Analytical Model of Heat Dissipation from Korean Total Artificial Heart

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Introduction

In the motor-driven blood pump, power loss in the energy converter is thought to be mainly converted into heat. The overall efficiency of our Korean Total Artificial Heart(KOTAH) was reported in the range of 7 to 8%, when power input was about 28W [11]. Therefore, if the power loss in the KOTAH is entirely changed into heat, we can estimate that over 20W of waste heat may be dissipated to the blood and surrounding tissues, such as the lungs and subcutaneous tissues.

Emoto H. [1], Fujimoto L. [2], Davies C. [3], et al have studied the effects of heat on the blood and tissue to prove the ability of tissue to increase its heat dissipation over time through angiogenesis. They carried out experiments with a thermally powered left ventricular assist system which requires 20W of heat dissipation and found that this amount of heat induced no deleterious local or systemic effects on recipient bovine animals.

There are several bio-heat transfer models for tissue. The most widely used model is the Pennes bio-heat transfer equation(BHTE) which was suggested by Pennes, H. H. in 1948 for obtaining the temporal and spatial distributions of temperature in the tissue [4]. In BHTE the net heat transfer from blood to tissue is proportional to the temperature difference between the arterial blood entering the tissue and the venous blood leaving the tissue.

The purposes of this work are to measure experimentally the amount of heat generated at the actuator and the temperature rise at the outer surface of pump housing, and to predict theoretically the amount of heat transferred to the blood, the amount of heat transferred to the surrounding tissues(lung) and temperature distributions in the tissues, which are in contact with the outer case of the TAH. The bio-heat transfer equation was used to calculate temperatures in the tissues.

Materials and Methods

Heat generation at the actuator

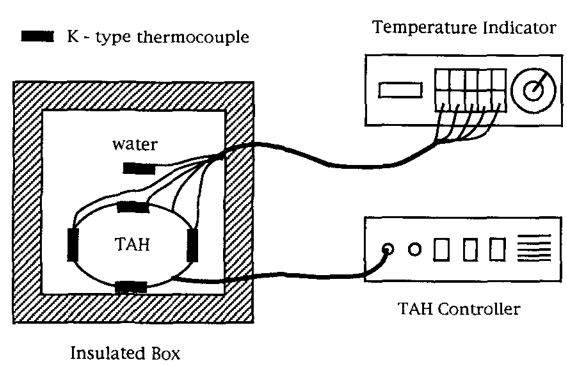

Figure 1. Experimental setup

Experimental setup is given in Figure 1. The TAH was submerged into 10L water contained in a thermally insulated box. K-type thermocouples were placed at four different sites of the pump housing surface and connected to an Omega DP-11 readout with 1/10℃ resolution. Temperature elevations of the water and outer surface of the pump housing were recorded every 5 minutes. The power input was 14W with stroke length 100 and velocity 11 which are proportional to stroke volume and heart rate, respectively. After steady state was reached, waste heat could be calculated as follows :

$$q = c_w \rho_w V \frac{\Delta T}{\Delta t} \quad [W] \tag{1}$$

Heat transfer equations in inside the pump housing

Figure 2 shows TAH waste heat pathways for heat generated at the actuator. Waste heat can be dissipated to the blood through blood sacs and to the surrounding tissues through pump housing, accordingly

$$q = q_b + q_t \tag{2}$$

After thermal equilibrium is reached, heat transfer equations can be formulated under the assumptions of one-dimensional and steady-state conditions.

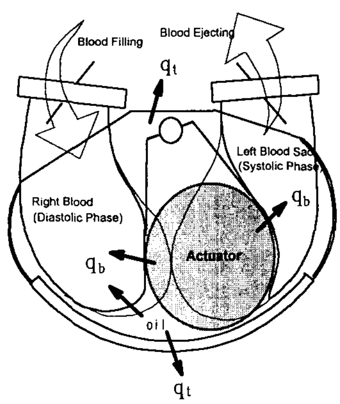

Figure 2. TAH waste heat pathways

The amount of heat transferred to the blood is the sum of the heat transferred from the silicon oil by convection and the heat transferred from the actuator by conduction.

It is assumed that (1)a half area of the actuator is in contact with blood sacs, while the actuator rolls back and forth (2)the inner surface area of the blood sac is the same as the outer surface area because the blood sac is made of very thin film (3)blood temperature is maintained at 37℃ constantly because if the entire 28W of heat is dissipated to flowing blood, the calculated bulk temperature increase is only 0.05℃ at 8L/min cardiac output.

The amount of heat transferred to the blood is

$$q_b = (A_s - A_a/2)\frac{T_{oil} - T_b}{1/h_{oil} + d_s/k_s + 1/h_b} + (A_a/2)\frac{T_a - T_b}{d_s/k_s + 1/h_b} \tag{3}$$

The amount of heat transferred to the surrounding tissues is

$$q_t = h_{oil} A_{hi} (T_{oil} - T_{hi}) \tag{4}$$

To calculate the convective heat transfer coefficients, h_{oil} and h_b, we must know conditions in the boundary layer which are influenced by surface geometry, the nature of the fluid motion, and various fluid properties [10]. In this system, however, such factors are too complicated to be determined theoretically. Therefore, q_t was calculated firstly considering temperature distributions in the pump housing and surrounding tissues, and then q_b could be obtained easily by equation (2).

Temperature distributions in the pump housing and surrounding tissues

As shown in Figure 3, the pump housing can be modeled as two possible geometries, a cylindrical shell and a spherical shell that are surrounded by the tissues.

When the Pennes BHTE is applied, it is generally assumed that the temperature of venous blood is in equilibrium with the local tissue temperature, and that the arterial blood temperature is constant [6]. Under these conditions, BHTE can be written as :

$$\rho_t c_t \frac{\partial T}{\partial t} = k_t \nabla^2 T + w_b c_b (T_{ar} - T) + Q_m \tag{5}$$

This is a modification of the ordinary transient heat conduction equation(first two terms) where the convective effects of the moving blood are treated as a volumetric isotropic heat source(third term) and metabolic heat production(fourth term) can be included if needed [8].

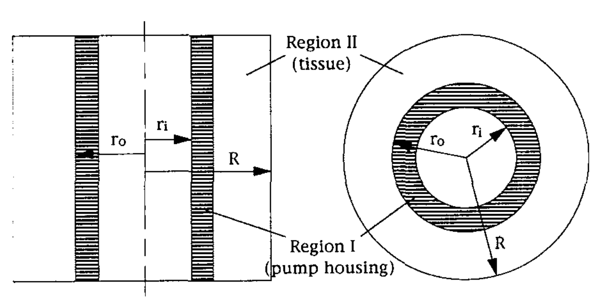

Figure 3. Models of pump housing

We use BHTE to calculate temperatures in the pump housing and surrounding tissues on the assumptions that (1)heat is transferred under one-dimensional and steady-state conditions (2)metabolic heat generation is ignored (3)thermal conductivities, k_h and k_t, blood perfusion rate, w_b, and arterial temperature, T_{ar}, have uniform values in both Region I and II (4)the tissue is held at a constant temperature T_R at some arbitrary radius, R.

(1) Cylindrical shell model

Region I :

$$\nabla^2 T(r)=0 \Rightarrow \frac{d}{dr}(r\frac{dT}{dr})=0 \quad (6a)$$

$$T_I(r)=A_1 \ln r+B_1 \quad (6b)$$

Region II :

$$k_t\frac{1}{r}\frac{d}{dr}(r\frac{dT}{dr})+w_b c_b(T_{ar}-T(r))=0 \quad (7a)$$

This equation can be transformed into the modified Bessel's equation of order zero whose solution is the linear combination of zero order modified Bessel's functions of first and second kinds, I_0 and K_0, respectively.

$$T_{II}(r)=T_{ar}+C_1 I_0(\lambda r)+D_1 K_0(\lambda r) \quad \text{where} \quad \lambda=\sqrt{\frac{w_b c_b}{k_t}} \quad (7b)$$

Boundary conditions :

$$T_I(r_i)=T_{hi} \quad (8a)$$

$$-k_h A_{hi}\frac{dT_I}{dr}\Big|_{r=r_o}=-k_t A_{ho}\frac{dT_{II}}{dr}\Big|_{r=r_o} \quad (8b)$$

$$T_I(r_o)=T_{II}(r_o) \quad (8c)$$

$$T_{II}(R)=T_R \quad (8d)$$

The coefficients A_1, B_1, C_1, and D_1 are determined as follows :

$$A_1=[I_1(\lambda r_o)+\alpha K_1(\lambda r_o)]\frac{T_{hi}-T_{ar}}{\gamma} \quad (9a)$$

$$B_1=T_{hi}-[I_1(\lambda r_o)+\alpha K_1(\lambda r_o)]\frac{(T_{hi}-T_{ar})\ln r_i}{\gamma} \quad (9b)$$

$$C_1=\frac{\beta(T_{hi}-T_{ar})}{\gamma} \quad (9c)$$

$$D_1=-\frac{\alpha\beta(T_{hi}-T_{ar})}{\gamma} \quad (9d)$$

$$\alpha=\frac{I_0(\lambda R)}{K_0(\lambda R)} \quad (9e) \qquad \beta=\frac{k_h}{\lambda k_t r_o} \quad (9f)$$

$$\gamma=[I_0(\lambda r_o)-\alpha K_0(\lambda r_o)]\beta-[I_1(\lambda r_o)+\alpha K_1(\lambda r_o)]\ln\frac{r_o}{r_i} \quad (9g)$$

In the expression of the coefficients, inner surface temperature of the pump housing, T_{hi} is to be determined.

(2) Spherical shell model

Region I :

$$\nabla^2 T(r)=0 \Rightarrow \frac{d}{dr}(r^2\frac{dT}{dr})=0 \quad (10a)$$

$$T_I(r)=\frac{A_2}{r}+B_2 \quad (10b)$$

Region II :

$$k_t\frac{1}{r^2}\frac{d}{dr}(r^2\frac{dT}{dr})+w_b c_b(T_{ar}-T(r))=0 \quad (11a)$$

$$T_{II}(r)=T_{ar}+\frac{C_2\sinh(\lambda r)+D_2\cosh(\lambda r)}{r} \quad (11b)$$

Boundary conditions are the same as those of cylindrical model.

The coefficients A_2, B_2, C_2, and D_2 are determined as follows :

$$A_2=-\frac{k_t r_o r_i(T_{hi}-T_{ar})\{\sinh[\lambda(R-r_o)]+\lambda r_o\cosh[\lambda(R-r_o)]\}}{[k_t(r_i-r_o)-k_h r_i]\sinh[\lambda(R-r_o)]+k_t\lambda r_o(r_i-r_o)\cosh[\lambda(R-r_o)]} \quad (12a)$$

$$B_2=T_{hi}+\frac{k_t r_o(T_{hi}-T_{ar})\{\sinh[\lambda(R-r_o)]+\lambda r_o\cosh[\lambda(R-r_o)]\}}{[k_t(r_i-r_o)-k_h r_i]\sinh[\lambda(R-r_o)]+k_t\lambda r_o(r_i-r_o)\cosh[\lambda(R-r_o)]} \quad (12b)$$

$$C_2=\frac{k_h r_o r_i(T_{hi}-T_{ar})\cosh(\lambda R)}{[k_t(r_i-r_o)-k_h r_i]\sinh[\lambda(R-r_o)]+k_t\lambda r_o(r_i-r_o)\cosh[\lambda(R-r_o)]} \quad (12c)$$

$$D_2=-\frac{k_h r_o r_i(T_{hi}-T_{ar})\sinh(\lambda R)}{[k_t(r_i-r_o)-k_h r_i]\sinh[\lambda(R-r_o)]+k_t\lambda r_o(r_i-r_o)\cosh[\lambda(R-r_o)]} \quad (12d)$$

Now, we can calculate the amount of heat transferred to the surrounding tissues. That is

$$q_t = -k_h A_{hi} \frac{dT_I}{dr} \mid_{r=r_i} \qquad (13)$$

Results

Table 1 represents measured temperature elevations for water and outer surface of the pump housing. Waste heat, as calculated by equation (1), also is shown. 10~11W of waste heat was generated, when power input was 14W.

Various parameters used in presenting results are tabulated in Table 2.

Analytically calculated temperatures in the pump housing and the surrounding tissues, which are modeled as the lungs, are represented in Figure 4 and Figure 5, respectively. T_{hi}, is assumed to be 50℃. Almost no differences are shown between the cylindrical model and the spherical model. As illustrated in Figure 4, lung interface temperature is about 38℃. Temperature drops as much as 12℃ through the pump housing. This relatively large temperature drop is due to low thermal conductivity of the pump housing made of polyurethane and high blood flow in the lungs.

The amount of heat transferred to the tissues, q_t, is dependent on T_{hi} as shown in Figure 6. At 50℃ of T_{hi}, q_t is 2.8W and the amount of heat transferred to the blood, q_b, is 8.2W if 11W of waste heat is generated at the actuator.

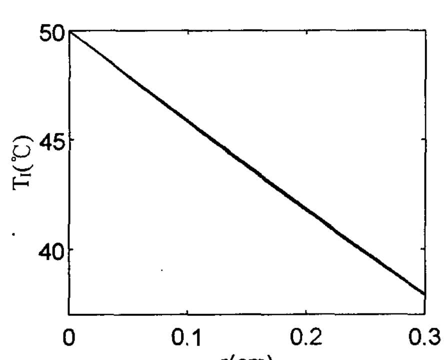

Figure 4. Temperature distributions in the pump housing (r: radial distance from the inner surface of the pump housing)

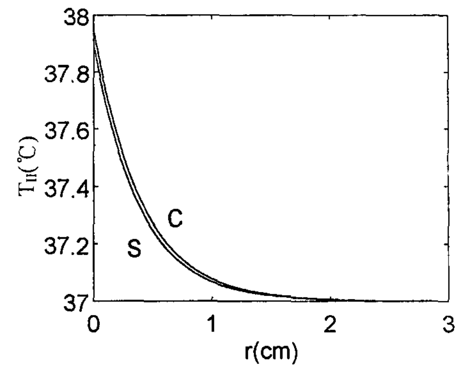

Figure 5. Temperature distributions in the surrounding tissues (r: radial distance from the outer surface of the pump housing, C:cylindrical model, S:spherical model)

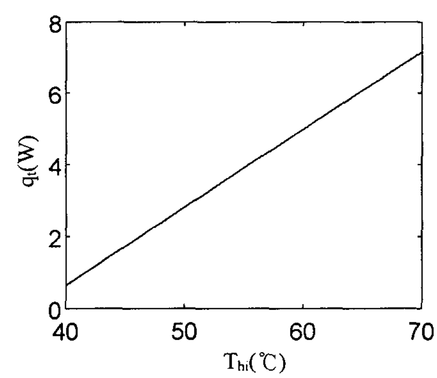

Figure 6. The dependence of q_t on T_{hi}

	Exp.1	Exp.2
elapsed time[min]	75	130
water △T[℃]	1.1	2.0
top △T[℃]	1.7	2.5
bottom △T[℃]	2.1	2.9
left side △T[℃]	1.2	2.1
right side △T[℃]	1.2	2.1
waste heat[W]	10.2	10.7

Table 1. Temperature elevations for water and outer surface of the pump housing, and calculated waste heat

k_t[W/mK]	0.487
k_h[W/mK]	0.03
w_b[kg/m^{3}s]	6.98
c_b[J/kg℃]	3900

Table 2. Parameters used in presenting results

Discussion

In the Korean Total Artificial Heart, 10~11W of waste heat was generated when power input was 14W. As predicted, most of the energy loss was converted into heat. There are two possible pathways for waste heat. Theoretically, about two thirds of the waste heat is dissipated to the blood but the bulk temperature increase of the blood is negligible. Tissue interface temperature is slightly higher than normal body temperature, 37℃, because the pump housing is well insulated and the lungs can dissipate heat effectively with the convection mechanism of blood flow. Similar results were obtained in the experiments. The temperatures of the hottest spots were only 1℃ higher than the surrounding water temperature after steady state was reached.

Results of the present study have shown that waste heat in the KOTAH could be dissipated primarily to the blood and secondarily to the surrounding tissues and that there were no harmful effects on the blood and the tissues, theoretically. In vivo test is planned to measure tissue interface temperature and to investigate the effects of heat on the tissues.

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<Nomenclature>

A = area(m^2)
c = specfic heat($J/kg°C$)
d = thickness(m)
h = convective heat transfer coefficient(W/m^2K)
k = thermal conductivity(W/mK)
Nu = Nusselt number
Pr = Prandtl number
q = heat rate(W)
Re = Reynolds number
r = radial distance(m)
T = temperature(°C)
T_R = reference temperature(°C)
V = volume(m^3)
w_b = blood flow(kg/m^3s)

Subscripts

a = actuator
ar = arterial
b = blood
h = pump housing
i = inner surface
o = outer surface
oil = silicon oil
s = blood sac
t = tissue
w = water