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Selection of working fluid for cryosurgical probe considering biological heat transfer

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Abstract-- **This paper describes the sensitive cooling performance change of J-T refrigerator for cryosurgical probe due to its working fluid. The analytical results of using 50 bar nitrous oxide are compared with the case of 300 bar argon. Bio-heat equation is numerically solved to investigate the effect of the probe temperature and the cooling power of the J-T refrigerator. The refrigerator using 50 bar nitrous oxide has larger cooling power above 185 K than the one with 300 bar argon, which enables fast cooling at early stage of cryosurgery, but the biological tissue away from the probe tends to be cooled slowly after the probe reaches its lowest operating temperature. When the repeated freeze-thaw cycle is employed for main tissue destruction mechanism, using high pressure nitrous oxide is more advantageous than argon if the freezing operation is within 2-3 minutes. The probe with high pressure argon is more suitable for the case of longer freeze-thaw cycle with fewer repetitions.**

1. INTRODUCTION

Cryosurgery is a medical operation method of using cryogenic temperature to destroy an abnormal tissue. The thin sharp cryosurgical probe is inserted into a body like a needle, and the probe tip touches a malignant tumor. The tumor cell is to be destroyed by the cryogenically cooled probe tip. J-T refrigerators are effectively applicable to the cryosurgical probe because they have so simple structure to be easily fabricated in small scale. They also have no vibration and electromagnetic interference at the probe tip [1].

It is known that the cell lethality is higher as the cell is exposed to lower temperature with fast cooling rate [2]. Thus, it is important to make a cryosurgical probe to possess large cooling power as well as low operating temperature.

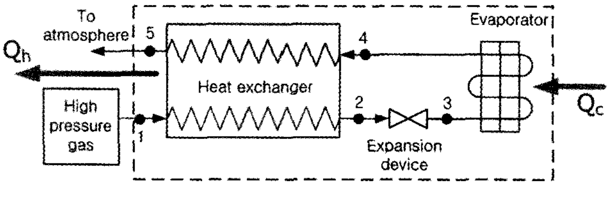

Fig. 1. Thermodynamic analysis of J-T refrigerator.

The characteristics of J-T refrigerator strongly depend on the thermodynamic properties of the working fluid [3]. The lowest operating temperature of J-T refrigerator is the same as the boiling temperature of the working fluid, and the cooling power is equal to the enthalpy difference at the hot end of heat exchanger (Fig. 1). The ideal cooling power of J-T refrigerator using 300 bar argon and that of J-T refrigerator using 50 bar nitrous oxide are presented in Fig. 2 with the assumption of perfect heat exchanger which has no pressure drop and infinite heat transfer area.

As shown in Fig. 2, the J-T refrigerator with lower boiling temperature has smaller cooling power (argon), but the one with higher boiling temperature has larger cooling power (nitrous oxide). In the design of cryosurgical probe, it is important to select an appropriate operating temperature with the cooling power in consideration of destruction mechanism of malignant tissue.

In this paper, the design issue of J-T refrigerator is investigated in conjunction with thermal properties and heat transfer in a biological tissue. The comparison between the J-T refrigerator using 300 bar argon and that using 50 bar nitrous oxide is performed with numerical analysis. The results are discussed to design an efficient cryosurgical probe.

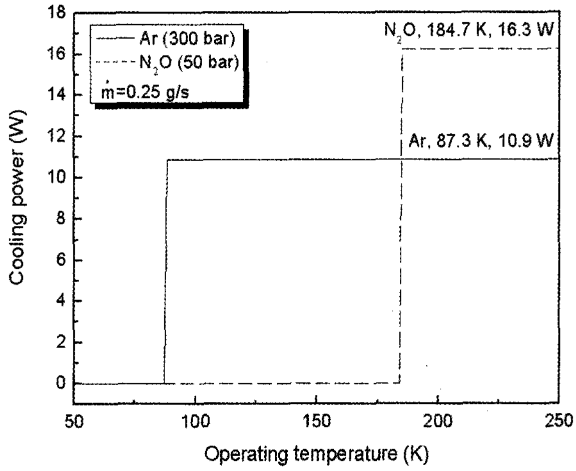

Fig. 2. Cooling performance of J-T refrigerators with different working fluids.

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2. ANALYTICAL METHOD AND RESULTS

2.1. Bio-heat equation

Pennes' bio-heat equation [4], which is well-known in bio-heat transfer research area, can be expressed as (1) in 1-D cylindrical coordinates (Fig. 3).

$$\rho c\frac{\partial T}{\partial t}=\frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+w_b\rho_b c_b\left(T-T_b\right)+\dot{Q}_m \qquad (1)$$

where ρ, c, and k indicate the density (kg/m^3), the specific heat (J/kg·K), and the thermal conductivity (W/m·K) of tissue, respectively, and w_b and $\dot{Q}_m$ express the blood perfusion rate per unit tissue volume (m^3/s·m^3) and the metabolic heat generation (W/m^3). The subscript b expresses the property of blood.

As written in (1), the cooling rate of tissue is related to the heat capacity of tissue itself, the relevant conduction with the neighboring tissues, the perfusion rate of blood, and the metabolic heat generation. The heat transfer in tissue is greatly influenced by its thermal properties like density, specific heat, and thermal conductivity. Those properties, however, are hard to be precisely defined because they depend on the state or the kind of tissue or the experimental environment. The heat transfer in tissue can be varied by the uncertainty of those properties [5]. In this paper, the analysis is carried out with the properties expressed in Table 1 [5-10]. They are chosen as the most acceptable values for the prostate cancer which is commonly treated in recent cryosurgery field.

The boundary condition is set like (2) and Fig. 3, which indicates that the tissue temperature of the probe side is same as that of the probe (dia.: 1.6 mm), and the tissue temperature of the other side, 10 cm away from the probe, is not affected by the cryosurgery operation [11].

$$T_{r=0.8\text{ mm}}=T_{prb},\quad T_{r=10\text{ cm}}=T_{body}=310\text{ K} \qquad (2)$$

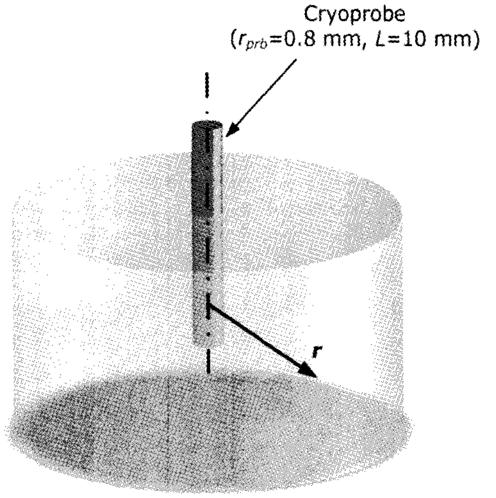


Fig. 3. Schematic diagram of cryosurgical probe.

TABLE I
THERMAL PROPERTIES OF TISSUE.

State	Unfrozen: $T > 273.15$ K
	Mushy: $251.15\text{ K} < T \le 273.15$ K
	Frozen: $T \le 251.15$ K
ρ (kg/m^3)	Unfrozen: 1000
	Mushy: $3.773T - 30.52$
	Frozen: 917
c (J/kg·K)	Unfrozen: 3600
	Mushy: Parabolic fitting*
	Frozen: $5.34T + 584.67$
k (W/m·K)	Unfrozen: 0.485
	Mushy: $-0.083407T + 23.268$
	Frozen: $2135T^{-1.235}$
$\rho_b w_b c_b$ (W/m^3·K)	Unfrozen: 20000
	Mushy: $909.091(T - 251.15)$
	Frozen: 0
$\dot{Q}_m$ (W/m^3)	$170 \times 2^{(T-310.15)/10}$

* $-126.343(T-262.451)^2+18061.8$
(Latent heat: 285 MJ/m^3)

The probe temperature is defined as (3).

$$(\rho c)_{prb}\frac{\partial T_{prb}}{\partial t}=2\pi r_{prb}Lk\left.\frac{\partial T}{\partial r}\right|_{r=0.8\text{ mm}}-\dot{Q}_c\left(T_{prb}\right) \qquad (3)$$

Subscript prb means the cryosurgical probe, L is the effective length of the probe (m), and $\dot{Q}_c$ is the cooling power (W) at the probe temperature. The configuration of the probe is assumed as a stainless steel 304 rod of 1.6 mm diameter and 10 mm length, and the temperature dependency of heat capacity is also considered as Fig. 4 [12]. The last term of (3), the cooling power of J-T refrigerator, is assumed as presented in Fig. 2.

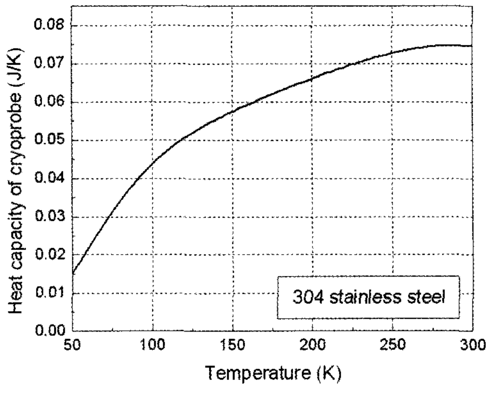


Fig. 4. Heat capacity of cryosurgical probe.

Unlike Fig. 2, however, the actual operating temperature of J-T refrigerator is higher than the expected value due to pressure drop of heat exchanger. Moreover, the cooling power becomes smaller because the heat exchanger effectiveness cannot be 100% owing to finite heat transfer rate, axial conduction, large pressure drop, and so on. These degradation effects, however, are not considered in this paper because our main concern is to focus on the fundamental different characteristics of the working fluids. In the transient operation of cryosurgical probe, the cooling power may be also smaller than the estimated value due to heat capacity of heat exchanger, but it does not result in appreciable error in our calculation.

In the numerical analysis, the Crank-Nicolson method is used. The number of generated grid and the time step are 5000 and 0.005 s, respectively, to obtain more reliable results. In our results, the percent relative errors calculated by the comparison between previous approximation and current approximation are less than 0.5% in both cases of using argon and nitrous oxide.

2.2. Numerical results and discussion

Typical numerical analysis results are depicted in Fig. 5. The probe and the neighboring tissues are cooled quickly for the case of nitrous oxide because of its cooling power, but the overall cooling rate of distant tissues is slow after the probe reaches its lowest operating temperature. The argon J-T refrigerator has slower cooling rate than the nitrous oxide one due to its small cooling power, but its expansion temperature continuously decreases during 1200 s-operation so that the neighboring tissues ultimately cool down further.

The performance of cryosurgical probe can be evaluated by the size of ice-ball, and it can form its propagation speed. The analysis result of isothermal surface propagation is shown in Fig. 6 to examine the extent of cell-lethal temperature (233 K to 273 K) region.

The nitrous oxide J-T refrigerator has a better performance than the argon J-T refrigerator initially (Fig. 6); whereas the argon J-T refrigerator has a better performance as time goes on. The difference of their performance is not noticeable in the comparison of 273 K isothermal surface propagation, but the greater difference is observed for the lower temperature isothermal surface as shown in Fig. 6.

2.3. Discussion for cryosurgery

All the propagation speeds in Fig. 6 are very slow even though the performance of J-T refrigerator is assumed for the ideal case. The reason for low thermal diffusion in a biological tissue is its inherently low thermal conductivity. Even though the cooling rate of probe, which is equal to that of tissue in contact with the probe, is extremely fast (Fig. 5), the cooling rate of tissue away from the probe is much lower (Fig. 7). This fact indicated that the cooling rate in practical cryosurgery is not high enough to destroy tissue effectively. Therefore, the repetition of freeze-thaw cycle must be frequently used in practical cryosurgery. The main mechanism of destructing tissue is not the rapid cooling but the repetition of freeze-thaw cycle [2]. The membrane of tissue is to be damaged by recrystallization of ice during slow-thawing of the frozen tissue. Moreover, the necrosis of tissue also causes the death of tissue by ceasing the blood perfusion and metabolism. The propagation speed becomes faster as the freeze-thaw cycle is repeated due to the necrosis of tissue, and the damage of tissue is accumulated during the repetition of cycle so that the malignant tissue is effectively destroyed.

When the repeated freeze-thaw cycle is employed, the nitrous oxide J-T refrigerator is useful in the case of short freezing operation typically within 2-3 minute. This fact is due to its fast cool-down characteristic. The argon J-T refrigerator is, on the other hand, advantageous for a longer freeze-thaw cycle with fewer repetition.

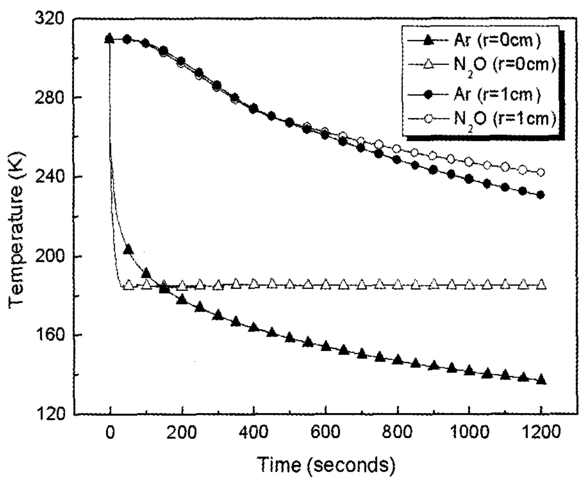


Fig. 5. Cooling curve of cryosurgical probe using Ar/N$_2$O.

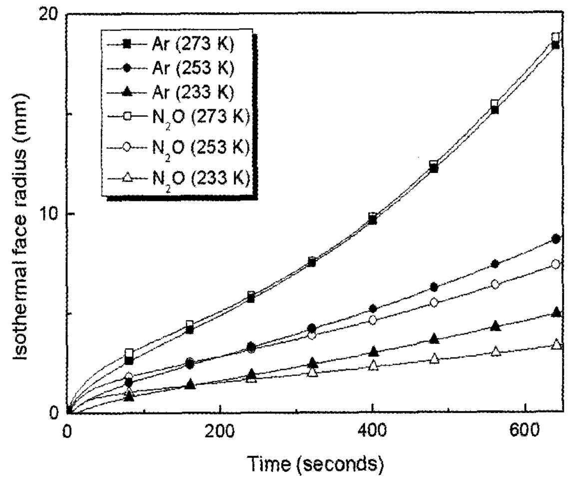
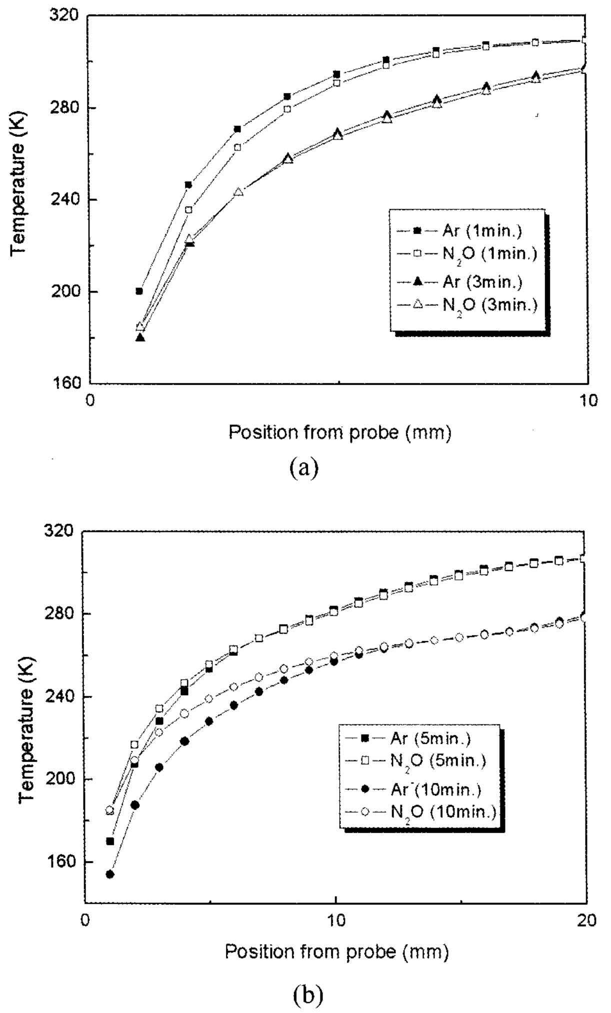


Fig. 6. Isothermal surface propagation.



(a)

(b)

Fig. 7. Temperature profile near cryosurgical probe using Ar/N_2O; (a) 1 min. / 3 min. (up to 20 mm) (b) 5 min. / 10 min. (up to 30 mm).

3. CONCLUSIONS

The J-T refrigerator using 50 bar nitrous oxide which has larger cooling power (16.3 W) above 184.7 K than the one with 300 bar argon, which enables fast cooling at early stage of cryosurgery, but the biological tissue away from the probe tends to be cooled slowly after the probe reaches its lowest operating temperature.

It is important for the J-T refrigerator of cryosurgical probe to have low operating temperature and large cooling power for effective tissue destruction, but it is practically difficult to achieve fast enough cooling rate due to the low thermal conductivity of tissue. Instead, the freeze-thaw cycle is mainly employed as the tissue destruction mechanism in cryosurgery treating prostate cancer. In this operation, the cryosurgical probe using nitrous oxide would be useful if the freezing operation is within 2-3 minute, and the argon cryosurgical probe would be appropriate in the case of longer freeze-thaw cycle with fewer repetitions.

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