Simulation of Refrigeration System in a Food Processing Company: A Case of Nigeria Bottling Company Ikeja

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Abstract:
A simulation software was developed for a single stage vapour compression cycle. A study which was carried out on an existing system and a mathematical analysis using the energy and mass balance principle was used to develop the simulation model for the system. At full capacity of the system, the simulation gave a result with an error of 4.3% and when a twenty four-hour real data was compared with simulated data from the software, it was found that there is no significant difference between real data and simulated data having a p-value of 6.22% at a significance level of 5%. Investigation of the effect of condensing temperature, evaporating temperature and compressor speed on other system properties gave trends which agree with experimental data from similar refrigeration system and this analysis was used to carry out an optimisation of the existing system.

Keywords: Simulation, Refrigeration, Vapour compression

Nomenclature:	
COP = Coefficient of performance	h = Enthalpy (kJ/kg)
C_p = Specific heat (kJ/(kg.K))	$\dot{m}$= Mass flow rate (kg/s)
P = Power (kW)	q = Heat per unit mass (kJ/kg)
Q = Heat (kJ)	*Subscripts:*
T= Temperature (^oC)	c = Condenser
W = Work (kW)	e = Evaporator

1. Introduction

Simulation is a present-day way to understand and improve processes to meet increasing efficiency demands and maintain the competitiveness of industry. It has become an important enabling technology in decision-making, engineering and operation, covering the whole life span of a production line [1]. It is used before an existing system is altered or a new system built, to reduce the chances of failure to meet specifications, to eliminate unforeseen bottlenecks, to prevent under or over-utilization of resources, and to optimize system performance [2]. This paper presents the application of simulation to refrigeration using a bottling company as a case study.

2. Methodology

The methodology involves a mathematical analysis and model of existing system, writing of software using the mathematical analysis, validation of software and use of software for steady state analysis of the system.

Figure 1 illustrates the typical vapour compression cycle as used at the case study industry. The system has a primary and a secondary cooling system. The refrigerant used in the primary system is the ammonia, while propylene glycol is used in the secondary system. The primary cooling system generates the actual cooling and then transfers the cooling onto the glycol in the secondary system through a heat exchanger in the primary cooling system. The secondary cooling system is used to cool the beverage on the production line by transferring the cooling to the beverage through another heat exchanger. The mathematical analysis of the system consists of the mass and energy balance of each of the components in the system.

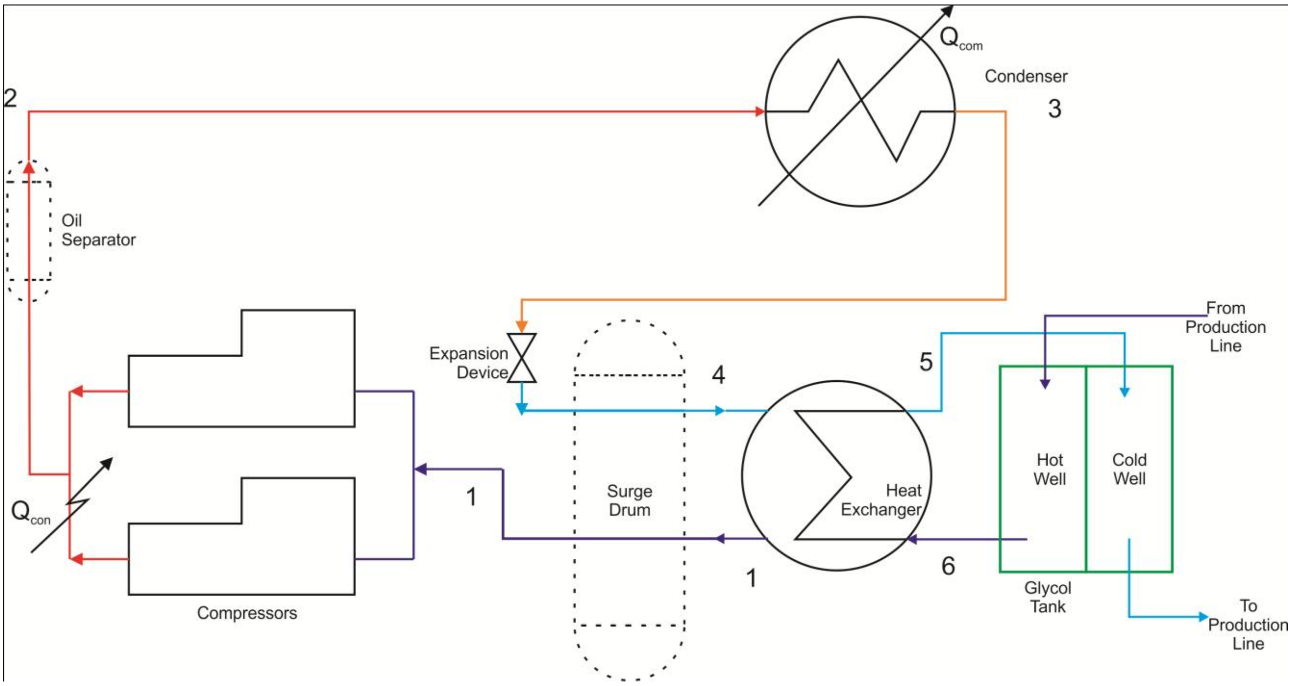

Fig. 1: A Schematic diagram of the refrigeration System

The following assumptions where made;

i. Flow in the pipes is assumed to be one-dimensional
ii. No diffusion of heat occurs in the flow direction
iii. No heat loss from compression to surrounding and no heat gain by evaporator from the surrounding
iv. Expansion process in valve is assumed to occur at constant enthalpy

Also that the:

v. Condition at exit evaporator is that of a saturated vapour
vi. Condition at exit of condenser is that of saturated liquid
vii. Condition at inlet to condenser is super-heated state

Expansion valve:

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_{ref} \quad (Total\ mass\ balance) \tag{1}$$

$$h_3 = h_4 \quad (Energy\ balance)$$

Evaporator/Heat Exchanger:

$$\dot{m}_4 + \dot{m}_5 = \dot{m}_3 + \dot{m}_6 \quad (Total\ mass\ balance) \tag{2}$$

$$\dot{m}_3(h_1 - h_4) = \dot{m}_6(h_5 - h_6) = (Energy\ balance) \quad (3)$$

Condenser:

$$\dot{m}_2 = \dot{m}_3 \quad (4)$$

The total heat rejected in the condenser, Q_c is given by Shan [3]:

$$Q_c = \dot{m}_{ref}(h_2 - h_3) = \dot{m}_{ext}c_{p,ext}(T_{ext,o} - T_{ext,i}) \quad (5)$$

Heat Rejection Ratio (HRR): ratio of heat rejected to the heat absorbed (refrigeration capacity) is calculated by Stoecker [4]:

$$HRR = \frac{Q_c}{Q_e} = \frac{Q_e + W_c}{Q_e} = 1 + \frac{1}{COP} \quad (6)$$

And an improved expression that can be used when compressor catalogue data are not readily available is

$$HRR = \left(\frac{T_{cond}}{T_{refrig}}\right)^{1.7} \quad (7)$$

Work Input:

$$W_{in} = h_2 - h_1 \quad (8)$$

Refrigerating Effect:

$$q_{ref} = h_1 - h_4 \quad (9)$$

Coefficient of performance;

$$COP = \frac{q_{ref}}{W_{in}} = \frac{h_1 - h_4}{h_2 - h_1} \quad (10)$$

Mass flow rate of refrigerant: $\dot{m}_r$ (kg/s) flowing through the evaporator is

$$\dot{m}_r = \frac{Q_{rc}}{q_{ref}} \quad (11)$$

Also, mass flow rate given by Richardson *et. al* [5]:

$$\dot{m}_r = \rho_{in} V N \eta_v \quad (12)$$

Where:

ρ_{in} = density of refrigerant at inlet
V = displacement or swept volume of compressor
N = compressor speed in rpm
η_v = volumetric efficiency

The refrigerant discharge state is given by the isentropic efficiency

$$h_2 = h_1 + \frac{(h_s - h_1)}{\eta_s} \quad (13)$$

Where: h_s = enthalpy of the refrigerant at the compressor discharge pressure, were the compression isentropic.

Refrigeration load:

$$Q_{rl} = \dot{m}_r(h_1 - h_4) \quad (14)$$

Power input to compressor:

$$P_{in} = \frac{Q_{rc}}{COP} \quad (15)$$

Refrigerating efficiency: the cycle refrigerating efficiency is given by ASHRAE [6] as

$$\eta_R = \frac{COP(T_3 - T_1)}{T_1} \quad (16)$$

System Design Conditions

The system investigated operates upon certain design conditions which are either variable or fixed. The model being created must therefore replicate these property values. Table 1 shows the values of the design conditions taken into consideration.

Table 1: System design conditions

Property	**Value**
Nominal Capacity	400kW
Evaporation Temperature:	-3 °C (2.8 bar)
Condensation temperature:	+41 °C (15 bar)
Coolant:	Glycol water
Coolant feed:	+1 °C
Coolant return:	+8 °C
Coolant flow:	50.3 m^3/h
Power input to Compressor:	132kW
Compressor Speed at full load	1500rpm
Compressor cylinder bore	110mm
Compressor cylinder stroke	85mm

The Simulation tool

The simulation tool called RefSim 1.0 was produced with a combination of Visual Basic.Net 2010 (VB.Net 10) and Microsoft Access 2010 Database (MADb). VB.Net 10 was the main programming software used while MADb was used to hold and save databases associated with the program. Each component of the refrigeration system was modelled using equations 1 to 14 to represent the appropriate component.

3. Results and discussion

The developed software simulates the requirements and performance of a single stage vapour compression refrigeration system by supplying, basically the Condensing temperature, and the Evaporating temperature.

The model was validated by comparing data from hourly recording of refrigeration technicians at the plant for twenty four (24) hours with simulated data. The change in temperature of the glycol inlet and exit was compared; Figure 3 shows a comparison of the real data with the result gotten from the simulation software. Effect of the condensing temperature and the evaporating temperature was investigated using the software and result gave similar trends as reported by Stoecker [4]. Figures 4-10 shows results of analysis carried out using the RefSim 1.0 Software.

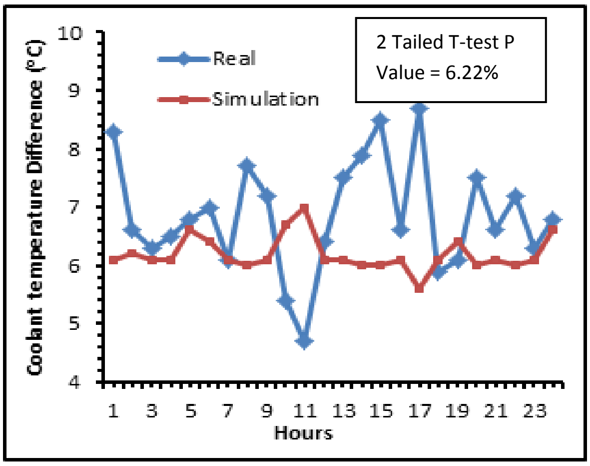

Fig. 3: result of comparison of real data with simulated result.

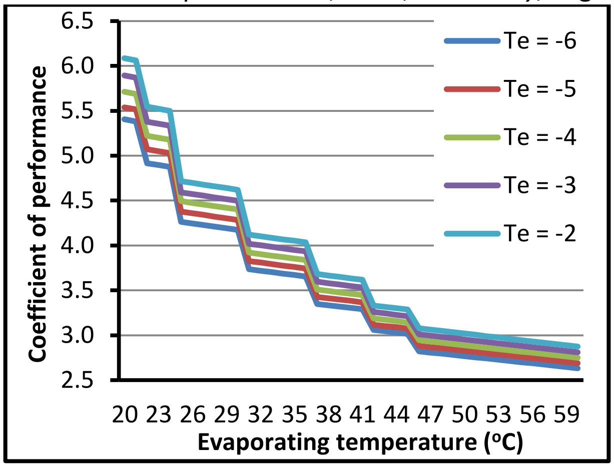

Fig 5: Effect of condensing temperature on refrigeration capacity.

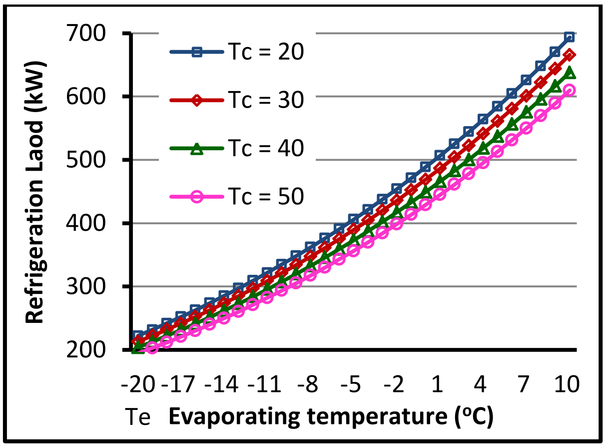

Fig 4: Effect of evaporating temperature on refrigeration capacity.

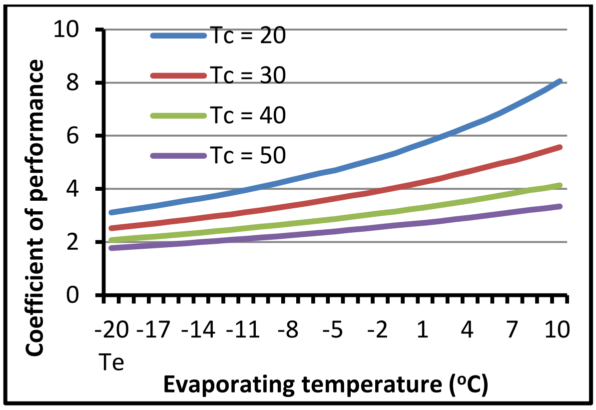

Fig 6: Effect of evaporating temperature on COP. Result of analysis by RefSim 1.0 software

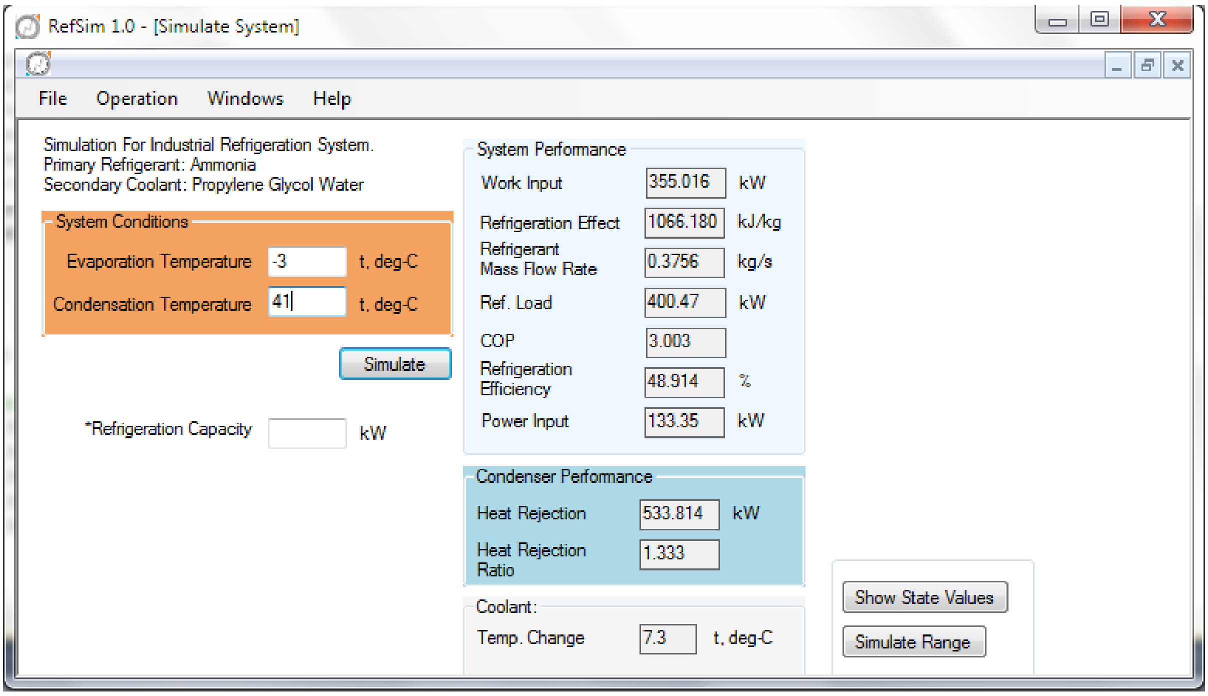

Fig. 7. Screenshot of the 'simulate system' module

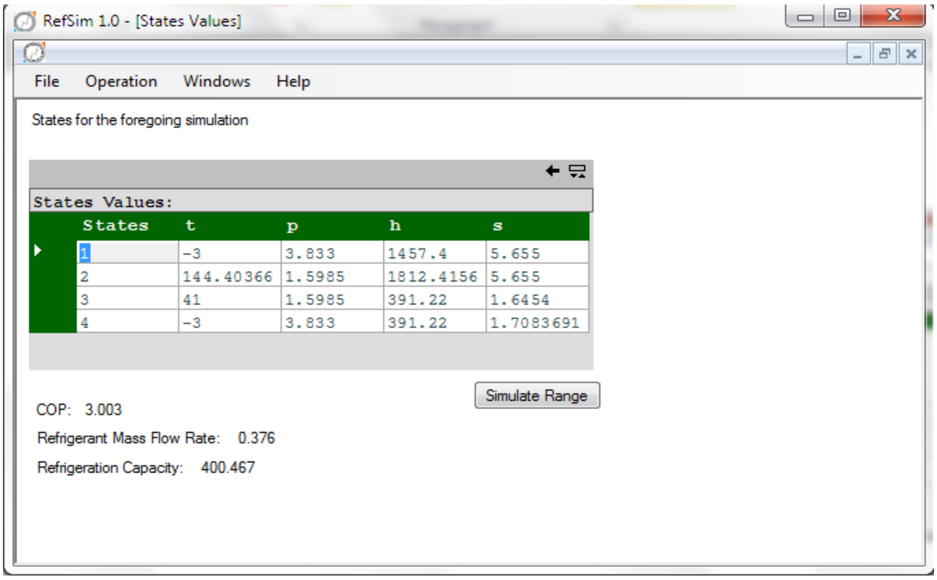

Fig. 8. Screenshot of the ‘States Values’ module

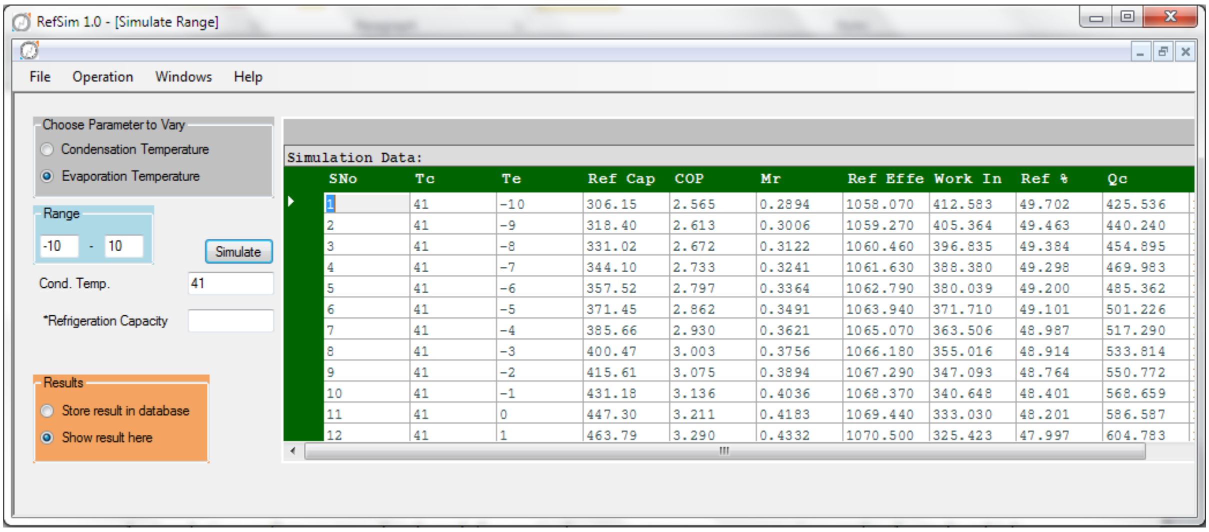

Fig. 9. Screenshot of the ‘Simulate Range’ module

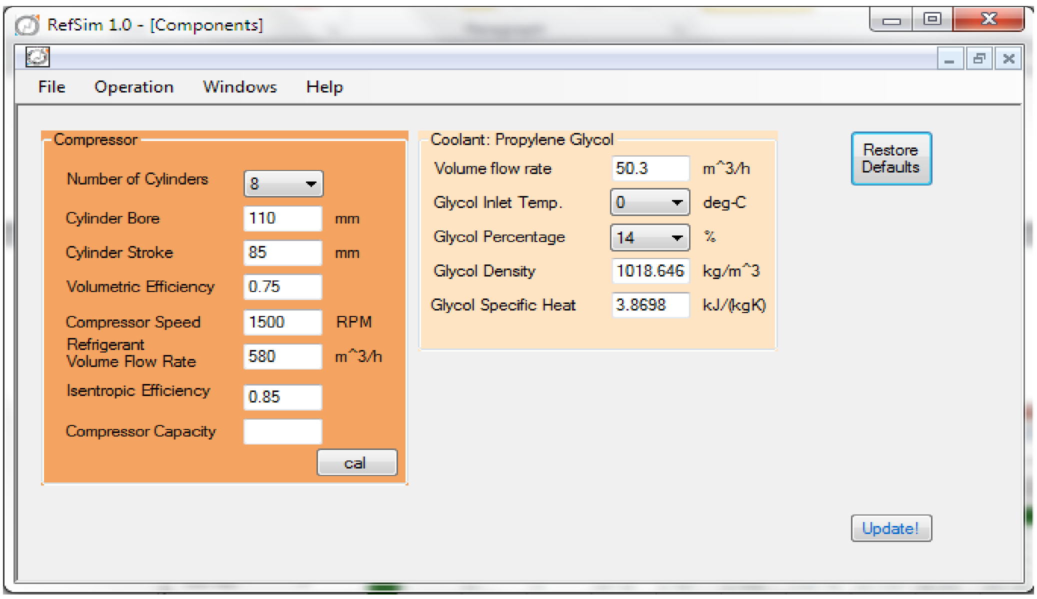

Fig 10. Screenshot of the components parameters module, showing the default values

4. Conclusion and Recommendation

In this paper, simulation of a single stage vapour compression cycle, using produced software called Refsim 1.0, was presented. The software predicts the requirements and performance of a single stage vapour compression refrigeration system by supplying the condensing temperature and the evaporating temperature. The software also helps to carry out a steady state analysis of a refrigeration system and furthermore to optimise the system. Case study presented was used to demonstrate the optimisation capability of the software. To this end, the software is recommended for prediction and analyses of an existing system, determination of optimum operating conditions and helping in decision making for the design of a new system and it can also be used for educational purpose in teaching, instruction and understanding of characteristics and operations of an industrial refrigeration system.

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