DESIGN IMPROVEMENT IN VACUUM COOLING SYSTEM

S.W Zhang[1], A.R Abu Talib[1,*], A.S Mokhtar[1] and S.M Mustapa Kamal[2]
[1]Department of Aerospace Engineering, Universiti Putra Malaysia, 43400 Selangor, Malaysia
[2]Department of Food and Process Engineering, Universiti Putra Malaysia, 43400 Selangor, Malaysia
[*]Email: abrahim@eng.upm.edu.my

ABSTRACT

Food safety concern has been one of the keenest drivers of quality within the fresh produce industry shelf life. It is important therefore to remove field heat as quickly as possible. The principle of vacuum cooling is based on rapid evaporation of part of the moisture of the product under vacuum. Vacuum cooling can be used to shorten processing time, extend product shelf life, and improve product quality and safety. This paper first discussed the principle and equipment of vacuum cooling and critical analysis the merits of this technique compared to other traditional pre-cooling methods. Much effort is then spend on reviewing the design and development of this technology. Tests have been carried out on the vacuum and temperature levels on water by vacuum cooling process. The results clearly indicated the advantage of short pre-cooling time by this new design of vacuum cooling system compared to existing system.

Keywords: *Vacuum cooling, food safety, design and development*

INTRODUCTION

The concept of pre-cooling is to remove the respiration heat from vegetables immediately after harvesting, before they are transported to market or placed in a cold store. The temperature of the vegetables will be reduced quickly in a few minutes or a few hours, so that the vegetables can remain fresh [1-2]. In order to facilitate the rapid cooling of cooked foods, there are several different kinds of cooling system such as room cooling, forced –air cooling, hydro-cooling, package icing, evaporative cooling, and sources of cold water. As a common, these pre-cooling methods have a disadvantage slow process. The pre-cooling time by refrigerator was about 2~3 hr, for hydro-cooling and air blast, the pre-cooling time is about 1~2 hr and 10~12 hr [3]. And other demerits such as higher cost by forced –air cooling and package icing, biological pollutants by hydro-cooling and sources of cold water are also some main problems in using pre-cooling process.

As a new pre-cooling method, vacuum cooling stand out many merits in this area. It 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.

Vacuum cooling achieved through evaporating part of the moisture of the product under vacuum condition. The major characteristic of vacuum cooling is its exceptionally fast cooling rate, which is unsurpassed by conventional cooling methods. The principle of vacuum cooling consists in removing of the latent (evaporating) heat of a solvent (usually water), which implies a fast decrease of the cooled liquid temperature. To keep the evaporation process running, continual reducing of the total pressure in the equipment must be applied. It is based on the rapid evaporation of moisture from the surface and within the products. When water evaporates, it needs to absorb heat in order to maintain higher energy level of molecular movement at gaseous state. The amount of heat required is called latent heat, which must be supplied from the product or from the surroundings that consequently are refrigerated. The temperature at which water starts to evaporate is directly dependent on the surrounding vapour pressure [4], as shown in Table 1.

For any product containing free water, if it is placed in a closed vessel where pressure is reduced through a vacuum pump, the pressure difference between the water in the product and the surrounding will cause water to evaporate and the generated vapour to escape to the surrounding atmosphere. Since the product is in non-contact with other medium than air, latent heat required for evaporation is obtained by converting from the sensible heat of the product. Consequently temperature of the product will drop and cooling is thus achieved. The generated vapour must be continuously evaporated which would otherwise accumulate inside the vessel and cease the cooling process. The final product temperature can be controlled precisely through the regulation of the final surrounding pressure that is usually set at no less than 6.5 mbar for food produce; otherwise freezing may occur, causing damage to the produce [5].

Table 1: Boiling point of water at different pressure

Pressure (kPa)	**Temperature (°C)**
101.42	100
47.41	80
38.59	75
31.20	70
25.04	65
19.84	60
15.76	55
13.35	50
9.59	45
7.38	40
5.63	35
4.25	30
3.17	25
2.34	20
0.61	0

Vacuum Cooling System

A basic vacuum system integrates with the following components: main structure as vacuum chamber and vacuum pump; extended structure as mounting frame and seal; service components as power and air supplies and monitors as pressure sensor, thermocouples. The application in vacuum technology causes high demands on the selection of material as well as the fabrication of these components.

Materials selection

The materials used for vacuum cooling system, it should be smooth; low enough vapour pressure; does not include impurities and gas; not easy to adsorb gas and outgas; can be baked under high temperature and frozen under low temperature. Many factors need to be taken into account to select the suitable material to be used in the vacuum system; vacuum performance, mechanical strength (stability, hardness), thermal conductivity, magnetic permeability, surface resistivity, materials vapour pressure, how easy the material is for fabrication, joining and cleaning. Include these; material property requirements are basic and important, they are:

Mechanical Properties

The material must be capable of being machined and fabricated. It must have adequate strength at maximum and minimum temperatures to be encountered, and must retain its elastic, plastic, and/or fluid properties over the expected temperature range.

Thermal Properties

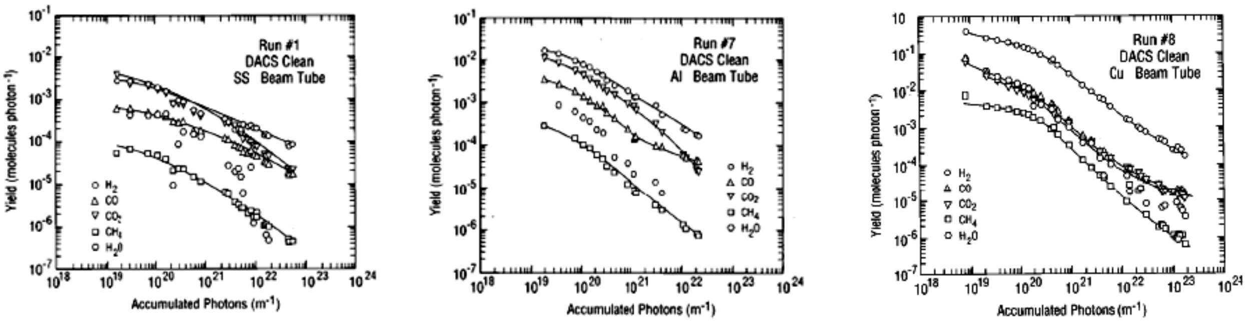
The material's vapour pressure must remain low at the highest temperature. Thermal expansion of adjacent materials must be taken into account, especially at joints.

Outgassing

Materials must not be porous. Materials must be free of cracks and crevices which can trap cleaning solvents and become a source of virtual leaks later on. Surface and bulk desorption rates must be acceptable at extremes of temperature and radiation.

Outgassing is also called gas loads. The performance of all vacuum systems is governed by the fundamental relationship $Q= SP$ (gas load in torr liters/sec. = pumping speed in liters/sec. × pressure in torr). It is obviously, when looking at the equation, that the pressure will be lower if either pumping speed is increased or the gas load is decreased. The pumping speed of a pump can be easily checked in the manufacturer’s specification and the effecting pumping speed at the chamber can be calculated fairly easily. The total gas load, though, is a little more elusive. This is due to the fact that each chamber design or process will have its own specific gas loads that will combine to make up the total that the pump is required to deal with. Although it is important to assess and control these gas loads in the design phase, it is also important to know and understand them in an already existing and working system.

Materials have in common consideration that the internal surfaces will be covered with layers of sorbed water molecules which will have to be desorbed during the pump down. Since most of the water molecules are sticking to themselves in a bed, the base material does not matter very much until enough water has desorbed to leave only a single monolayer on the surface. It needs a material that does not bond too strongly to the water molecules. This, along with surface desorption, is what called outgassing [6]. The main vacuum property to be discussed is the photon desorption yield and its reduction with beam dose, see Figure 1.



(a) stainless steel *(b) aluminium* *(c) copper*

Figure 1: Photon stimulation desorption yield reduction with accumulated beam dose for stainless steel, aluminium and copper

Commonly, the material use for vacuum has such as stainless steel, aluminium, copper [7]. It can be notice that almost all behave similarly, however copper and aluminium show higher photon desorption initially than stainless steel. It has been shown by experiments that a surface which has been vented after being ‘scrubbed’ by the beam will not give yields as high as a surface which has not been ‘scrubbed’, however, aluminium is the worst in comparison to stainless steel and copper.

Aluminium has good properties such as: it is easy for manufacturing by extrusion especially for long beam tubes and complex chambers, also it has good thermal conductivity and it is completely non magnetic. However aluminium has several disadvantages such as it has weak mechanical properties, higher desorption yield and it is difficult for joining.

Copper is used for UHV applications; it has good thermal conductivity but it has higher desorption yield compared to stainless steel. Also its production process is more complicated and expensive in comparison to aluminium.

Stainless steel is usually used for UHV applications. It has good mechanical strength, is easy to weld, and has high hardness and low outgassing rates. It also has a low magnetic permeability so it can be used within magnets. The thermal conductivity of stainless steel is very poor in comparison to copper and aluminium. Therefore, stainless steel is the better choice for fabricating vacuum chamber by comparison.

Vacuum Chamber Design

Shapes

Pressure chamber has several geometric shapes. It has spherical, cylindrical, cone-shaped and rectangular combination shapes. Compared with all the shapes, because of center symmetry, force apply on spherical chamber is most uniformly. At the condition of same thickness, spherical chamber has the best carrying capacity. On the other word, with the condition of same pressure, the thickness of spherical chamber is the smallest. At the condition of same cubage, spherical chamber has the smallest surface area. Thus, for fabrication, spherical chamber can save materials. According to all these characteristics, it seems spherical is best choice. However, since spherical is very hard to fabricate, welding, and the quality of welding is difficult to guarantee. The good performance of welding spherical is the main problem for the chamber, so looking to cylindrical which has almost same characteristics compared to spherical. Although carrying capacity of cylindrical is not good as spherical, but compared with other shapes, it is still the best. And most important is that cylindrical can be good welding by fabrication.

Minimum thickness

Vessel working with low pressure, if its thickness is too small by calculated with intension formula, maybe this cannot satisfy the requirement of manufactory, transportation and installation, and then must increase thickness, so generally there is a rule of minimum thickness. For carbon steel and low alloy steel vessel, if vessel's inner diameter Di≤3800mm, δmin≥2Di / 1000mm, but cannot less than 3mm (not include corrosion capacity) if vessel's inner diameter Di>3800mm, minimum thickness should follow the conditions of manufactory and transportation. For stainless steel chamber, δmin≥2mm and δmin≥3mm for aluminium chamber [8].

Vacuum Pump Selection

Vacuum pump is used to evacuate air from the vacuum chamber, during this process, it reduce the pressure in the vacuum chamber. Obviously, as another essential part of vacuum cooling system, the vacuum pump choosing is important, first of all, knowing about the classified by vacuum level is necessary. There are three main of vacuum level of vacuum pump, there are:

i) Roughing pumps such as rotary vane pump (atmosphere to 10^{-3} torr)
ii) High vacuum pumps (10^{-4} to 10^{-8} torr)
iii) Ultrahigh vacuum pumps (10^{-9} to 10^{-12} torr)

Roughing pumps are required by any vacuum process when it is necessary to reduce the pressure within the chamber from atmospheric pressure. This is, of course, true for both batch systems, which are cycled often and repeatedly, and systems that are pumped down and remain at high vacuum for long periods. Roughing pumps can be broken down in turn to oil-sealed and oil-free categories. At this point, can be as simple as deciding whether the possibility of oil contamination is of extreme importance or whether there are process gases that will react with the pump oil.

High vacuum pumps and ultrahigh vacuum pumps (UHV pumps) operate efficiently in the high vacuum region (less than 0.001 torr) and develop molecular flow, rather than physical mechanical compression, for highly evacuated systems. When selecting high vacuum pumps, configuration is an important specification to consider. Individual high vacuum pumps are designed for insertion into or use with a larger system or process. Combination pumps and multi-technology pumps can be used together for increased capacity or feature optimization. High vacuum pump systems and high vacuum pump stations include multiple pumps as well as piping, valves, controls, and receivers. Specifications high vacuum pump configurations include ultimate operating vacuum, pumping speed, motor power, and power source, number of stages, drive type, mounting style and features.

The available varieties of pumps seem to present a bewildering collection of choices, this requires a careful analysis of the process and its pumping needs before begin the elimination sequence. It also helps to breakdown the types of pumps into overall groups to simplify the process. When choosing the pump, the following should be considered: Significant specification includes pressure range, ultimate vacuum pressure, pumping speed; gas selectivity and operating mechanics includes gas transfer for high gas load, gas capture or HV and UHV pressure.

Vacuum level selection

The first major step in selecting the right vacuum pump is to compare application vacuum requirements with the maximum vacuum ratings of commercial pumps. At low levels, there is a wide choice of pumps. As vacuum level increases, the choice narrows, sometimes to the point where only one type of pump may be available. To calculate a system's vacuum needs, consider all work devices to be driven. The working vacuum of the devices can be determined by calculations based on handbook formulas, theoretical data, catalog information, performance curves, or tests made with prototype systems. Once know the vacuum required, and then can begin looking for pumps that can accommodate application requirements. Vacuum pump is working pressure ought to satisfy the vacuum level of the required vacuum chamber. Commonly, the vacuum level of vacuum pump needs to be twice of the required vacuum chamber. For example, the required vacuum chamber needs a vacuum level of 1×10^{-5} mmHg, the vacuum level of vacuum pump needs 5×10^{-6} mmHg.

Pumping speed selection

The pumping speed is the volume rate of the entrance [9]. The unit m^3/hr or liter/min is in common use for pumping speed. The value of the pumping speed effects the time used for chamber to achieve the required vacuum level. The pumping speed will go down as curve when the vacuum level goes up.

Ideal pumping

$$S = KS_t \tag{1}$$

Where, S is pumping speed, liter/min; K is safety factor (Figure 2), S_t is ideal pumping speed, liter/min (Figure 3)

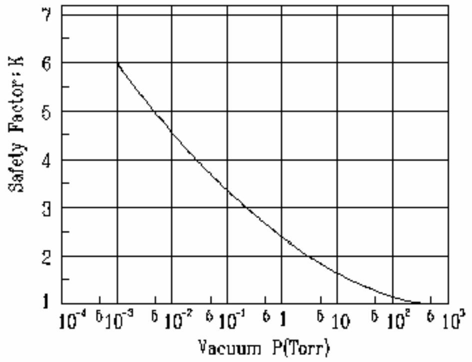


Figure 2: Diagram of vacuum pump safety factor K

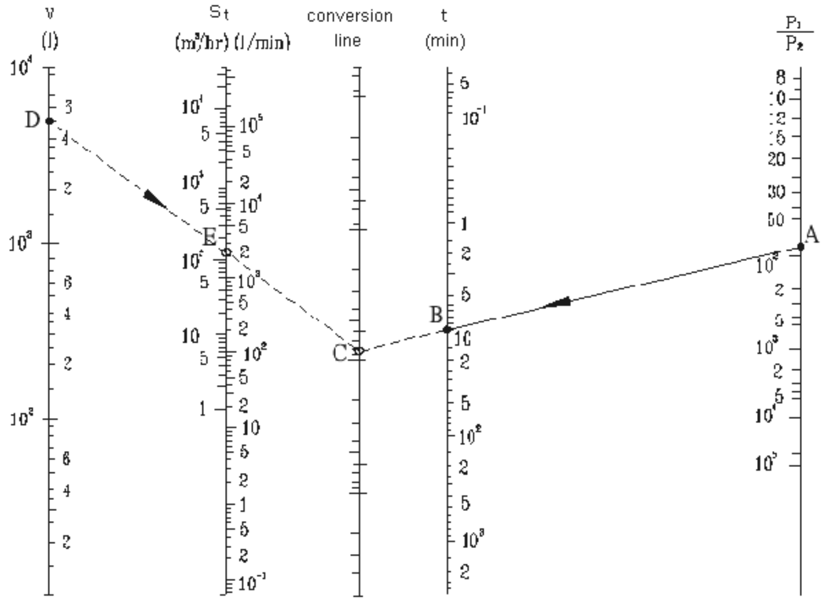


Figure 3: Pumping speed of ideal system

In Figure 3, where, P_1 is original pressure; P_2 is required vacuum pressure; t is time used for pumping to get the required vacuum; V is volume of vacuum chamber. For the case, there have three steps to define the pumping speed.

Step 1: point A (P_1/P_2) and point B (t) were made on Figure 3, a line was drawn through point A and B, the line was extended to conversion line, and to another point C.

Step 2: point D (V) was made on Figure 3, and then a line was drawn through point D and C. The line meets on S_t axis and through another point E which is the value of ideal pumping speed.

Step 3: the safety factor K can be checked on Figure 2 using the formula $S = KS_t$ to calculate the pumping speed S.

Pumping with leaking

$S = KQ/P$ (2)

where, S is pumping speed, liter/min; K is safety factor; Q is quantity of ingoing atmosphere, torr liter/min; P is required vacuum pressure.

For this case, it has two steps to define the pumping speed.

Step1: the volume rate of ingoing atmosphere is assumed to be 0.25liter/min, so the quantity of ingoing atmosphere Q = 0.25x760 = 190 torr liter/min.

Step2: the safety factor K can be checked on Figure 2 using the formula S = KQ/P to calculate the pumping speed S.

Selecting the right vacuum-pumping system for the vacuum cooling is important, before selecting of any vacuum pump, clearly define the application in order to determine a vacuum system solution to meet the specific needs. An important point of view is concerned to the needs to protect the process from the pump as it pertains to contamination, or the needs to protect the pump from the process as it pertains to reactive gas or dust, particulate, and corrosives. In vacuum cooling system, only foods are dealt with, such as water, fruits, vegetables and etc. During the vacuum cooling process, there will be a lot vapor from the cooling product. The vapour is not only can affect the vacuum grade, but also can break the vacuum pump. Most of oil-sealing vacuum pump cannot be used independently as it will be damaged by the vapor into the oil. So for the vacuum pump selection, vacuum pump system will be chosen, it is consisted by several vacuum pumps, for example water-ring vacuum pump series with a scroll pump or roots vacuum pump. As the process focus on the vacuum grade, the ultimate pressure of the vacuum pump is very important, it must be below 613 Pa which is the value boiling point of water at 0°C.

EXPERIMENTAL SETUP

The vacuum cooling system is shown in Figure 4.

1 Control panel
2 Vacuum chamber
3 Vacuum pump
4 Data acquisition system
5 Computer
6 Pressure transmitter
7 Digital display pressure switch
8 Temperature sensor
9 Pipe

Figure 4: Vacuum cooling system

Vacuum Chamber and Vacuum Pump

The vacuum chamber has two layers column stainless steel vessel with the rig is outer diameter 420 mm, inner diameter 390 mm, 490 mm height, 2 mm and 5 mm thickness for outer and inner layer respectively. Insulation foam Elastopor MH 2123 is inside the interlayer for the chamber modification of reducing heat exchange conductivity. The chamber also has rectangle window of 120 mm length and 130 mm height, and with elastomer seals on the window door, the chamber can be sealed from atmosphere leakage. The vacuum pump is connected onto the top of the chamber with a pipe 1.5 m length.

Pressure Instrumentation

The initial pressure of the inside chamber is measured with a SMC ZSE40F-01-62L digital display pressure switch sealed with the inner space of the chamber. This pressure switch can test the pressure range up to -1 bar to 1 bar. And the initial pressure also can be measure with a RS-YB2 absolute pressure transmitter with range -1 bar to 0 bar. Both of them can read the pressure value on computer and display respectively.

Temperature Instrumentation

The temperature is measure by a stainless steel platinum resistance thermometer with 6 mm diameter and 150 mm length. It is fixed on the top of the chamber with its probe inside the chamber. This thermometer can measure the temperature from -50 to 250°C.

The temperature sensor and the pressure transmitter are both connected to computer by Agilent 34970A BenchLink Data Logger. The operation procedures are controlled manually. While the pump motor is on or off, the shut off valve of solenoid will also be auto followed. This is to prevent the atmosphere and oil back to the chamber.

MATERIALS AND METHODS

In order to design an efficient vacuum cooling system, a study was carried out using a water fountain size vacuum cooling system to examine how cooling characteristics change by manipulating the vacuum and other factors. The trials were realized in vacuum pre-cooling experimental system consisted of vacuum chamber, vacuum pumps and measuring devices.

As the principle of vacuum cooling is based on water evaporation, this experimental was vacuum cooling of water. The temperature sensor was inserted into the water for a sensitive measurement of the temperature in the water during vacuum cooling process. The inside pressure in chamber was tested by both digital display pressure switch and pressure transmitter.

RESULTS AND DISCUSSION

The vacuum cooling of water was experimentally studied. The time–temperatures and time–pressure has been measured to predict whether the time of cooling is a size dependent parameter.

Vacuum Cooling of Water

When looking into the physics properties of water (Heat of Latent Evaporation of Water at Different Temperature), at a certain condition, the boiling point of water decreases as the ambient pressure goes down, but it is the heat of latent evaporation goes up. At 613 Pa which is the boiling point pressure of water at 0°C.
Under a certain state, 1 kg water increase 1°C needs to absorb the heat of latent evaporation is:

$$Q_{h1} = Cm\delta t = 4.186\times1\times1 = 4.186 \text{ KJ} = 1 \text{ Kcal} \qquad (3)$$

Nevertheless, under vacuum cooling process, the condition is changing; water needs to absorb heat of evaporation to turn into gas. Under the changing state, the heat 1 kg water needed to absorb to turn into gas at 10°C is:

$$Q_{h2} = mr_{LG} = 1\times591.5 = 591.5 \text{ Kcal} \qquad (4)$$

Compare Q_{h2} and Q_{h1}:
$Q_{h2}/ Q_{h1} = 591.5 \text{ Kcal}/1 \quad \text{Kcal} = 591.5$

The process to get to vacuum is 50 s shown in Figure 5 and 6, when the pressure got -1 bar, it presented steady afterwards. Below the atmosphere pressure, water began to evaporate continuously. Figure 7 shows the water reached 0°C at 25 min. And form the above calculations, it tells us that the heat absorbed by water when it is changing into gas is almost 600 times bigger than water at liquid state get 1°C increased.

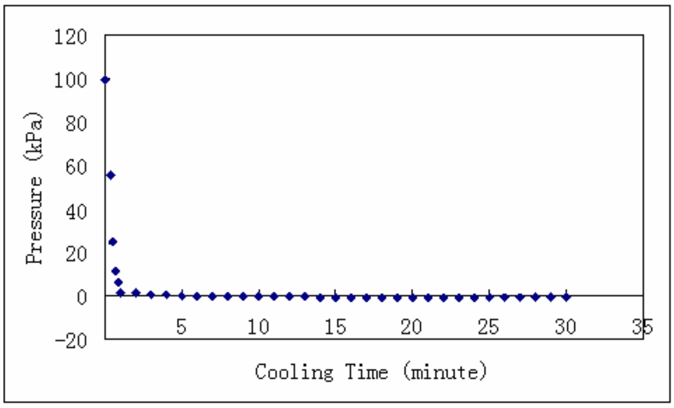


Figure 5 Experimental results of water in vacuum cooling P-t diagram

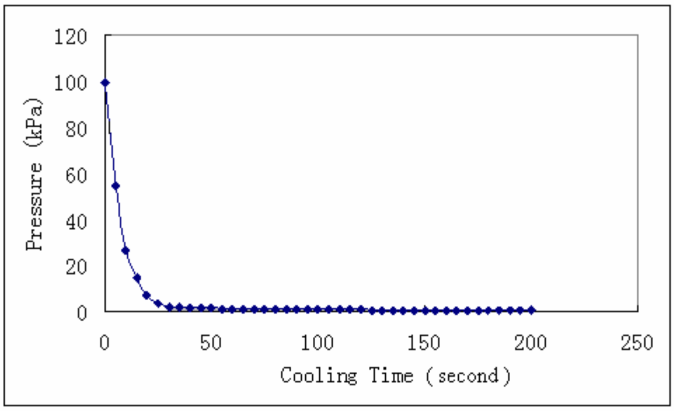


Figure 6 Time of water in vacuum cooling to reach vacuum

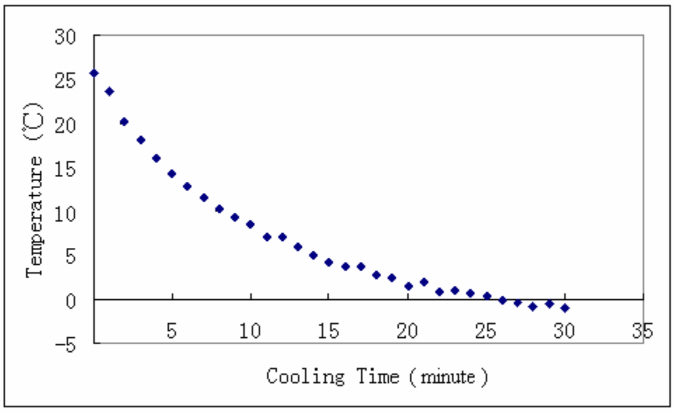


Figure 7 Experimental results of water in vacuum cooling T-t diagram

CONCLUSION

A vacuum cooling system has been design and successfully operated. For the system design, low outgassing rates of material selection, pumping speed and vacuum level for vacuum pump selection are the main considerations. The experimental work successfully reached the function of vacuum cooling system. It is demonstrated that pre-cooling by this method is short compared to conventional cooling method. As vacuum cooling is innovative cooling technique, better equipment design and process control will make this technology even more attractive. It is expected that its usage will become more competitive and widespread in future.

ACKNOWLEDGEMENT

The work is funded by the Ministry of Higher Education Malaysia under the Fundamental Research Grant Scheme project no. 5523392.

REFERENCES

[1] Gao, L. P., Zheng, S. F., Li W., Jiang Y. and Qu K. Y., 2003, Application and Design of Forced-air Pre-cooling Equipment and Technology for Fruits and Vegetables, Transactions of the Chinese Society of Agricultural Engineering, 19(6): 185-189.

[2] Ma, Z., Yang, Z, Zhao C. E and Zhu, B. Q., 2007, Research Advances in Forced-air Pre-cooling Equipment for Fruits and Vegetables, Food and Machinery, 23(2): 114-117.

[3] Karen, L. B. G. and Rolando F., 1991, Pre-cooling Procedure: Fruits and Vegetables, Postharvest Management of Commercial Horticultural Crops report, Kansas State University, Manhattan.

[4] Xue, X. Z. and Wang, Z. J., 1993, Studies of Development of Vacuum Conception, Natural Communication, 1: 59-66.

[5] McDonald, K. and Sun, D. W., 2001, Effect of Evacuation Rate on the Vacuum Cooling Process of a Cooked Beef Product, Journal of Food Engineering, 48: 195-202

[6] John, F.O., 2005, Pumping Speed, A User's Guild to Vacuum Technology, 123-132.

[7] Halliday, B. S., 2000, An Introduction to Materials for Use in Vacuum, R and D magazine, 37(8): 583-585.

[8] Zhou, Y. A. and Wang, Y. F., 1999, Design and Calculation of Vacuum Proceeding Freeze Equipment, Refrigeration, 56(3): 36-40.

[9] Van Atta, C. M. and Hablanian, M., 1991, Vacuum and Vacuum Technology, Encyclopaedia of Physics, 2: 1330-1333.