Experimental and Theoretical Study of Vacuum Cooling System

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ABSTRACT

A vacuum cooling system and the parameters which affect on its performance were studied experimentally and theoretically. For the experimental study the rig was built up to studying the performance of cooling system in three cases. These cases are: Cooling water by vacuum only, cooling water in conventional method, and cooling water by vacuum with condensation.

The experimental results show that the addition of a condenser to the vacuum cooling system leads to sweep of largest amount of generated vapor, also the time consumed for the process was decreased. The times required for cooling 45 g from water from temperature 29ºC to 10ºC for the three test cases were 4375 second, 3535 second and 263 second, respectively. Vacuum cooling with condenser is a fast cooling of three systems test, which is about (13.7 times) faster than the system of natural convection cooling. To work properly, the existence of condenser is very important in vacuum cooling. It normally removes the large amount of water vapor generation (about 94%).

For the theoretical study, a computer program was built up by employing the governing equation to simulate the performance of the vacuum cooling system. The theoretical results indicate an acceptable agreement with the experimental results. Also, the results show that the decreasing of condenser temperature causes decreasing of cooling time according to the equation ($t = 0.2031Tcd^4 - 2.8958\ Tcd^3 + 16.406\ Tcd^2 - 21.104\ Tcd + 313.39$), and increasing the evaporation surface area leads to decreasing of cooling time according to the equation (t=1/ (0.0006*Area+0.0005)), and the increasing of water mass causes in increasing of cooling time according to the equation (t=7.2667*mass+14).

Keywords: Vacuum Pump; Condenser; Cooling Effect; Compared; Vacuum Cooling; Mass Transfer.

دراسة تجريبية ونظرية لمنظومة التبريد بالتفريغ

الخلاصة

تم اجراءدراسة عملية ونظرية لمنظومة التبريد بالتفريغ ودراسة العوامل المؤثرة على اداءها.في هذه الدراسة تم تصنيع جهاز لاجراء التجارب عليه تم تجميعه مختبريا وبني لدراسة اداء منظومة التبريد بثلاث حالات مختلفة وهي ا- تبريد الماء باستخدام مضخة تفريغ فقط ب- تبريد الماء باستخدام حيز بارد (الطريقة التقليدية) ج- تبريد الماء باستخدام مضخة تفريغ مع مكثف.

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تبين من خلال النتائج العملية بان اضافة المكثف الى منظومة التبريد بالتفريغ يؤدي الى سحب الكمية الاكبر من البخار المتولد من المنتج, ويعمل على تقليل فترة التبريد. الفترة الزمنية اللازمة لتبريد ٤٥ غرام من الماء من درجة حرارة 29ºC الى درجة حرارة 10ºC كانت للحالة الاولى (4375 ثانية) والثانية (3535 ثانية), اما الحالة الثالثة فكانت (263 ثانية).التبريد بالتفريغ مع المكثف هو اسرع بي (١٣,٧) مرة من التبريد بالحمل. كذلك فان وجود المكثف يعمل على سحب ٩٤% من البخار المتولد من الماء.

في الدراسة النظرية, تم بناء برنامج حاسوبي عن طريق استخدام المعادلات الحاكمة في عملية محاكاة اداء منظومة التبريد بالتفريغ. النتائج النظرية تظهر اتفاق مقبول مع النتيجة التجريبية. كذلك بينتالنتائج النظرية ايضا ان تقليل درجة حرارة المكثف تؤدي الى تقليل فترة التبريد وحسب العلاقة ($t = 0.2031Tcd^4 - 2.8958 Tcd^3 + 16.406 Tcd^2 - 21.104 Tcd + 313.39$) و زيادة المساحة السطحية تؤدي الى تقليل فترة التبريد وحسب العلاقة($t=1/ (0.0006*Area+0.0005)$) .اما زيادة كتلة المنتج فانهاتؤدي الى زيادة فترة التبريد وحسب العلاقة($t=7.2667*mass+14$).

LIST OF SYMBOLS

Symbol	Description	Unit
A_S	Gas–liquid interface area (surface)	m^2
C_P	Specific heat capacity of cooled liquid	kJ/kg.K
h_{fg}	Latent heat of vaporization of water	kJ/kg
h_m	Mass transfer coefficient	kg/Pa m^2 s
T_C	Critical temperature of water= 674	K
$\dot{V}$	Volumetric flow rate	m^3/s
V	Volume	m^3
M	Molecular weight	kg/kmol
m	Mass	kg
$\dot{m}$	Mass flow rate	kg/s
P	Absolute pressure	Pa
P`	Pressure after a time step of evacuation process	Pa
Q	Heat removed (produce)	kJ/kg
R	Universal gas constant = 8314	J/kmol.K
t	Time	s
T	Temperature	K
Tt	Triple point temperature of water= 273.16	K

Symbol	Meaning	unit
η_T	temperature decrease per unit of percentage weight loss	ºC / 1% weight loss
ρ	Density	kg/m^3
υ	Specific Volume	m^3/kg
Δt	Time step	s

Symbol	Description
0	Initial
A	air
a, o	air out
Atm	Atmosphere
Cd	Condenser
End	End
f	fluid
Fp	flash point
O	Out
P	Product
S	Surface
Sat	Saturation
V	Vapor
v, c	vapor condensing
v, i	vapor generate
v, o	vapor out through pump
Vc	vacuum chamber (cooler)
W	Water
vcd	required condensation

INTRODUCTION

Vacuum cooling is a method of precooling began on a commercial scale in Salinas, California in 1948.

The vacuum coolers are equipped with three main components: a vacuum chamber, a vacuum pump, and a refrigeration system with evaporative coils inside the vacuum chamber (used to condense the water vapor) Figure (1). The vacuum chamber must be constructed to withstand low pressures (high vacuum). The vacuum pump must evacuate the air from the chamber in a reasonable amount of time. To avoid water vapor entering the vacuum pump and because the volume of the vapor is large, the refrigeration system is used to condense most the generated vapor.[1]

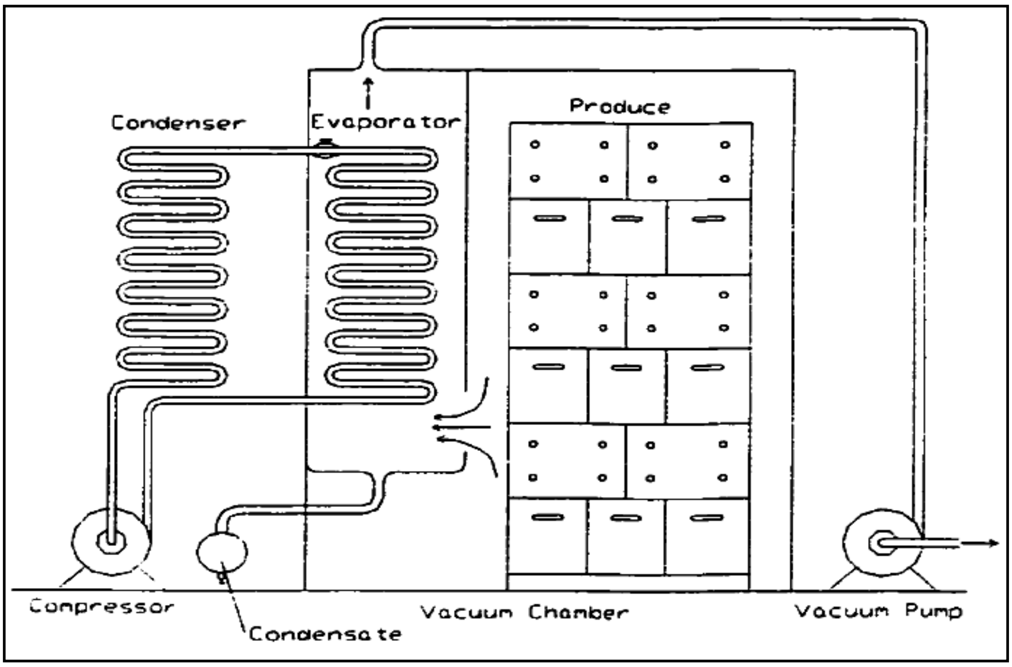

Figure (1) Schematic of a vacuum cooling system.

Vacuum cooling which is very often used when a fast temperature decrease of products is required. Particularly food industry, pharmaceutical and other areas take advantage of a fast cooling process and uniform temperature distribution which reduces high temperature effects and minimizes the time during which can occur, for example, increased growth of micro-organisms [2].

Vacuum cooling, like vapor-compression refrigeration, is based on liquid evaporation to produce a cooling effect. The difference between vacuum cooling and conventional refrigeration methods is that for the vacuum cooling the cooling effect is achieved by evaporating some water from a product directly, rather than by blowing cold air or other cold medium over the product. Speed and efficiency are two features of vacuum cooling, which are unsurpassed by any conventional cooling method, especially when cooling boxed or palletized products. [3].

Thompson ET. al. [4] evaluated the energy consumed of two commercial vacuum coolers. it found that the energy use can be reduced by reducing vacuum pump capacity after commodity begins cooling,operating cooler with maximum amount of commodity, and shutting off equipment between cooling cycles. The energy consumed of two vacuum cooler various components.

Thompson and Chen [5] compared the energy efficiency of varies cooling systems type used. Energy efficiency is a ratio of sensible heat removed from the product to electrical energy consumed in operating the cooler. It found that the vacuum coolers are the most efficient, followed by hydro coolers, water spray vacuum coolers, and forced-air coolers. Energy coefficient was 1.8 for vacuum cooling, 1.4 for hydrocoo1ing, 1.1 for water, spray vacuum cooling, and 0.4 for forced-air cooling Figure (2).

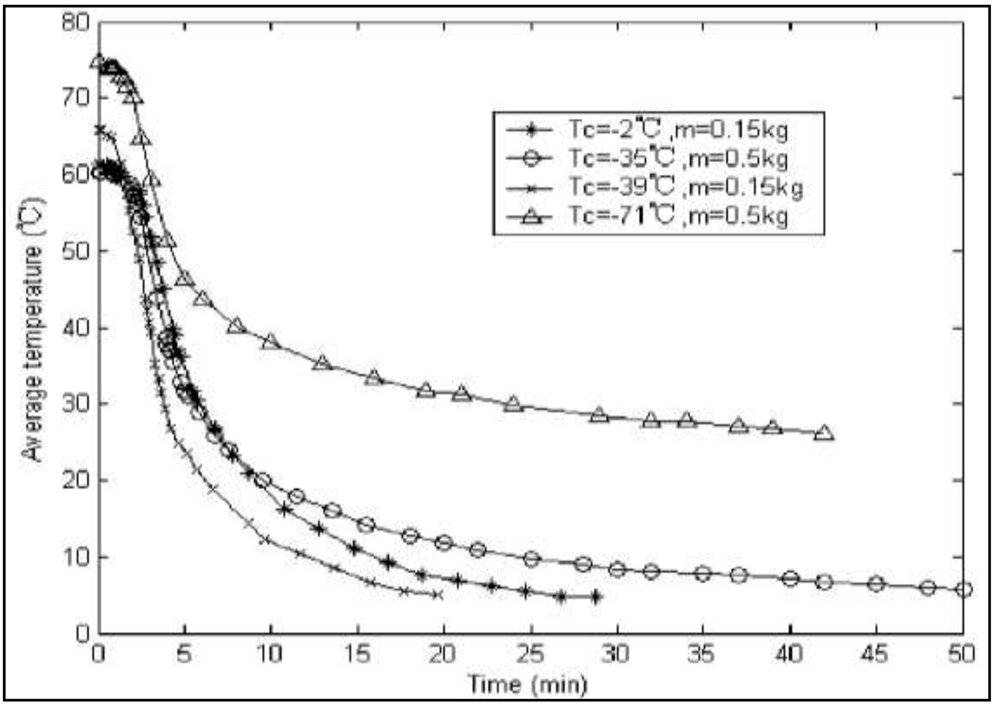

Figure (2) Effect of temperature of vapor condenser on cooling rate during vacuum cooling.[5]

Kenny and Sun [6] investigated vacuum cooling as a technique for rapid chilling of cooked meat joints. Vacuum cooling gave significant reduction in cooling time e.g. from core temperature 70ºC to 4ºC in 1.9h for 5 – 6 kg meat, compared to 11.7h for blast chilling and 14.3h for slow air chilling. However, vacuum cooling gave an increased weight loss of about 11% compared to about 4% for the other methods.

Jin et. al. [7] analyzed experimentally the temperature of condenser below 0ºC and the final pressure in the vacuum chamber below 0.61kPa during vacuum cooling. The temperature of condenser, -2ºC, -35ºC, -39ºC and -71ºC, and the final pressure in the vacuum chamber, 0.3kPa, 0.4kPa, 0.5kPa and 0.61kPa, were chosen.

The experimental results showed that the cooling rate varies with the temperature of condenser and the final pressure in the vacuum chamber as shown in Figure (2). Water vapor becomes the frost on the surface of condenser when the initial temperature of vapor-condenser is below 0ºC, which is trap water vapor for condenser. They found that the cooling time for vacuum cooling can be reduced when the final pressure in the vacuum chamber varied from 0.4kPa to 0.61kPa. However, the surface temperature of cooked meat occurred freeze when the final pressure in the vacuum chamber was 0.3kPa. Therefore, in order to reduce the cooling time and avoid freezing, the temperature of condenser should be set around - 30ºC~-40ºC and the final pressure in the vacuum chamber can be defined at from 0.4kPa to 0.61kPa.

MATHEMATICAL MODELING

The vacuum chamber is the place where the product is kept during the cooling process. The volume of the chamber is determined by the requirement of the process. The vacuum pressure of the chamber is the most important factor since the cooling process is controlled by the corresponding boiling temperature of water.

The mass flow rate of air through the vacuum pump can be expressed as [8]:

$$\dot{m}_{a,o} = \dot{V} * \rho_a \quad \dots (1)$$

Where the density of air in the chamber is given by [8]

$$\rho_a = \frac{P_a * M_a}{R * T_{vc}} \quad \dots (2)$$

The decrease rate of the air pressure in the chamber is calculated by [9]

$$\frac{dP_a}{dt} = -\frac{\dot{m}_{a,o} * R * T_{vc}}{M_a * V_{vc}} \quad \dots (3)$$

In numerical presentation the air partial pressure after one time step of cooling is given by[9]

$$P_a^{'} = P_a + \frac{dP_a}{dt} * \Delta t \quad \dots (4)$$

VAPOR GENERATION

The vapor generation rate is different from one product to another. Normally, for a given product during the vacuum cooling, the rate of vapor generated is a function of the product temperature and the vacuum pressure, which is illustrated as:

$$\dot{m}_{v,i} = f(T_f, P_{vc}) \quad \dots (5)$$

For water, Eq. (5) can be simply expressed as: [10]

$$\dot{m}_{v,i} = \frac{dm_P}{dt} = h_m * A_s * (P_{f,sat} - P_{vc}) \dots (6)$$

Where [h_m=8.4×10^{-7} (kg/Pa m^2 s) for the boiling of pure water].
The density of the vapor in the chamber can be calculated by [11]

$$\rho_v = \frac{P_v * M_w}{R * T_{vc}} \quad \dots (7)$$

And the mass flow rate of the vapor through the vacuum pump can be determined by[11]

$$\dot{m}_{v,o} = \dot{V} * \rho_v \quad \dots (8)$$

HEAT AND MASS TRANSFER

The heat removed from the product can be expressed as the mass of the water vaporized (m_L) multiplied by the latent heat of vaporization [12]

$$Q = m_L * h_{fg} \quad \dots (9)$$

The heat removed, Qis also can be expressed as a function of the mass of the product to be cooled (m_P), the product specific heat C_P and the product temperature reduction ($T_1 - T_2$). The calculation of the heat removed takes the form of:[13]

$$Q = m_P * C_P * (T_1 - T_2) \quad \text{... (10)}$$

Theoretically, the mass lost (m_L) during vacuum cooling can be predicted by the knowing the mass of the product (m_P), its specific heat (C_P), the temperature change (ΔT), and the latent heat of vaporization of water (h_{fg}) as following Eq. [14]

$$m_L = \frac{m_P * C_P * \Delta T}{h_{fg}} \quad \text{... (11)}$$

The mass of evaporated vapor can be calculated from a mass balance of the condenser control volume [8]

$$\dot{m}_{cd} = \frac{dm_{cd}}{dt} = \dot{m}_L - \dot{V} * \rho_V \quad \text{... (12)}$$

ASSUMPTIONS FOR SIMULATION PROGRAM

Before building up the simulation program, a number of assumptions must be applied for simplification these assumptions are:

1- No air leakage inside the vacuum chamberfrom the surrounding.

2- The initial temperature of the product and the air chamber are equal.

3- The initial total pressure in the vacuum chamber is equal to the atmospheric pressure.

4- The system is adiabatic, that is no heat transfer between the inside and the outside of the system.

5- No pressure drops in a chamber.

COMPUTER SIMULATION APPROACH

A computer program was built by using software MATLAB language to solve the equations mathematical model by an interactive procedure. The input data can be divided into two groups: first operating parameters such as temperature of the condenser, free volume in the chamber and vacuum pumping speed(chosen based on the analytical solution from other experiment); and second the initial temperature of the product, atmospherically pressure, time step; and the final temperature of the product.

THE TEST RIG

The rig consists of number of parts. The most important part in the system is the main chamber. It consists of two hemispherical, parts joinable and separated where the product (water vessel) can be placed and removed. The two chamber parts are joined with adhesive and gasket to prevent leakage of air. Figure (3) shows a picture of the main chamber. A vessel filled with water (product) is placed inside the main chamber. The thin channel is provided with two ports for accessing and exiting of cooling water.

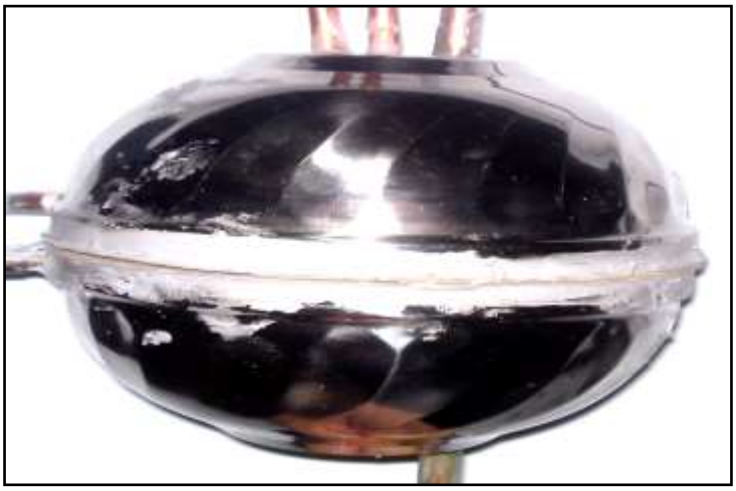

Figure (3) Photographic picture for the main chamber.

Figure (4) shows a schematic diagram of the main chamber and its accessories. The main chamber is attached to a cold water tank with immersion circulating pump. The main chamber is connected to a vacuum pump for creation vacuum inside it. Three thermocouples (type T) are used for measuring temperature. The first thermocouple is for measuring the temperature of the product (water to be cooled). The other two thermocouples are for measuring the inlet and outlet cold water temperatures passed through the thin channel (condenser). Pressure gauge is connecting to the suction pipe of the vacuum pump to measuring the vacuum pressure. The test rig equipment with attached measuring devices as shown in Figure (5).

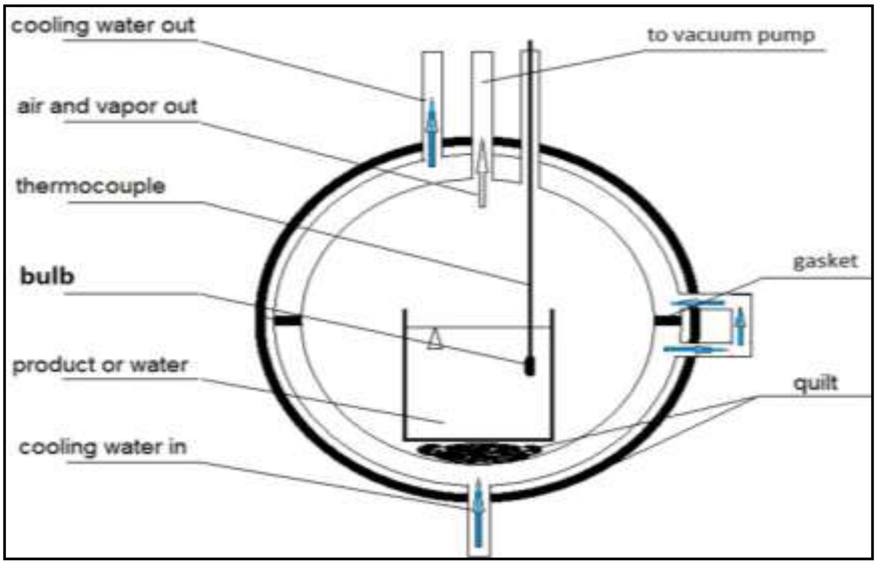

Figure (4) schematic giagram for the main chamber used in the second test rig.

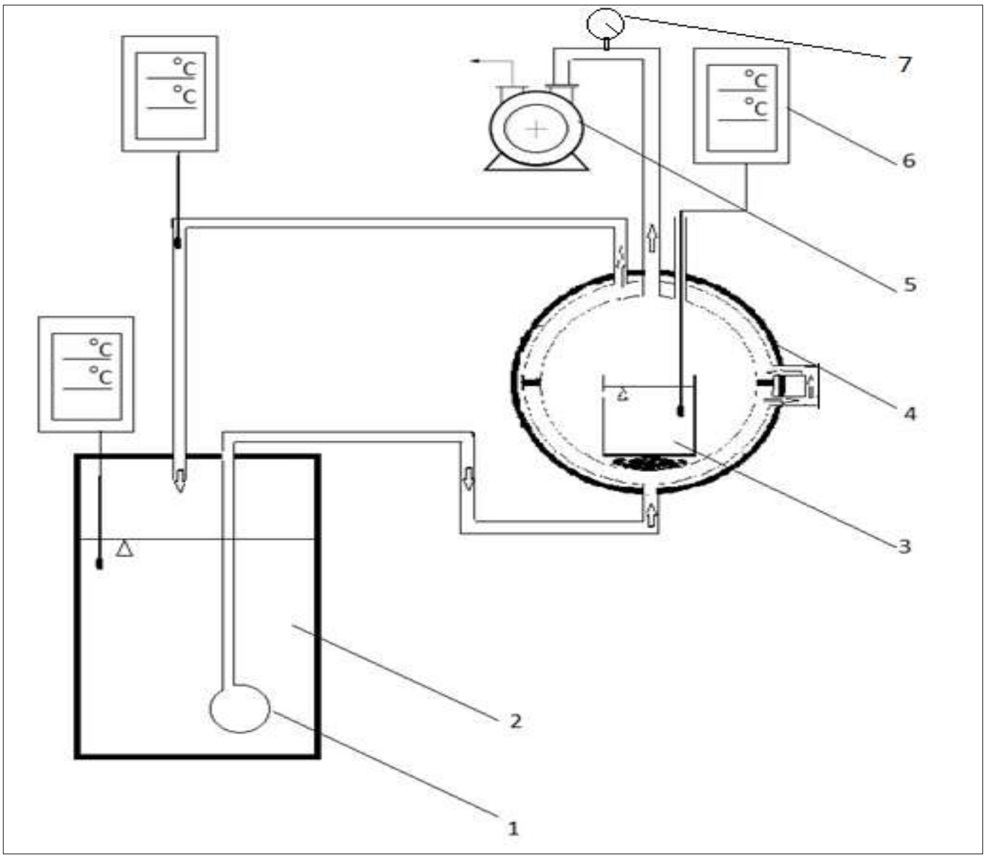

Figure (5) diagram of the second rig vacuum cooler demonstration unit.1 water pump; 2 cold water ; 3 product vessel ; 4 vacuum chamber; 5 vacuum pump; 6 thermometer; 7 pressure gauge.

THE TEST EXPERIMENTS

In the experiments test, the product was cooled in three ways. These methods are:

1 - Vacuum cooling only.

2 - Cooling the product through the cold water (1°C) passing through the thin channel in the main chamber without running the vacuum pump, and the pressure of chamber is at the atmospheric pressure. The wall acts as a cooler of the product by natural convective heat transfer.

3 - Cooling by using both previous ways vacuum pump with vapor condensation on the cold wall of the main chamber. It means that the wall work as a condenser in a vacuum cooler.

RESULTS& DISCUSSIONS

Experiments were carried out to compare the times of three types of cooling. Figure (6) shows the cooling curves of the different cooling methods.It can be seen that the minimum time required to reach 10°C is achieved by using cooling and evacuation (case No.3) comparing then the rest, that's because of vacuuming without cooling could maintain high specific volume of water vapor so it wasn't overcame by vacuum pump only.

The time of cooling product was 3535 second in the second case (free convection or refrigerator). In this case, the cooling rate depends only on the natural heat convection between the water surface and the cold wall of the chamber, But in the third case (vacuum pump and condensation of vapor), the time of cooling product was very rapid (263 second), because large amount of vapor can be removed by condensation, this means no need to use large vacuum to sweep the water vapor from chamber.

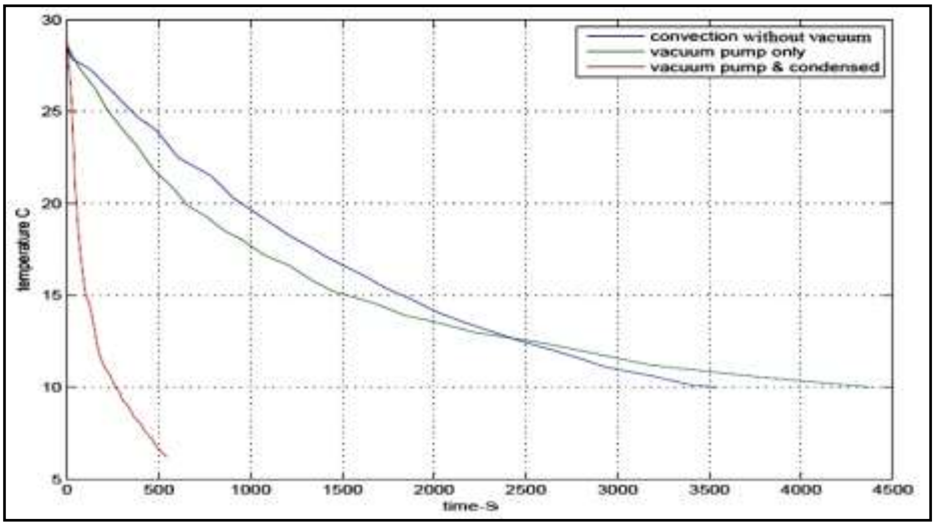

Figure (6) water temperature cooling time relation by three methods of cooling.

When comparing the first case with the third case, it can be found that the condenser has the greatest impact in accelerating the cooling rate, according to the conclusion reached by researcher Thompson [5]

Figure (7) presents the theoreticaltemperature – time dependence (a) and the rate of the percentage weight losses of water during vacuum cooling (b). It's show the trend of the two relations.

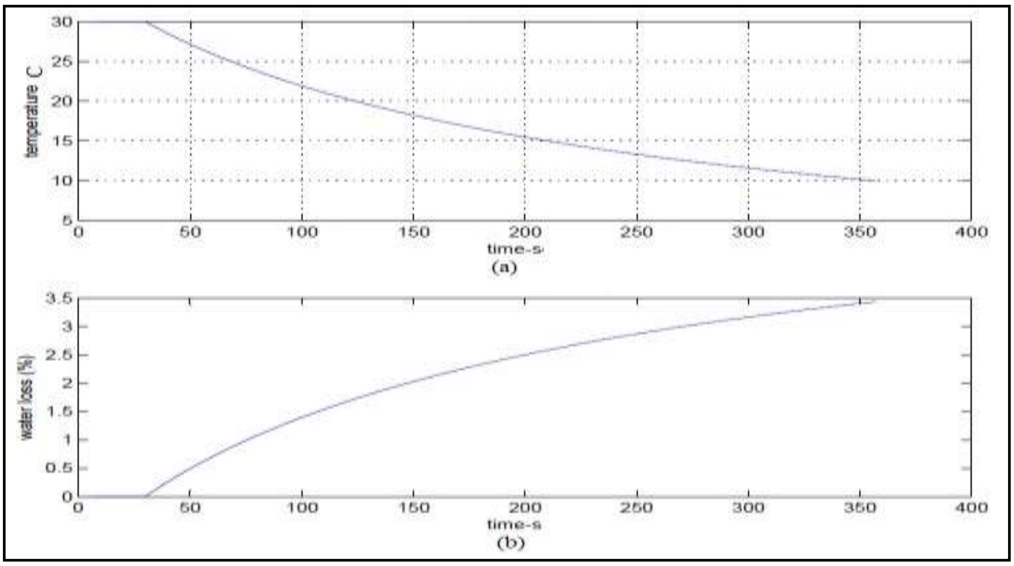

Figure (7) the predicted rate of the percentage weight losses during vacuum cooling.

The effect of condenser temperature on the cooling rates was shown in Figure (8). It can be seen that the cooling rate of the product was increased by reducing the condenser temperature. The time of these processes was 306, 336, 383, 464 and 674 second when the used temperature of condenser was 1, 3, 5, 7 and 9^{o}C, respectivelytocool the same amount of product from 30oC to 10^{o}C.

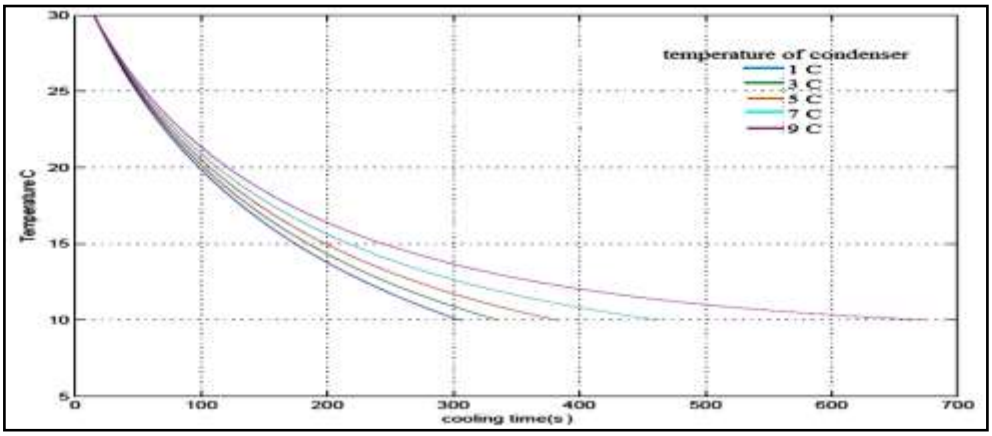

Figure (8) effect of temperature of vapor condenser on cooling rate during vacuum cooling.

The largest time of cooling process occurred when the condenser temperature was 9^{o}C, because the amounts of mass transfer from the product depend on the pressure difference between the saturation pressure of water (product) and pressure at the condenser temperature.

Figure (9) manifests the experimental and analytical relation between the times required for the vacuum pump operation and temperature of product. In general, the two curves reflect an acceptable matching with error about 10.7%. The difference between two curves might be occurred as a result of some assumptions, like no leak, no heat loss, and also may be due to some water spillage during boiling from the vessel (some of water drop leave the vessel) due to the flash evaporation of water. Thus, the mass of water was less than the initial mass, and the time of cooling in the experimental work was less than the time of computational program.

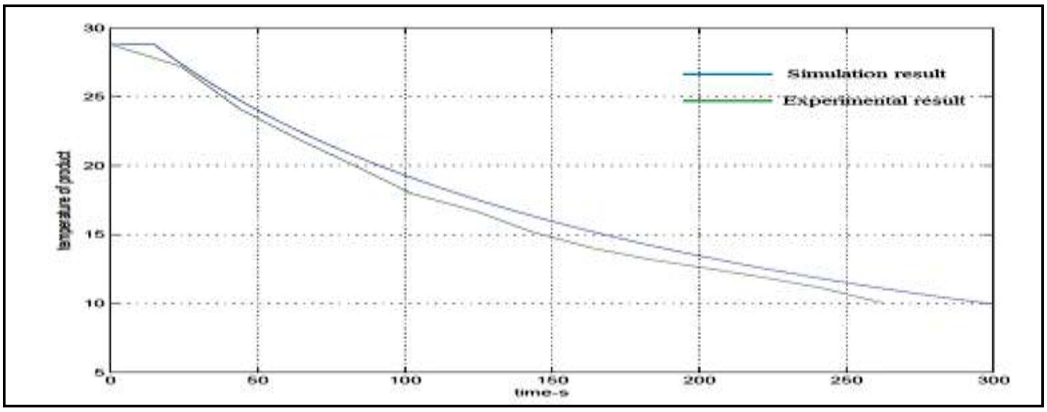

Figure (9) the variation of the temperatures of product by simulation and experimental data.

The relation between the time of cooling and surface area of product has a reverse behavior, as shown in Figure (10). This Figure includes the equation which states that.

Also the effect of mass of product on the cooling rates has been studied. The cooling rate of the product was increased with the reduction in mass of product. The time of these processes was 341, 668 and 995 seconds when the mass of product was 45, 90 and 135 g, respectively at the same cooling condition from 30ºC to 10ºC. The minimum time of cooling occurred when mass of product was 135g. The relation (linear) between the cooling time and the mass of product is ejective, as shown in Figure (11).

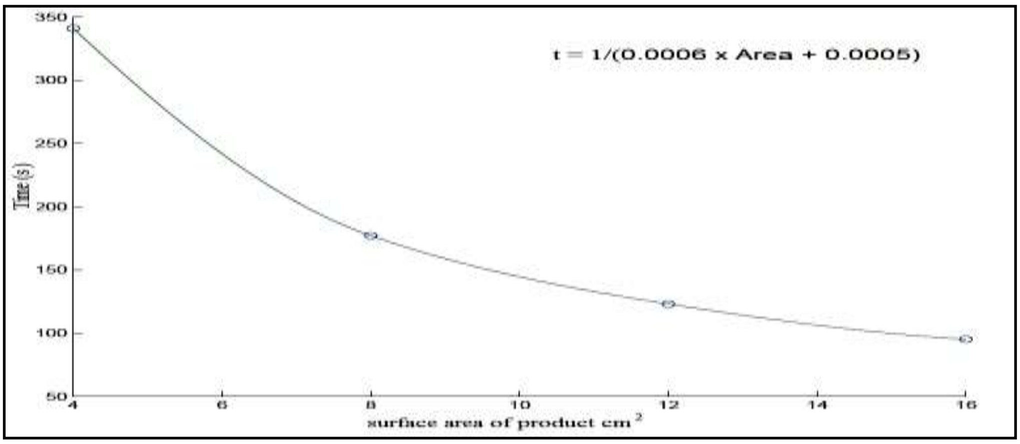

Figure (10) cooling time for various surface area of product during vacuum cooling.

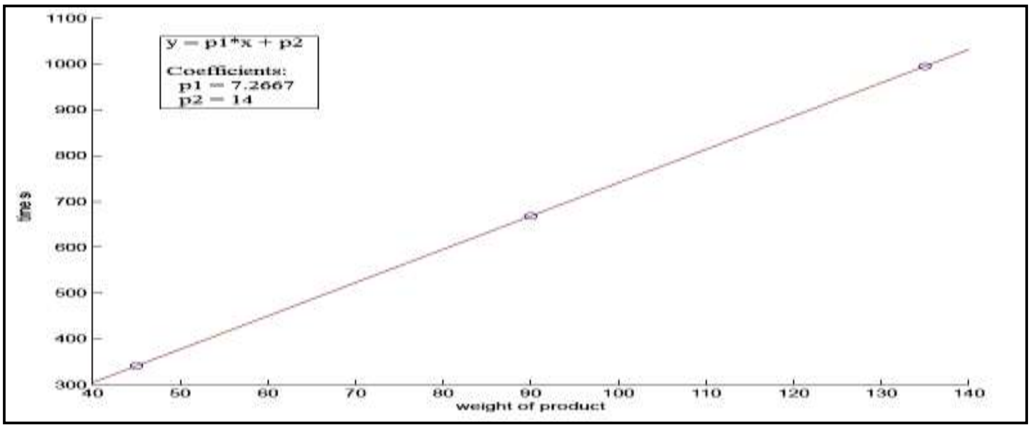

Figure (11) cooling time for various mass of product during vacuum.

CONCLUDING

The following points can be concluded from the present experimental and numerical work:

1. Vacuum cooling with condenser is a fast cooling of three systems test, which is about (13.7 times) faster than the system of natural convection cooling.
2. The existence of condenser is very important in vacuum cooling. It normally removes the large amount of water vapor generation.

3. The overall energy could be reduced by reducing vacuum pump capacity after commodity begins cooling
4. Vacuum cooling system had not needed to circulate the cooling medium through the systems, such as fan or pump, therefore energy saving could be occurred.
5. The condenser temperature affected significantly on the cooling time of product.
6. The cooling rates increased with increasing the product surface area and decreased with increasing product mass and condensing temperature.

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