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# Numerical study on a cryogenic treatment process with near-zero loss of cold energy

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**Abstract.** Cryogenic treatment generally means that the material is held at a cryogenic equipment for a given soaking time and temperature, then heated to room temperature to improve the mechanical properties. In this paper, a cryogenic treatment process with near-zero loss of cold energy is proposed, and then an equipment is designed according to the proposed process. The operational characteristics of the designed equipment, such as temperature field and cold energy recovery rate, are verified by using CFD. The calculations show that the recovery rate of cold energy can get close to 100%, but it is difficult for materials to be processed according to a given process because of the uncontrolled diffusion of heat. Then, this paper further discusses improvement schemes: replenishing a certain amount of cold energy in the space where the material is cryo-treated, and setting some gas vents at a certain position in the middle of the device to reduce the amount of air that transports cold energy.

## 1. Introduction

In cryogenic treatment, the finished or half-finished workpieces are cooled from room temperature at an appropriate cooling rate to the temperature of liquid nitrogen (around 77K) [1], kept at that temperature for an appropriate period of time, and then warmed up to room temperature or higher at a proper rate [2]. Cryogenic treatment is mainly applied to alloy steels, tool steels, copper alloys and sintering alloys [3]. The treatment can be carried out using cryogenic equipment with different refrigerator depending on the temperature range [4]. Cryogenic treatment equipment is a device that can cool and warm materials with a specific process. Liquid nitrogen (LN<sub>2</sub>) has become a commonly used refrigerant in cryogenic treatment equipment with the advantages of low temperature, easy acquisition, low cost and no pollution. LN<sub>2</sub> immersion type is used to cool down parts at 77K during conventional cryogenic treatment [5]. The LN<sub>2</sub> gasification type is divided into radiation heat exchange, convection heat transfer, and radiation and convection combined. What is used by Yan X.G. is one of the conventional equipment (process 1) [4]. Heat transfer between nitrogen and materials generated after LN<sub>2</sub> vaporization. After heat exchange with the material, the relatively hot nitrogen gas is discharged to the atmosphere from the exhaust port [6]. Conventional cryogenic treatment equipment is not continuous in processing, and the low-temperature nitrogen with relatively high heat exchange rate is directly discharged into the air. Therefore, there are two disadvantages of the conventional cryogenic treatment equipment: (1) the cold nitrogen can't be recovered after the workpiece is processed, resulting in waste of cold energy. Especially for large cryogenic treatment equipment, whose treatment volume is large and treatment frequency is high. (2) Cryogenic treatment and subsequent processes usually need to be carried out separately resulting in the production efficiency is low.

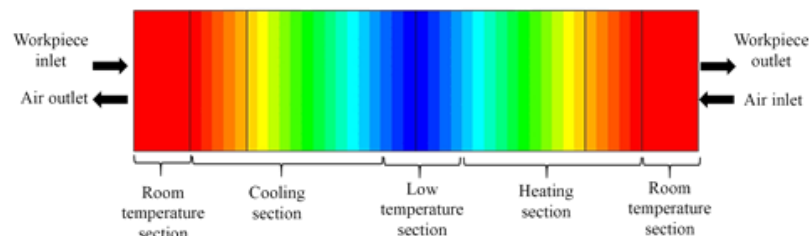
This paper proposed a cryogenic treatment process, which could achieve near-zero loss of cold energy. The cryogenic treatment process solved the problem that cold energy could't be recovered after the workpiece was processed and low production efficiency. Taking the cryogenic treatment of M2 taps as an example, CFD numerical simulation was carried out to calculate temperature field of the equipment for ideal cryogenic process. Then some improvements were proposed to achieve near-zero loss of cold energy and meet the requirements of cryogenic process.



## 2. A cryogenic treatment process with near-zero loss of cold energy

### 2.1 The conception of cryogenic process with near-zero loss of cold energy

What Figure 1 shows is a conception of cryogenic treatment process with near-zero loss of cold energy, for the workpiece: It enters from the left end and is gradually cooled by the cold air to the set temperature. After a period of low temperature heat preservation, it is gradually heated by the hot air and then removed from the right end. For working gas (air) used to transfer heat: the air at room temperature enters from the right end, and its temperature gradually decreases due to heat exchange with the workpiece with lower temperature; after passing through the cryo-treatment space, then the temperature is gradually raised to room temperature due to heat exchange with the workpiece with higher temperature and then discharged. Therefore, whether it is a workpiece or air, it is room temperature when entering the equipment, and it is still room temperature when the device is discharged, so that the theoretical recovery of the cold energy can reach 100%. In addition, the processing of this equipment is continuous, which can improve the processing efficiency of the workpiece.



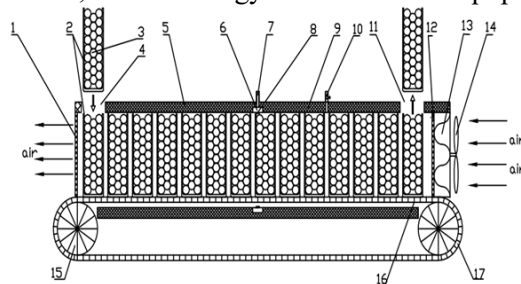
**Figure 1.** The ideal cryogenic treatment process with near-zero loss of cold energy

### 2.2 A structure of the cryogenic treatment equipment

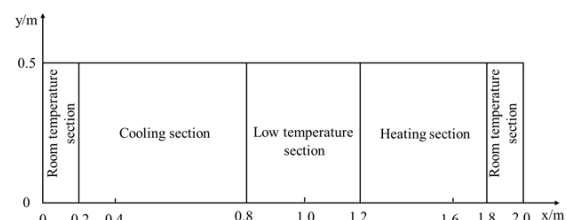
According to the theoretical conception of cryogenic process, an equipment structure is designed, as shown in Figure 2. LN<sub>2</sub> is to refrigeration, and hot air is to tempering. Controlling the supply of LN<sub>2</sub> and hot air into the equipment can achieve the processing temperature gradient and uniformity. Cryogenic treatment equipment includes: LN<sub>2</sub> storage tanks, tube, magnetic valve and controllers. The cryogenic cabinet is made of stainless steel, where inner and outer layers are filled with a rigid polyurethane foam insulation material. CFD numerical simulation is used to study whether the process is feasible.

## 3. Mathematical models

M2 taps (composition is given [4]) have to be cryogenic treated in industry. The hardness and wear resistance of the parts after the cryogenic treatment will be further improved, as well as the wear resistance can be improved by 40% [4]. Taking the cryogenic treatment of M2 taps as an example, the equipment is improved. The cryogenic equipment is simplified as a cuboid of 2×0.5×0.5 m, as shown in Figure 3. The bulk density of taps is 36.08%. The zone at x=0~0.2 m and x=1.8~2.0 m is room temperature, so cold energy is stored in the equipment. The zone at x=0.2~1.8 m is divided to cooling

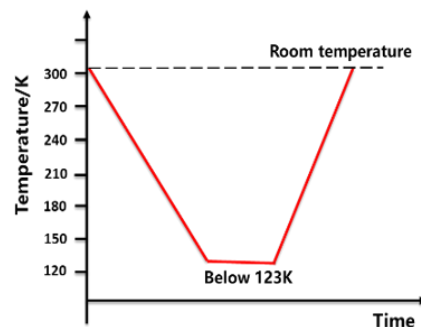


**Figure 2.** The structure of the equipment



**Figure 3.** Cryogenic processing equipment model

(1- hot air outlet; 2- hopper; 3- workpiece; 4- hopper inlet; 5- cryogenic cabinet; 6- cryogenic fluid inlet; 7- tube; 8- nozzle; 9- temperature sensor; 10- gas vents; 11- hopper outlet; 12- hot air inlet; 13- gas heater; 14- fan; 15- turning wheel; 16- weight sensor; 17- conveyor belt)



**Figure 4.** Deep cryogenic treatment process of M2 taps

section, low temperature section and heating section. M2 taps need to be cryogenically treated in 77K~123K for a period of time. What is shown in Figure 4 is one of commonly used cryogenic treatment process. The workflow is simplified as follows. (1) The process requires at least 20 min at a temperature not higher than 123k, then M2 taps are tempered by room temperature hot air; (2) It is calculated that the conveyor belt advances 0.2m each time to meet low temperature preservation time. Taps that has been processed were removed in the right end, and the left end is loaded with taps to be processed. Thermophysical parameters of M2 taps are imported to the CFD software [7]. M2 taps in the equipment are porous material, formed of a solid skeleton whose voids are partly filled with air or  $N_2$ . Porous media modeling should consider the multiphase nature of these materials, several physical as well as chemical phenomena, and the pore-scale physics [8].

## 4. Numerical results and discussion

### 4.1 Ideal cryogenic process (process 2)

In ideal conditions, cold energy can be used infinitely being input into the equipment only once without cold energy loss. Assume that the initial temperature distribution in the equipment is as shown in Figure 5 (A). When the flow of 303K hot air is  $339.81\text{m}^3/\text{h}$ , the temperature distribution in the equipment after running 20 minutes is shown in Figure 5 (B). It can be seen that the temperature at  $x=0\text{ m}$  and  $x=1.8 \sim 2.0\text{ m}$  are close to room temperature. The workpiece is at low temperature at  $x=0.8\sim 1.4\text{ m}$ . There are 3 problems with this ideal cryogenic process.

Problem 1: Due to uncontrolled diffusion of heat, the low temperature of equipment ( $x=0.8\sim 1.4\text{m}$ ) gradually increases and becomes greater than 123 K.

Problem 2: The range of the room temperature and low temperature sections are changed because of unreasonable hot air flow. The temperature is lower than room temperature at  $x=0 \sim 0.2\text{ m}$ . The range of low temperature section is reduced.

Problem 3: The temperature of some part of the room temperature zone ( $x = 1.8 \sim 2.0\text{ m}$ ) did not reach room temperature.

### 4.2 Equipment improvement

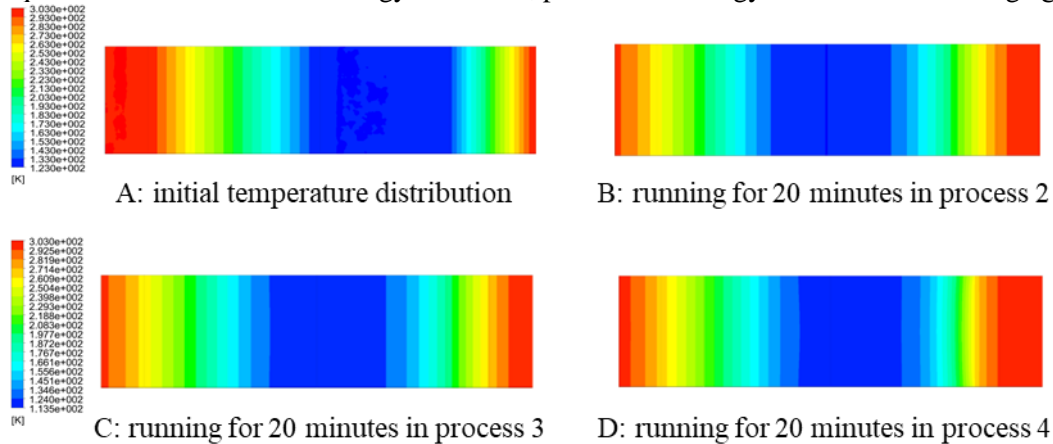
In view of the problems in Figure 5 (B), some improvements are proposed: replenish cold energy, set some gas vents, increase the axial length of the equipment and the low temperature section.

#### 4.2.1 Replenishing cold energy (process 3)

Replenishing cold energy to the low temperature section for problem 1. Setting the supercooling of 10K, the model is simplified by adding 113K  $N_2$  into the low temperature section through the cryogenic fluid inlet(9). It is calculated that low temperature can be maintained when the flow rate of  $N_2$  is  $35.25\text{m}^3/\text{h}$ . For problem 2, reduce the hot air flow to  $247.21\text{m}^3/\text{h}$ . Taking Figure 5 (A) as the initial state, the temperature field after running 20 minutes is shown in Figure 5 (C). It can be seen the lowest temperature lower than 123K. In order to avoid cold energy going out of the equipment, the hot air flow will be reduced to  $247.21\text{m}^3/\text{h}$ . Finally, the temperature at  $x=0\text{ m}$  will be close to room temperature after running 20 minutes. However, part of the workpiece on the right side of the equipment ( $x=1.8 \sim 2.0\text{ m}$ ) isn't tempered to reach room temperature.

#### 4.2.2 Set some gas vents (process 4)

For problem 2 and 3, two gas vents (10) of 0.02 m diameter are set as shown in Figure 2. Taking Figure 5 (A) as the initial state, the flow of 113K N<sub>2</sub> is 35.25m<sup>3</sup>/h, while the flow of 303K hot air is 463.52m<sup>3</sup>/h. Conclusions after running 20min are shown in Figure 5 (D). Temperature are close to 303K at x=0m and x=1.8~2.0m. The workpiece is cryogenically treated at low temperature. Process 4 meets M2 requirements and saves cold energy. However, part of cold energy will be wasted through gas vents.



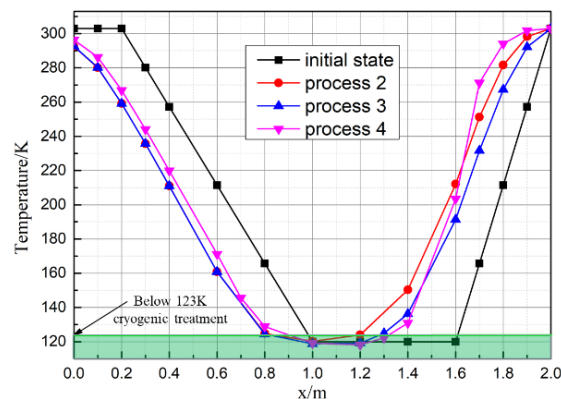
**Figure 5.** Temperature distribution of the equipment after running for 20 minutes in different process

#### 4.2.3 Other improvements

Increase the axial length of the equipment and the low temperature section. If the axial length of the equipment increases to a certain extent (process 5), cold energy will be stored in the device with minimal loss. However, it is still necessary to replenish cold energy. Increasing the length of the low temperature section (process 6), internal cold energy is sufficient to circulate. At this time, the advancement speed of processing workpieces have to be accelerated to meet the process requirements. However, this method is only suitable for workpieces with a relatively small specific heat and thermal conductivity.

#### 4.3 Comparison of different cryogenic process

Figure 6 shows the average temperature of different cross sections in the x direction in the initial state and process 2~4. The area of 123K and below increases after replenishing cold N<sub>2</sub> in process 3 and 4. Comparison of cold energy recovery in different process is shown in Table 1. Compared with LN<sub>2</sub> consumption, the power consumption of fans is too small. Only cold energy recovery of LN<sub>2</sub> is taken into consideration. The conventional treatment (process 1) can meet the cryogenic process while most energy wasted. Cold energy recovery is close to 100% but low temperature section will decrease in process 2. Cold energy recovery is close to 100% but the tempering temperature can't meet in process 3. Process 4 is the best and feasible for the cryogenic treatment, which can meet the requirements, and cold energy recovery is close to 100%. Anyway, process 5 and 6 will meet the requirements theoretically.



**Figure 6.** Average temperature values at different cross sections in the x direction

**Table 1.** Comparison of cold energy recovery in different cryogenic process

Cryogenic treatment process	Hot air flow (m <sup>3</sup> /h)	Meet the cryogenic process (Yes / No)	Exhaust gas temperature after running 20min (K)	Cold energy recovery
The conventional treatment (process 1)	-	Yes	123~240	<<100%
A cryogenic treatment process with near-zero loss of cold energy	process 2	No	293	<100%
	process 3	No	293	<100%
	process 4	Yes	296	<100%
	process 5, process 6	Yes	303	100%

## 5. Conclusion

This paper proposed a cryogenic treatment process with near-zero loss of cold energy. The process is as follow: the workpiece to be processed enters from the left side through the room temperature section, the cooling section, the low temperature section, the heating section and the room temperature section; in order to maintain the process, the room temperature air enters from the right side through equipment. Taking the cryogenic treatment of M2 taps as an example, CFD was carried out to study the equipment and some improvements were proposed. Conclusions are as follow. (1) Cold energy in the low temperature section will decrease in ideal cryogenic process (process 2). (2) Cold energy recovery is close to 100% but the tempering temperature can't meet when only adding cold energy to the low temperature section (process 3). (3) It is the best and feasible for the cryogenic treatment when replenishing cold energy and setting two gas vents on heating section (process 4), in which cold energy recovery is close to 100%. Numerical improving showed that cryogenic treatment process can achieve near-zero loss of cold energy and meet the requirements of cryogenic process. The specific equipment structure design is determined according to the process requirements.

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