}_L + \dot{Q}_M}{\dot{W}_L + \dot{W}_H + \dot{W}_P} \quad (15)$$

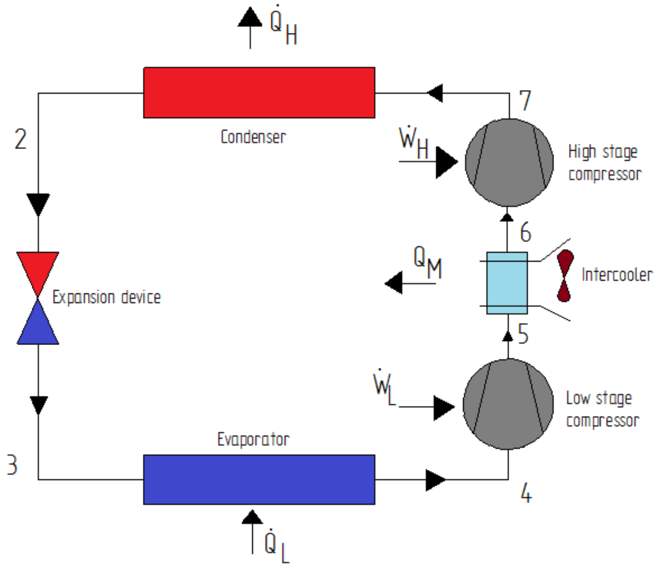

Fig. 3. Two stage vapor compression system

Table 6. Energy and mass balance for a two stage vapor compression system

Component	**Mass flow (kg/s)**	**Enthalpy change(kJ/kg)**	**Energy flow (kW)**
High stage compressor	$\dot{m}$	$h_7 - h_6$	$\dot{W}_H = \dot{m}(h_7 - h_6)/\eta_{is}$
Low stage compressor	$\dot{m}$	$h_5 - h_4$	$\dot{W}_L = \dot{m}(h_5 - h_4)/\eta_{is}$
Intercooler	$\dot{m}$	$h_5 - h_6$	$\dot{Q}_M = \dot{m}(h_5 - h_6)$
Condenser	$\dot{m}$	$h_7 - h_2$	$\dot{Q}_H = \dot{m}(h_7 - h_2)$
Evaporator	$\dot{m}$	$h_4 - h_3$	$\dot{Q}_L = \dot{m}(h_4 - h_3)$
Expansion device	$\dot{m}$	$h_2 = h_3$	0

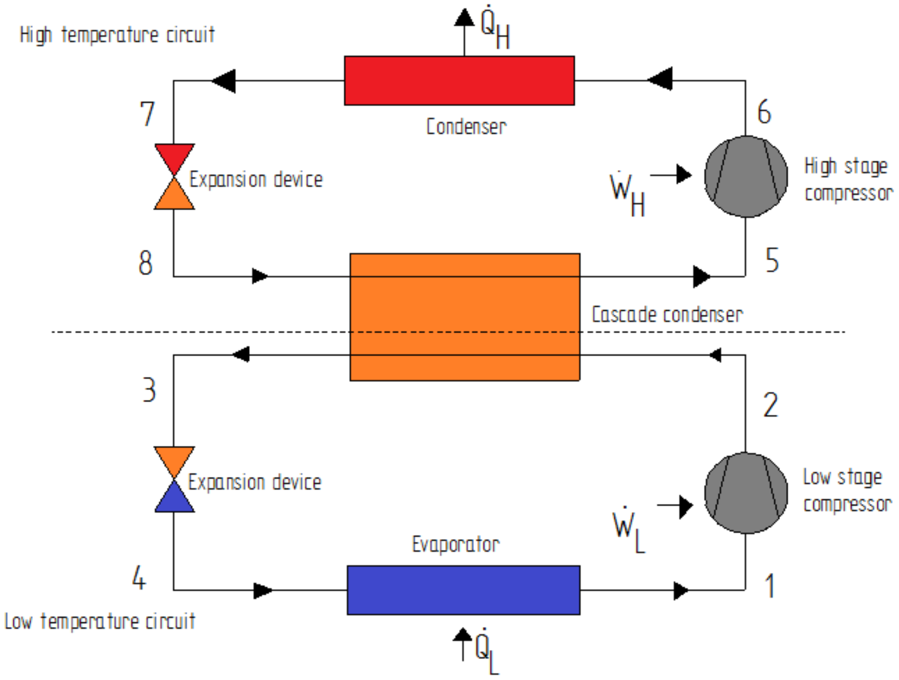

Fig. 4. Schematic of a cascade refrigeration system

Table 7. Energy and mass balance for a cascade refrigeration system

Component	**Mass flow (kg/s)**	**Enthalpy change (kJ/kg)**	**Energy flow (kW)**
High temperature circuit			
High stage compressor	$\dot{m}_H$	$h_6 - h_5$	$\dot{W}_H = \dot{m}_H(h_6 - h_5)/\eta_{is}$
Condenser	$\dot{m}_H$	$h_6 - h_7$	$\dot{Q}_H = \dot{m}_H(h_6 - h_7)$
Cascade condenser	$\dot{m}_H$	$h_5 - h_8$	$\dot{Q}_{cas} = \dot{m}_H(h_5 - h_8)$
Expansion device	$\dot{m}_H$	$h_7 = h_8$	0
Low temperature circuit			
Low stage compressor	$\dot{m}_L$	$h_2 - h_1$	$\dot{W}_L = \dot{m}_L(h_2 - h_1)/\eta_{is}$
Evaporator	$\dot{m}_L$	$h_1 - h_4$	$\dot{Q}_L = \dot{m}_L(h_1 - h_4)$
Cascade condenser	$\dot{m}_L$	$h_2 - h_3$	$\dot{Q}_{cas} = \dot{m}_L(h_2 - h_3)$
Expansion device	$\dot{m}_L$	$h_3 = h_4$	0

3. RESULTS AND DISCUSSION

3.1 The Current Status of Refrigeration in Uganda

In the fish industry, the refrigerants used are R12, R22, R717 and R404A. R12, R22 and R717 are mainly used in the cold rooms where the fish is kept under cold storage at the company premises before being sent to the market. R404A is used in the ice making plants that produce ice for cold storage of fish during transportation to the market. The systems used are single stage vapor compression systems. The compressors used are positive displacement machines i.e. reciprocating and screw compressors of open design. In this sector, 30 respondents were interviewed of which 18 used R404A, 6 used R22 and 6 used R717.

In the beer, soft drinks and dairy industries, the refrigerants used are R22, R404A, R717 and R134a. R22 and R404A are the refrigerants used in the milk processing factory while R717 is used in beer processing. In addition to the installed systems at the factories, these companies have coolers similar to home refrigerators that are distributed to retail centers like shops, groceries, kiosks, bars and supermarkets. It is the companies that are responsible for the procurement, servicing, repair and maintenance of these coolers. The systems are single stage vapor compression and the models include FV 1000, FV 400, FV 200, FV 1200D which are manufactured by Frigorex as well as CVC 250 and Easy reach 100 Generic. The compressors used are reciprocating type of hermetic design. In this sector, 39 respondents were contacted and of these 9 used R717, 9 used R404A and 21 used R134a.

In the meat industry, the refrigerant used is R134a with simple vapor compression systems having single stage compression, 18 respondents were interviewed and they all used R134a. In residential and commercial (supermarket) refrigeration, the dominant refrigerants are R404A and R134a. R404A is used in large systems while R134a is used in refrigerators used for storage and preservation of soft drinks, alcoholic drinks, ice cream, etc. Here, 72 respondents were interviewed and of these 15 used R404A, 3 used R410A, 3 used R407C, 33 used R134a and 18 used R22. In hospitals, R404A and R134a are the refrigerants mainly

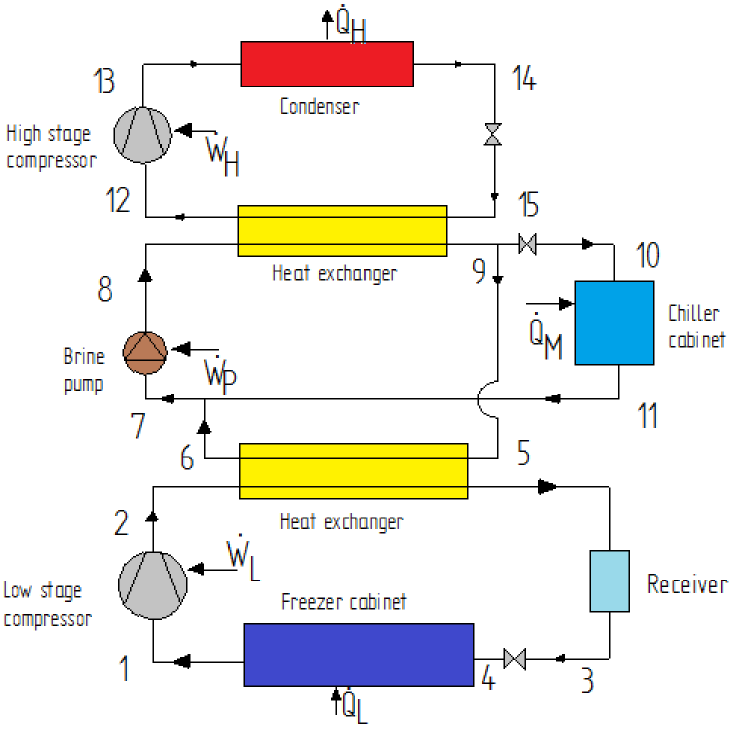

Fig. 5. Schematic of a cascade refrigeration system for supermarkets

Table 8. Energy and mass balance of a cascade refrigeration system for supermarkets

Component	Mass flow(kg/s)	Enthalpy change(kJ/kg)	Energy flow(kW)
Low temperature circuit			
Low stage compressor	$\dot{m}_L$	$h_2 - h_1$	$\dot{W}_L = \dot{m}_L(h_2 - h_1)/\eta_{is}$
Freezer cabinet	$\dot{m}_L$	$h_1 - h_4$	$\dot{Q}_L = \dot{m}_L(h_1 - h_4)$
LTC heat exchanger	$\dot{m}_L$	$h_2 - h_3$	$\dot{Q}_{cas,LTC} = \dot{m}_L(h_2 - h_3)$
Expansion valve	$\dot{m}_L$	$h_3 = h_4$	0
Medium temperature circuit			
Brine pump	$\dot{m}_1$	$h_8 - h_7$	$\dot{W}_P = \dot{m}_1(h_8 - h_7)/\eta_m$
HTC heat exchanger	$\dot{m}_1$	$h_8 - h_9$	$\dot{Q}_{cas,HTC} = \dot{m}_1(h_8 - h_9)$
Chiller cabinet	$\dot{m}_3$	$h_{11} - h_{10}$	$\dot{Q}_M = \dot{m}_3(h_{11} - h_{10})$
LTC heat exchanger	$\dot{m}_2$	$h_6 - h_5$	$\dot{Q}_{cas,LTC} = \dot{m}_2(h_6 - h_5)$
Expansion device	$\dot{m}_3$	$h_9 = h_{10}$	0
High temperature circuit			
High stage compressor	$\dot{m}_H$	$h_{13} - h_{12}$	$\dot{W}_H = \dot{m}_H(h_{13} - h_{12})/\eta_{is}$
Condenser	$\dot{m}_H$	$h_{13} - h_{14}$	$\dot{Q}_H = \dot{m}_H(h_{13} - h_{14})$
HTC heat exchanger	$\dot{m}_H$	$h_{12} - h_{15}$	$\dot{Q}_{cas,HTC} = \dot{m}_H(h_{12} - h_{15})$
Expansion device	$\dot{m}_H$	$h_{14} = h_{15}$	0

employed i.e. 6 respondents were contacted and 3 used R404A and the other 3 R134a while in space conditioning of commercial buildings, R404A is the main refrigerant, 12 respondents were contacted and they all used R404A. R12, R406A and R134a are the refrigerants used in automobile air conditioning. Here, 30 respondents were interviewed and 21 used R134a, 3 used R406A and 6 used R22.

In total, 213 respondents were contacted and 57 used R404A, 96 used R134a, 3 used R12, 6 used R406A, 30 used R22, 15 used R717, 3 used R410A and 3 used R407C. The refrigeration industry in Uganda still relies on synthetic refrigerants and single stage vapor compression systems. However most of the applications use HFC with R134a being the dominant refrigerant. Few applications use CFC and HCFC while natural refrigerants i.e. R717 have the least applications. Table 9 and Fig. 6 represent the findings of the field survey; natural refrigerants (R717) account for 7% of the refrigerant mix in Uganda which is extremely low.

The refrigeration industry in Uganda is generally at an elementary level that is characterized by single stage vapor compression systems that use synthetic refrigerants as opposed to developed countries that have advanced refrigeration systems with multiple stage compression that use synthetic refrigerants in form of HFC (R404A and R134a) that are environmentally less harmful compared to CFC and HCFC together with natural refrigerants (R744, R717, R290) [25-28], vapor absorption refrigeration systems using NH_3-H_2O and H_2O-LiBr solution pairs in commercial refrigeration in Turkey and India [9, 28]. Vapor compression systems used in commercial refrigeration using conventional R404A systems [29], cascade refrigeration systems for supermarket and biomedical refrigeration using R744/R717, R744/R404, R744/R290 and R744/R290+R170 especially in the EU, USA, Republic of China, Republic of Korea and Indonesia [19-22] and R744 transcritical systems for residential, commercial and automobile air conditioning [30-32].

3.2 Computer Modeling and Simulation

3.2.1 Fish industry

The schematic is as shown in Fig. 2 and the thermodynamic cycle is represented on the h-logP diagram in Fig. 7. The evaporation temperature is -20°C, the condensing temperature is 36°C and the power demand of the compressor is 85 kW. R22 is the dominant refrigerant in this sector.

Simulation of the above model gave a COP of 2.5. The low value of COP can be attributed to a large temperature difference between the evaporation and condensing temperatures and hence a high pressure ratio necessitating a high compressor power requirement. Therefore, the COP of the system can be improved by employing a two stage vapor compression system. The variation of the COP with evaporation temperature and pressure as well as heat flow in the evaporator and condenser is shown in Fig. 8 and Fig. 9. From the plots, it can be observed that the COP increases with evaporation temperature and pressure as well as heat flow in the condenser and evaporator of the system.

3.2.2 Beer, soft drinks and dairy industries

The schematic is as shown in Fig. 2 and the thermodynamic cycle is represented on the h-logP diagram in Fig.10. The evaporation temperature is 5°C, the condensing temperature is 43°C and the power demand of the compressor is 750 W. R134a is the dominant refrigerant in this sector.

Simulation of the above model gave a COP of 4.1. The high value of the COP can be attributed to a lower temperature difference between the evaporator and condenser (<40°C) and hence a lower pressure ratio necessitating the compression process to be accomplished by a compressor of small size. The variation of COP with refrigerant mass flow, pressure ratio of the system, condensing temperature and pressure is shown in Fig. 11 and Fig. 12. From the plots, it can be seen that the COP increases with increase in mass flow rate and also increases with a decrease in pressure ratio, condensing temperature and pressure.

Table 9. Summary of current status of refrigeration in Uganda

Sector	Refrigerant	System type
Automobile	R12, R22,R134a and R406A	Single stage, vapor compression
Beer	R717 and R134a	Single stage, vapor compression
Commercial	R22, R134a, R407C, R410A and R404A	Single stage, vapor compression
Dairy	R22, R134a and R404A	Single stage, vapor compression
Fish	R12, R22, R717 and R404A	Single stage, vapor compression
Health	R134a and R404A	Single stage, vapor compression
Meat	R134a	Single stage, vapor compression
Residential	R22 and R134a	Single stage, vapor compression
Soft drinks	R134a	Single stage, vapor compression

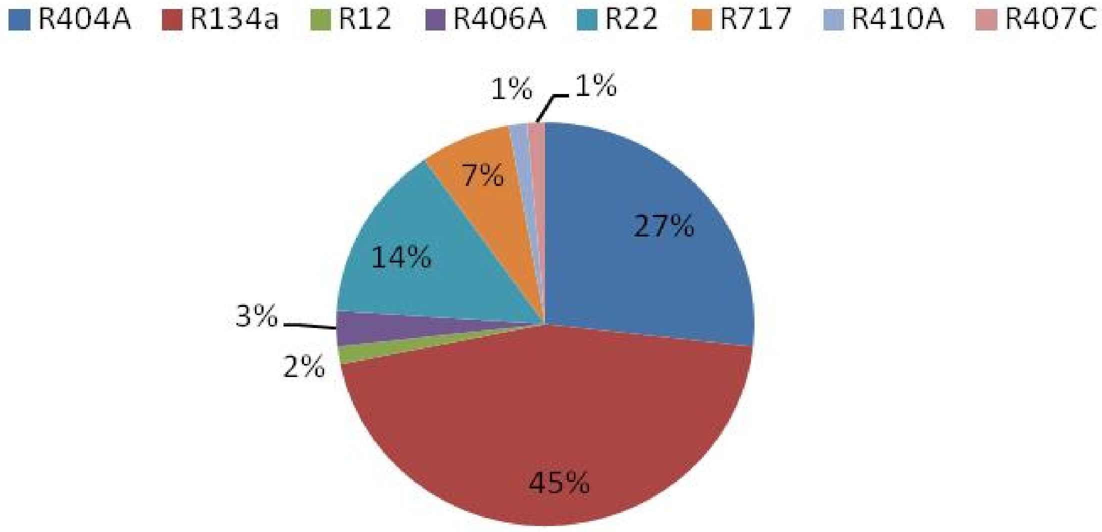

Fig. 6. Refrigerant mix in Uganda

3.2.3 Meat industry

The schematic is as shown in Fig. 2 and the thermodynamic cycle is represented on the h-logP diagram in Fig. 13. The evaporation temperature is -18°C, the condensing temperature is 36°C and the power demand of the compressor is 2.2 kW. R134a is the dominant refrigerant in this sector.

Simulation of the above model gave a COP of 2.4. The low value of COP can be attributed to a large temperature difference between the evaporation and condensing temperatures, and hence a high pressure ratio necessitating a high compressor power requirement. Therefore, the COP of the system can be improved by employing a two stage vapor compression system.

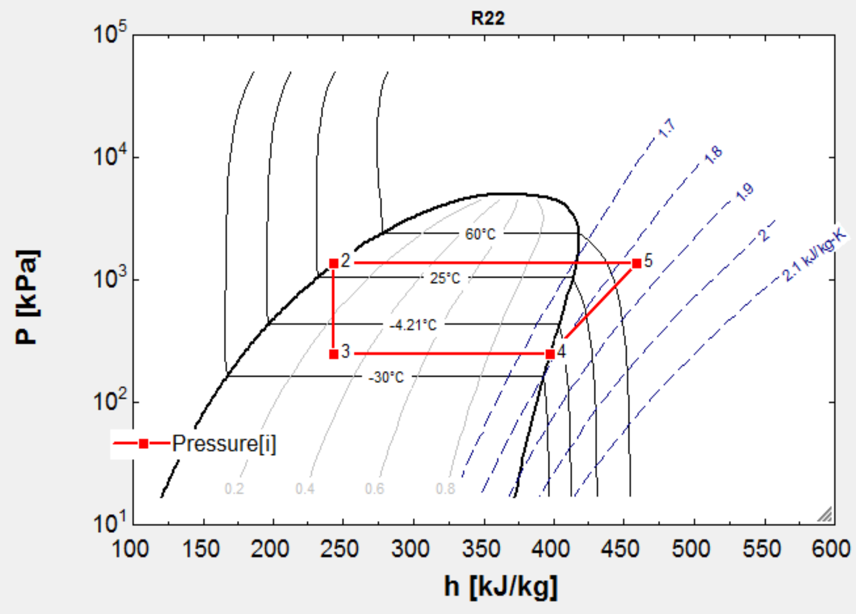

Fig. 7. h-logP diagram for the system

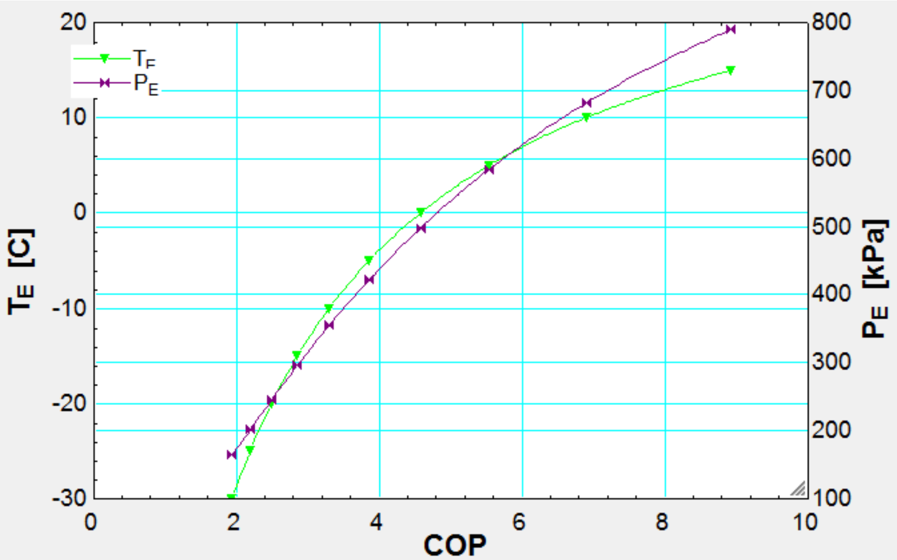

Fig. 8. Plot of COP against evaporation temperature and pressure

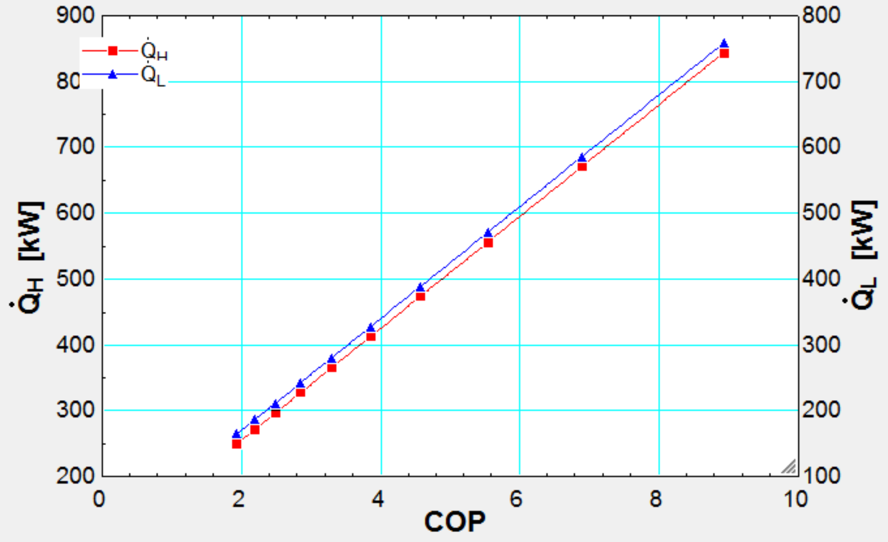

Fig. 9. Plot of COP against heat flow in the evaporator and condenser

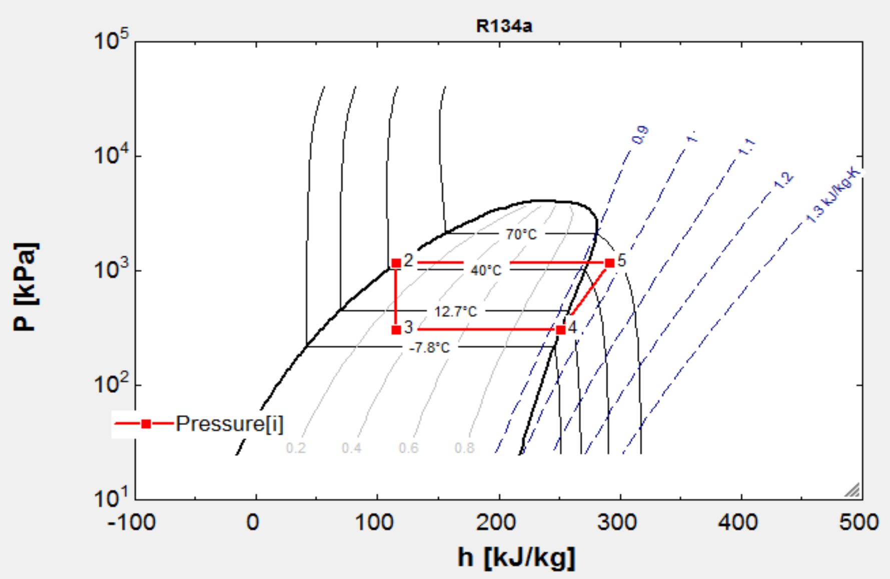

Fig. 10. h-log P diagram for the system

3.2.4 Supermarkets

The schematic is as shown in Fig. 2 and the thermodynamic cycle is represented on the h-logP diagram in Fig.14 and Fig.15 for the chiller and freezer unit respectively. The evaporation temperature is 5°C and -18°C, the condensing temperature is 43°C and 36°C and the power demand of the compressor is 37 kW and 43 kW respectively for the chiller and freezer units. R404A is the dominant refrigerant in this sector.

Simulation of the above models gave a COP of 3.6 and 2.2 for the chiller and freezer units respectively. The COP value for the chiller is reasonable but that of the freezer is relatively low due to the large temperature difference between the evaporator and condenser. The overall COP of the system is 2.9. This relatively low value can be improved by use of a cascade refrigeration system.

3.3 Design and Recommendation of an Appropriate System Solution for Each Sector

3.3.1 Fish and Meat industry

In the fish and meat industry, R717 two stage refrigeration system with intercooling between compressor stages is deemed more appropriate because of the high temperature lift. However, special care should be taken during design and installation by adhering to industry standards due to the flammability and toxicity of this refrigerant. The schematic is shown in Fig. 3 and the h-log p diagram shown in Fig. 16. The evaporation temperature is -20°C, condensing temperature is 40°C.

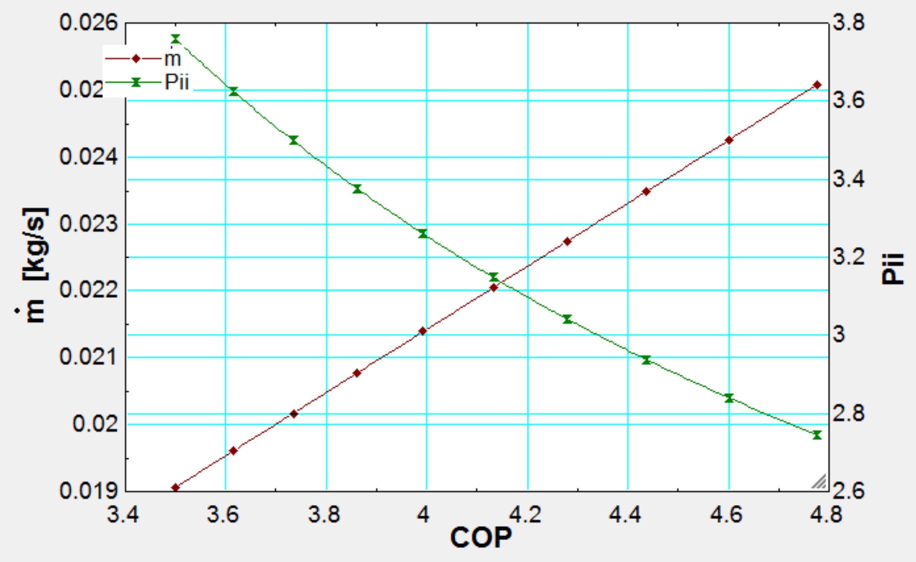

Fig. 11. Plot of COP against mass flow and pressure ratio of the system

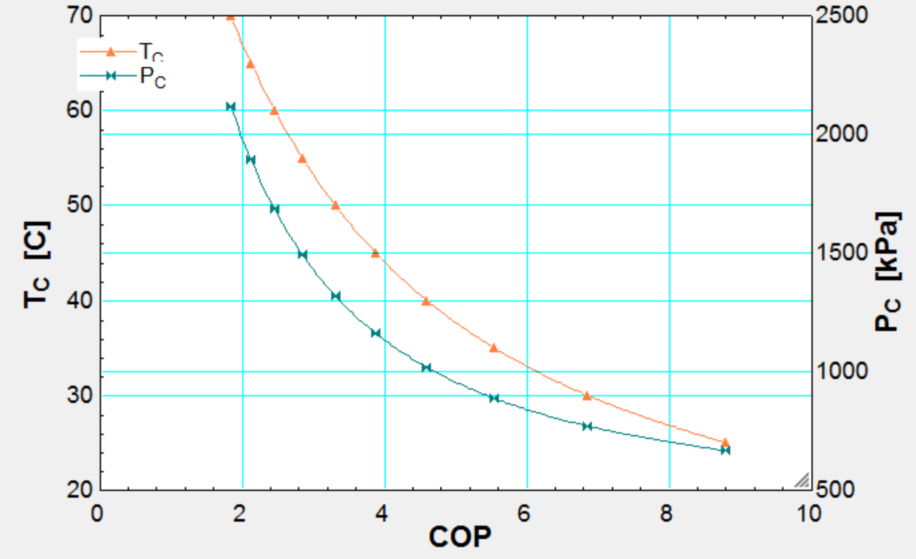

Fig. 12. Plot of COP against condensing temperature and pressure

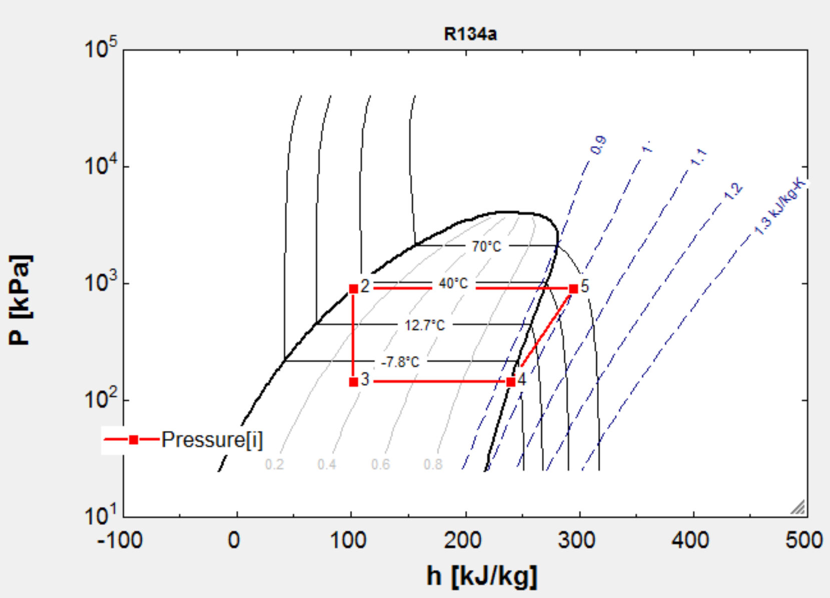

Fig. 13. h-log P diagram for the system

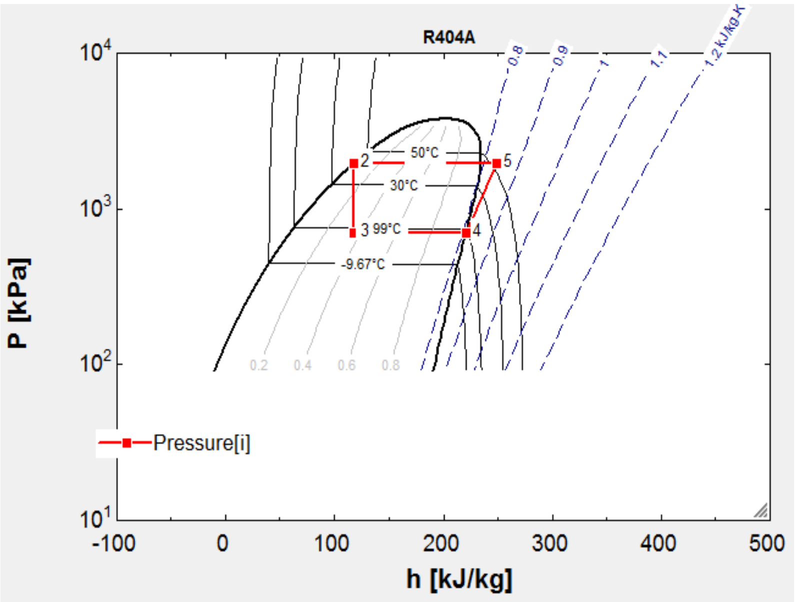

Fig. 14. h-log P diagram for the chiller unit

From computer modeling and simulation, the system gave a COP of 2.9. Plots of the variation of COP with refrigerant mass flow, pressure ratio, evaporation pressure and intermediate pressure, heat flow in the condenser as well as power demand in the low and high stage compressors and evaporation temperature are shown in Figs. 17-20. It can be seen that the COP increases with a decrease in the mass flow, pressure ratio, power demand of the compressors and heat flow in the condenser; also the COP increases with increase in evaporation temperature and pressure.

3.3.2 Hospitals

The schematic is shown in Fig. 4. The evaporation temperature is -18°C, condensing temperature is 45°C. From the simulation results, the system has a COP of 2.3. This value of COP is a fairly reasonable value and can further be improved by incorporating an expander/ vortex/ ejector to reduce the high throttling losses in the R744 circuit. Plots of variation of parameters such as mass flow ratio of refrigerant in the high to low stage, temperature difference in the cascade heat exchanger, heat flow in the both the condenser and cascade heat exchanger and power demand of the compressors are shown in Figs. 21-23. From the plots, it can be noted that COP increases with decrease in compressor power demand, heat flow in the condenser and cascade heat exchanger and temperature difference in cascade condenser while the COP increases with increase in mass flow ratio of the system.

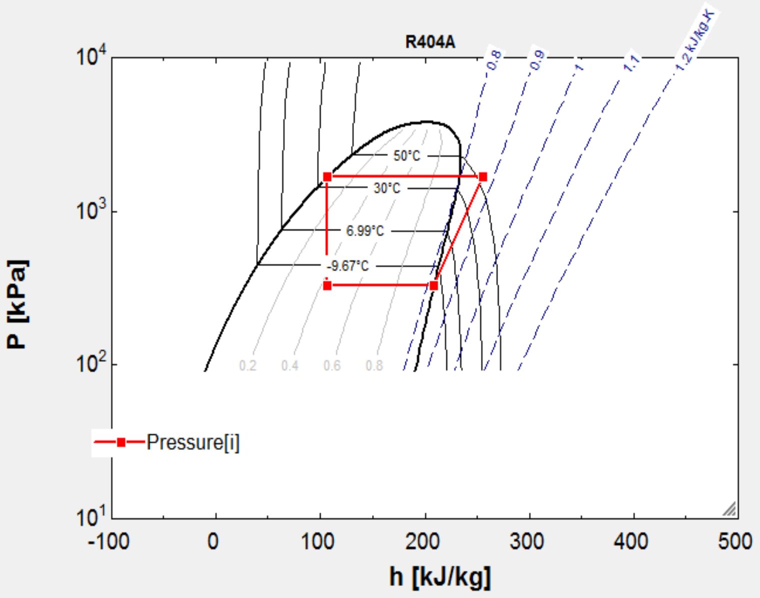

Fig. 15. h-log P diagram for the freezer unit

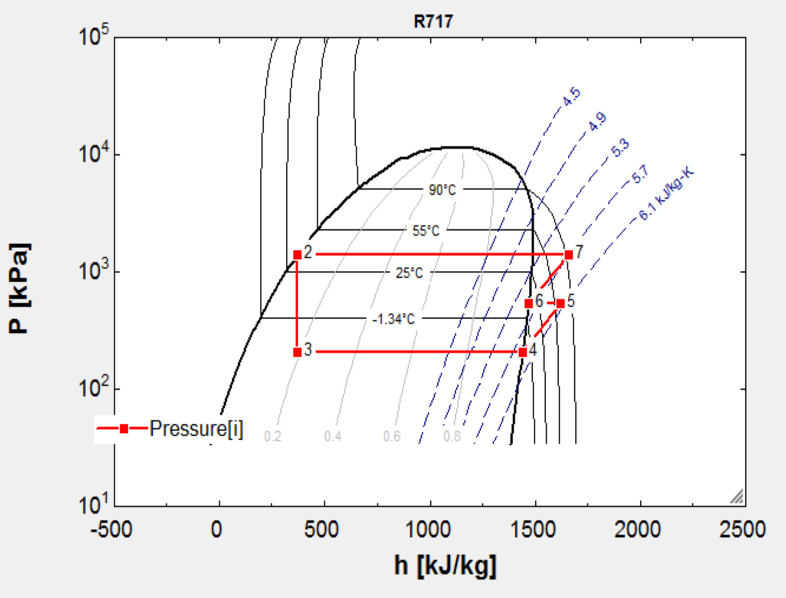

Fig. 16. h-log P diagram for the system

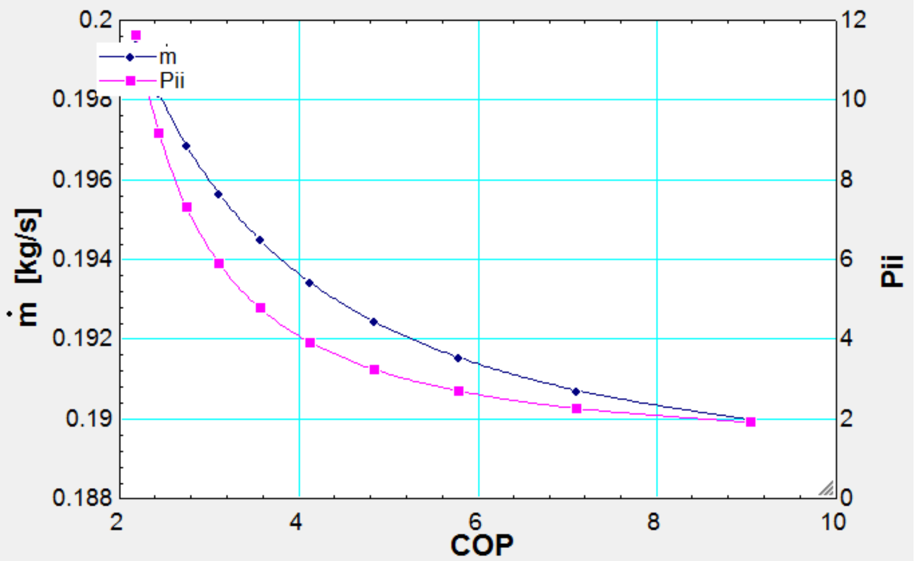

Fig. 17. Plot of COP against mass flow and pressure ratio of the system

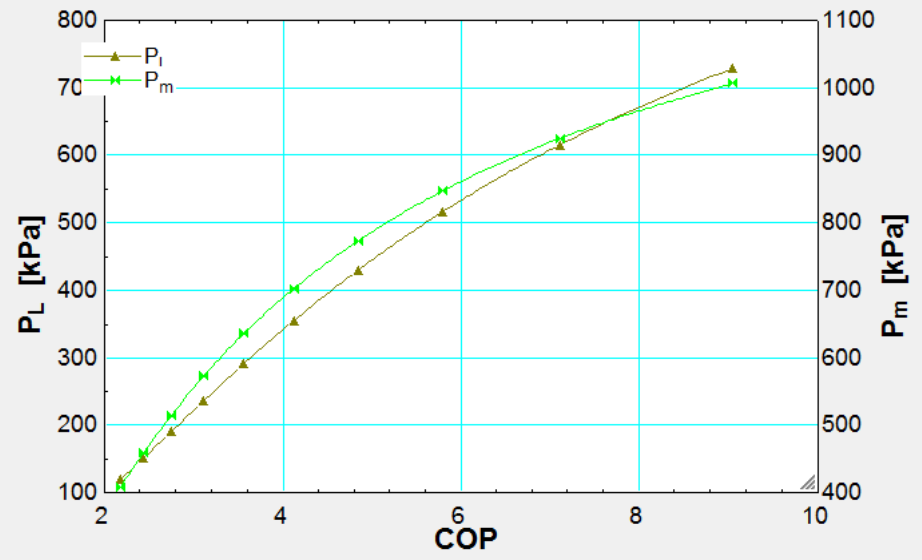

Fig. 18. Plot of COP against pressure in the low and intermediate stage

3.3.3 Beer, soft drinks and residential sectors

In these industries, R134a coolers available should be retained for now since the smaller capacity systems available cannot operate efficiently and safely with natural refrigerants i.e. R717 cannot be used in these systems since it's difficult to source components for small ammonia systems as well as posing a challenge of high hot gas temperatures after compression since these coolers are situated indoors. Also the flammability and toxicity nature of this refrigerant requires that the system components be situated in a well ventilated area and safety considerations should be taken into account during design, installation, operation and maintenance of such systems. HC on the other hand cannot be used due to their high flammability; therefore R717 and HC would pose a severe health and safety hazard. It should be noted that R744 transcritical systems offer a promising solution but the main challenge is redesigning the systems to accommodate the high operating pressures, low critical temperature and high throttling losses in the systems for the systems to be considered reliable and cost effective.

3.3.4 Supermarkets

Fig. 5 shows a cascade refrigeration system for supermarket refrigeration with brine in the medium temperature level. The freezer cabinet temperature is -18°C, the chiller cabinet temperature is 5°C and condensing temperature is 40°C. Simulation of the above model gave a COP of 2.9. The variation of COP with operating parameters is similar to Figs. 21-23.

3.4 Comparison of the Systems

From the modeling and simulation results, it can be seen that using an R717 two stage system in the fish and meat industry improved the COP by 16% and 22% respectively; therefore an R717 two stage system should be adopted in these sectors for energy and environmental reasons.

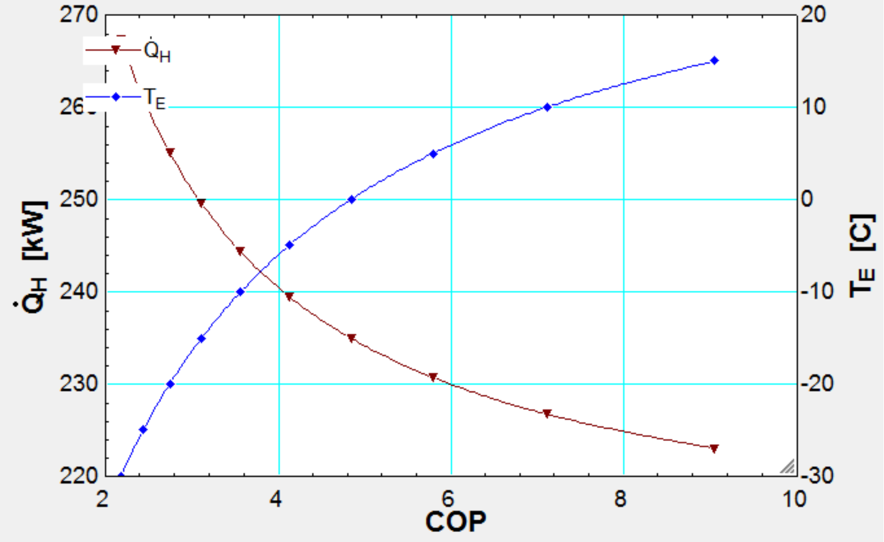

Fig. 19. Plot of COP against evaporation temperature and heat flow in the condenser

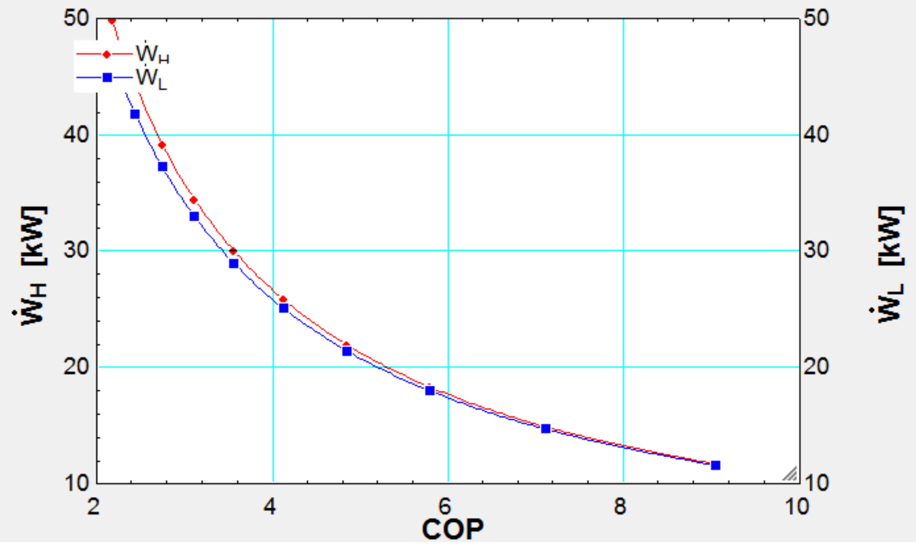

Fig. 20. Plot of COP against power demand of the high and low stage compressors

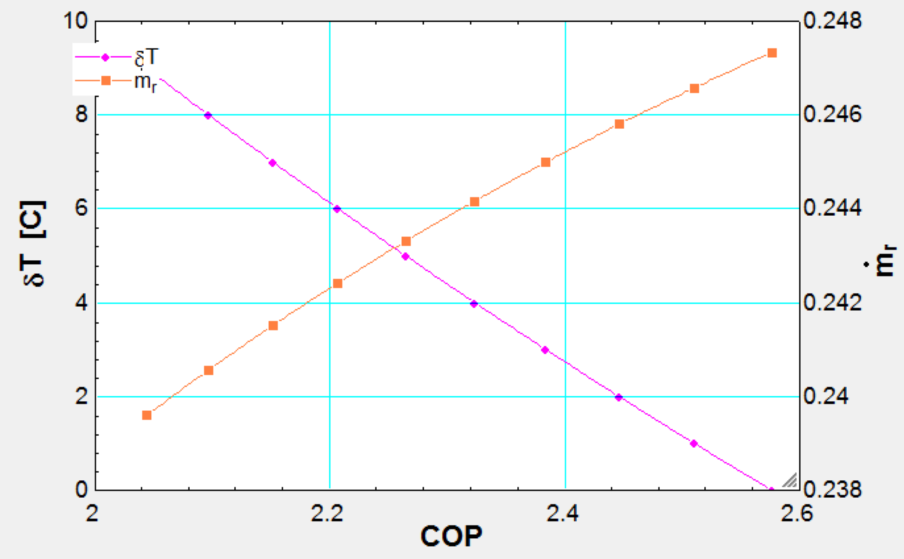

Fig. 21. Plot of COP against mass flow ratio and temperature difference in the cascade condenser

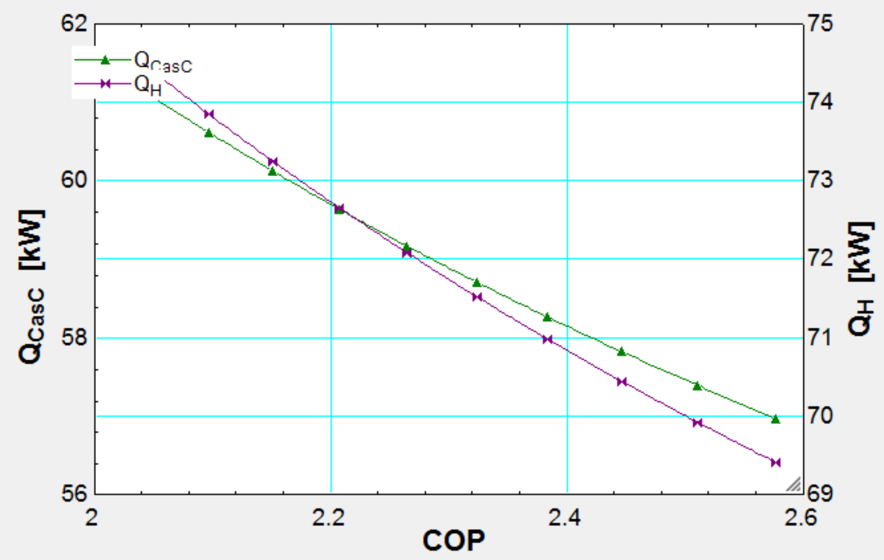

Fig. 22. Plot of COP against heat flow in the condenser and cascade heat exchanger

In commercial refrigeration (supermarkets) and biomedical refrigeration, the R717-R744 cascade refrigeration system offers a promising solution. Using a R717-R744 cascade refrigeration system led to a 12% improvement in the COP, although not a big improvement when compared to the performance of existing systems (conventional R404A) but with an additional advantage that the utilization of R744 (ODP=0, GWP=1) and R717 (ODP=0, GWP=0) is preferred in the light of more pressing environmental issues since they are natural substances and environmentally benign unlike synthetic refrigerants such as R404A (ODP=0, GWP=3863) and R134a (ODP=0, GWP=1410) currently used for commercial and industrial refrigeration. Furthermore, the R717-R744 cascade refrigeration system gives good safety guarantees since it is possible to confine the high pressure circuit containing R717 within the

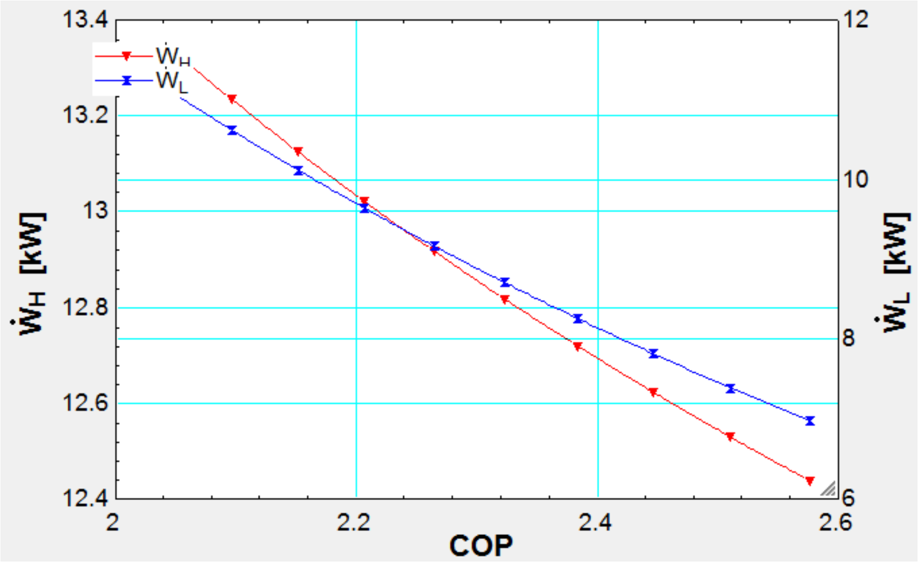

Fig. 23. Plot of COP against power demand of the high and low stage compressors

machine room or well ventilated area that is endowed with all safety devices provided for by the legislative safety standards and the fluid that circulates in the low pressure circuit located indoors (sales area) with human occupants is R744 which is non toxic and non flammable. Therefore, in commercial refrigeration, with low temperature applications i.e. rapid freezing and storage of frozen products, the use of an R717-R744 cascade refrigeration system to replace conventional systems using R404A is certainly a valid application from an energy, safety and environmental point of view.

In the automobile industry and air conditioning of buildings, R134a should be retained for the time being since it's more environmentally benign than the other available refrigerants i.e. R12, R22 and R406A. However, more environmentally benign refrigerants for this purpose include R152a and R744. R152a has similar properties like R134a with a GWP of less than 150 but the main challenge is the flammability of this refrigerant. R744 transcritical systems seem to offer a more attractive solution but the system cost, low efficiencies and service issues still pose a huge challenge.

4. CONCLUSION

In this study, the investigation of environmentally benign options in the refrigeration industry of Uganda was done. Results reveal that synthetic refrigerants dominate the current applications and the systems installed are vapor compression with single stage compression.

From computer modeling and simulation, it has been ascertained that natural refrigerants offer a better performance than the synthetic ones that they can replace i.e. higher efficiencies coupled with a null environmental burden makes them suitable for the refrigeration applications in Uganda. However, the major challenges are safety, system modifications especially in systems that are to use R744, lack of technical expertise to design, install, operate and service the systems as well as failure to have a government policy to spearhead this transition. Therefore for the transition to be realized there is need to come up with policy concerning the use of environmentally harmful refrigerants most especially the CFC and HCFC and penalties should be stipulated for those companies that fail to comply.

The results show that the COP of the refrigeration systems is affected by parameters such as evaporation temperature, condensing temperature, mass flow rate of the refrigerant and the temperature difference in the heat exchanger in case of cascade systems; and for a given system, it is possible to determine the optimum operating conditions in terms of the above parameters.

Simulation results also show that an increase in evaporation temperature increases the COP of the system and decreases the mass flow ratios, where as an increase in the condensing temperature results in a decrease in COP and an increase in refrigerant mass flow ratios. On the other hand, an increase in the temperature difference of the cascade condenser reduces both the COP and mass flow ratios.

The proposed systems seem to offer a better performance when compared to the existing systems from an energy and environmental perspective and should be adopted although it is recommended that rigorous testing of these systems with alternate refrigerants being recommended be conducted to verify the results of the simulation before adoption. Furthermore, performing an economic analysis would give a better justification from an industrial point of view.

Also, future research in this area should focus on the use of more environmentally benign refrigerants (R729 and R718) and alternative cooling techniques such as magnetic refrigeration and acoustic refrigeration. Additionally, more research should be conducted on secondary fluids used for refrigeration such as ethanol, ethylene and propylene glycols due to their good thermophysical properties and unbeatable environmental credentials. Furthermore, future research should aim at vapor absorption refrigeration systems since these systems use natural refrigerants (water, ammonia, methanol, etc) and are driven by waste heat, solar or geothermal hence contributing to the reduction of fossil fuel consumption and the associated greenhouse gas emissions.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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