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APPENDIX A.1

One-Dimensional Derivation of Irradiative Heating (Radial)

The one-dimensional derivation in radial direction profile of steady state temperature distribution within flux tube assembly exposed to irradiative heating (gamma cell) is shown.

The set of equation and the boundary conditions determining the radial temperature distribution within the irradiative-heating exposed flux tube assembly containing a center cylinder surrounded by two tubes, capsule tube and guide tube, with gaps between each tube and a fluid flowing over the outside tube is given in this section.

In the case of irradiative heating, all three parts, center cylinder, inner tube and outside tube, generate heat as indicated in the derivation below. Steady state is applied with the defined geometry shown in Figure 3.3.

Outside tube

$$\frac{d}{dr} r\frac{dT_3}{dr} = -\frac{q_1 r}{k} \qquad \text{(A.1-1)}$$

Inner tube

$$\frac{d}{dr} r\frac{dT_2}{dr} = -\frac{q_2 r}{k} \qquad \text{(A.1-2)}$$

Center cylinder

$$\frac{d}{dr}\, r\frac{dT_1}{dr} = -\frac{q_1 r}{k} \qquad (A.1\text{-}3)$$

The boundary conditions based on internal irradiative heating of the mass within the flux tube assembly are

$r = 0$ $\qquad \frac{dT_1}{dr} = 0$

$r = R_1$ $\qquad h_1(T_1 - T_2) = -k\,\frac{dT_1}{dr}$

$r = R_2$ $\qquad h_1(T_1 - T_2) = -k\,\frac{dT_2}{dr}$

$r = R_3$ $\qquad h_2(T_2 - T_3) = -k\,\frac{dT_2}{dr}$

$r = R_4$ $\qquad h_2(T_2 - T_3) = -k\,\frac{dT_3}{dr}$

$r = R_5$ $\qquad h_3(T_3 - T_s) = -k\,\frac{dT_3}{dr}$

Integration of equation A.1-1 yields:

$$r\frac{dT_1}{dr} = -\frac{q_1 r^2}{2k} + C_1 \qquad \text{(A.1-4)}$$

Using the first boundary condition:

$$r = 0, \frac{dT_1}{dr} = 0, C_1 = 0$$

Integration of equation A.1-4:

$$T_1 = -\frac{q_1 r^2}{4k} + C_2 \qquad \text{(A.1-5)}$$

In the same method, the double integration of equation A.1-2 and A.1-3:

$$T_2 = -\frac{q_2 r^2}{4k} + C_3 \ln r + C_4 \qquad \text{(A.1-6)}$$

$$T_3 = -\frac{q_1 r^2}{4k} + C_5 \ln r + C_6 \qquad \text{(A.1-7)}$$

The remain coefficients, C_2, C_3, C_4, C_5 and C_6, in equations, A.1-5, A.1-6 and A.1-7, are calculated from the rest of boundary conditions.

The solution of temperature difference between the center cylinder and the surrounding fluid flowing around the outside tube is given by:

$$\Delta T = T_1 - T_s = \frac{q_1 R_1}{2h_1} + \frac{1}{2h_2}\ q_2 R_3 - \frac{R_2}{r_3}(q_2 R_2 - q_1 R_1)$$

$$+\frac{1}{2h_3}\ q_1 R_5 + \frac{q_2 R_3 R_4}{R_5} - \frac{R_2 R_4}{R_3 R_5}(q_2 R_2 - q_1 R_1) - \frac{q_1 R_4^2}{R_5}$$

$$+\frac{1}{2k}\ \frac{1}{2}\left(q_1 R_5^2 - q_1 R_4^2 + q_2 R_3^2 - q_2 R_2^2 + q_1 R_1^2\right) + R_2 (q_2 R_2 - q_1 R_1)\ln\frac{R_2}{R_3}$$

$$+\frac{R_2 R_4}{R_3}(q_2 R_2 - q_1 R_1)\ln\frac{R_4}{R_5} + q_2 R_3 R_4 \ln\frac{R_5}{R_4} + q_1 R_4^2 \ln\frac{R_4}{R_5} \qquad \text{(A.1-8)}$$

Using the values for the test cell

$q_1 = 0.0156$ W/cm^3

$q_2 = 0.024$ W/cm^3

$k = 0.023$ W/cm^3 °K

$R_1 = 0.297$ cm

$R_2 = 0.775$ cm

$R_3 = 0.8255$ cm

$R_4 = 0.939$ cm

$R_5 = 1.019$ cm

$h_2 = 0.06$ W/cm^3

Then, the related yield is:

$$\Delta T = T_1 - T_s = \frac{2.32\ \ 10^{-3}}{h_1} + \frac{4.29\ \ 10^{-3}}{h_3} + 0.0345 \qquad \text{(A.1-9)}$$

where: q_1 is the heat generation per unit volume of the center cylinder and outer tube respectively, W/cm°C.

q_2 is the heat generation per unit volume of the inner tube and water in the outer gap between the two tubes, W/cm°C.

k is the thermal conductivity of the center cylinder, inner tube and outer tube, W/cm°C.

T_1 is the temperature within the center cylinder, °C.

T_2 is the temperature within the inner tube, °C.

T_3 is the temperature within the outer tube, °C.

T_s is the temperature of flowing fluid surrounding the outer tube, °C.

h_1 is the heat transfer coefficient between the center cylinder and the inner tube, W/cm^2°C.

h_2 is the heat transfer coefficient between the inner tube and the outer tube, W/cm^2°C.

h_3 is the heat transfer coefficient between the outer tube and the water flowing over the outer tube, W/cm^2°C.

r is the distance from the center of the model, cm.

APPENDIX A.2

One-Dimensional Derivation of Electrical Heating (Radial)

The one-dimensional derivation in radial direction profile of steady state temperature distribution within flux tube assembly exposed to electrical heating is shown.

The set of equation and the boundary conditions determining the radial temperature distribution within flux tube assembly containing a center cylinder surrounded by two tubes, capsule tube and guide tube, with gaps between each tube and a fluid flowing over the outside tube that is given in this section.

This assembly is received the electrical heating only at the center of cylinder and then heat is transferred to the other parts of the equipment.

In the case of electrical heating, only center cylinder has heat generation as indicated below. Steady state is applied with the defined geometry shown in Figure 3.3.

Outside tube

$$\frac{d}{dr} r\frac{dT_3}{dr} = 0 \qquad \text{(A.2-1)}$$

Inner tube

$$\frac{d}{dr} r\frac{dT_2}{dr} = 0 \qquad \text{(A.2-2)}$$

Center cylinder

$$\frac{d}{dr}\,r\frac{dT_1}{dr} = -\frac{qr}{k} \qquad \text{(A.2-3)}$$

The boundary conditions based on internal electrical heating of the mass within the flux tube assembly are

$r = 0 \qquad \frac{dT_1}{dr} = 0$

$r = R_1 \qquad h_1(T_1 - T_2) = -k\,\frac{dT_1}{dr}$

$r = R_2 \qquad h_1(T_1 - T_2) = -k\,\frac{dT_2}{dr}$

$r = R_3 \qquad h_2(T_2 - T_3) = -k\,\frac{dT_2}{dr}$

$r = R_4 \qquad h_2(T_2 - T_3) = -k\,\frac{dT_3}{dr}$

$r = R_5 \qquad h_3(T_3 - T_s) = -k\,\frac{dT_3}{dr}$

Integration of equation A.2-1 yields:

$$r\frac{dT_1}{dr} = -\frac{qr^2}{2k} + C_1 \qquad \text{(A.2-4)}$$

Using the first boundary condition:

$$r = 0, \frac{dT_1}{dr} = 0, C_1 = 0$$

Integration of equation A.2-4:

$$T_1 = -\frac{qr^2}{4k} + C_2 \qquad \text{(A.2-5)}$$

In the same method, the double integration of equation A.2-2:

$$\frac{dT_2}{dr} = \frac{C_3}{r}$$

And then:

$$T_2 = C_3 \ln r + C_4 \qquad \text{(A.2-6)}$$

In the same method, the double integration of equation A.2-3:

$$\frac{dT_3}{dr} = \frac{C_5}{r}$$

And then:

$$T_3 = C_5 \ln r + C_6 \qquad \text{(A.2-7)}$$

The remain coefficients, C_2, C_3, C_4, C_5 and C_6, in equations, A.2-5, A.2-6 and A.2-7, are calculated from the rest of boundary conditions.

$$C_2 = \frac{qR_1}{2h_1} + \frac{qR_1^2}{4k} - \frac{qR_1R_2}{2k}\ln R_2 + \frac{qR_1R_2}{2h_2R_3} + \frac{qR_1R_2}{2k}\ln R_3 - \frac{qR_1R_2R_4}{2R_3k}\ln R_4 + \frac{qR_1R_2R_4}{2R_3R_5h_3}$$
$$+ \frac{qR_1R_2R_4}{2kR_3}\ln R_5 + T_s$$

$$C_3 = -\frac{qR_1R_2}{2k}$$

$$C_4 = \frac{qR_1R_2}{2h_2R_3} + \frac{qR_1R_2}{2k}\ln R_3 - \frac{qR_1R_2R_4}{2R_3k}\ln R_4 + \frac{qR_1R_2R_4}{2R_3R_5h_3} + \frac{qR_1R_2R_4}{2R_3k}\ln R_5 + T_s$$

$$C_5 = -\frac{qR_1R_2R_4}{2R_3k}$$

$$C_6 = T_s + \frac{qR_1R_2R_4}{2R_3R_5h_3} + \frac{qR_1R_2R_4}{2R_3k}\ln R_5$$

The solution of temperature difference between the center cylinder and the surrounding fluid flowing around the outside tube is given by:

$$\Delta T = \frac{qR_1}{2}\left[\frac{1}{h_1} + \frac{R_2}{R_3h_2} + \frac{R_2R_4}{R_3R_5h_3}\right] + \frac{1}{k}\left[\frac{R_1}{2} - R_2\ln\frac{R_2}{R_3} - \frac{R_2R_4}{R_3}\ln\frac{R_4}{R_5}\right] \quad (A.2\text{-}8)$$

Using the values for the test cell

$k = 0.023$ W/cm^3 °K

$R_1 = 0.297$ cm

$R_2 = 0.775$ cm

$R_3 = 0.8255$ cm

$R_4 = 0.939$ cm

$R_5 = 1.019$ cm

Then, the related yield is:

$$T_l - T_s = q\left(\frac{0.1485}{h_1} + \frac{0.1394}{h_2} + \frac{0.12847}{h_3} + 0.1763\right) \qquad \text{(A.2-9)}$$

where: q is the heat generation per unit volume of the center cylinder, W/cm°C.

k is the thermal conductivity of the center cylinder, inner tube and outer tube, W/cm°C.

T_l is the temperature within the center cylinder, °C.

T_2 is the temperature within the inner tube, °C.

T_3 is the temperature within the outer tube, °C.

T_s is the temperature of flowing fluid surrounding the outer tube, °C.

h_l is the heat transfer coefficient between the center cylinder and the inner tube, W/cm^2°C.

h_2 is the heat transfer coefficient between the inner tube and the outer tube, W/cm^2°C.

h_3 is the heat transfer coefficient between the outer tube and the water flowing over the outer tube, W/cm^2°C.

r is the distance from the center of the model, cm.

APPENDIX A.3

One-Dimensional Derivation of Electrical Heating (Axial)

The one-dimensional derivation in axial direction profile of steady state temperature distribution within flux tube assembly exposed to electrical heating is shown.

Steady state is applied with the defined geometry shown in Figure A.3. This model assumes the mass of the flux assembly can be divided into four parts. The first three parts are the same as in the radial heat transfer case, an outer tube representing the guide tube, an inner tube representing the detector capsule tube, a center cylinder representing the bundle of detector wells. The last part, which is of importance for this analysis, is a small part close to the center cylinder representing the strap wrapping the detector wells in position.

The set of equation and the boundary conditions determining the axial temperature distribution within the center cylinder of the flux tube assembly that has the strap wrapping around to keep the bundle of detector wells in position.

At the center of cylinder, there is the electrical heating generation. Generating heat from center cylinder is transferred to the other parts of the equipment.

Steady state energy balances for the inlet and outlet of center cylinder are given by

<u>Inlet</u>

$$\text{inlet} = -k\frac{dT}{dx}A_c + q_v A_c dx$$

<u>Outlet</u>

$$\text{outlet} = -k\left(\frac{dT}{dx} + \frac{d^2T}{dx^2}dx\right)A_c + h_a A_a (T - T_a)dx$$

Inlet – Outlet = 0:

$$\frac{d^2T}{dx^2} - \frac{h_a A_a}{kA_c}(T - T_a) = -\frac{q_v}{k} \quad \text{(A.3-3)}$$

Set:

$$\theta = \frac{T - T_a}{T_a}$$

$$x = \frac{X}{L}$$

Then:

$$\frac{d^2\theta}{dx^2} - \frac{h_a A_a}{kA_c} L^2\theta = -\frac{q_v L^2}{kT_a} \quad \text{(A.3-4)}$$

Let:

$$b = \frac{h_a A_a L^2}{kA_c}$$

$$c = -\frac{q_v L^2}{kT_a}$$

Then:

$$\frac{d^2\theta}{dx^2} - b\theta = c \quad \text{(A.3-5)}$$

Solving A.3-5 by the differential method with the boundary conditions.
The boundary condition based on electrical heating at the center cylinder:

$$x = 0 \qquad \frac{dT}{dx} = 0$$

$$x = 0 \qquad \frac{d\theta}{dx} = 0$$

And:

$$x = L \qquad T = T_s$$

$$x = 1 \qquad \theta_s = \frac{T_s - T_a}{T_a}$$

Then:

$$\theta = \frac{\theta_s + \frac{c}{b}}{e^{b^{\frac{1}{2}}} + e^{-b^{\frac{1}{2}}}} \left(e^{b^{\frac{1}{2}}x} + e^{-b^{\frac{1}{2}}x} \right) - \frac{c}{b} \qquad (A.3\text{-}3)$$

Where: q_v is the heat generation per unit volume of the center cylinder, W/cm°C.

A_c is the considering cross-section area, cm^2.

A_a is the heat transfer area, cm^2.

T_a is the fluid temperature between the center cylinder and the inner tube, °C.

h_a is the heat transfer coefficient between the center cylinder and the inner tube, $W/cm^2{}^{\circ}C$.

k is the thermal conductivity of the center cylinder that is constructed from zircalloy metal, W/cm°C.

L is the studied length of the center cylinder, cm.

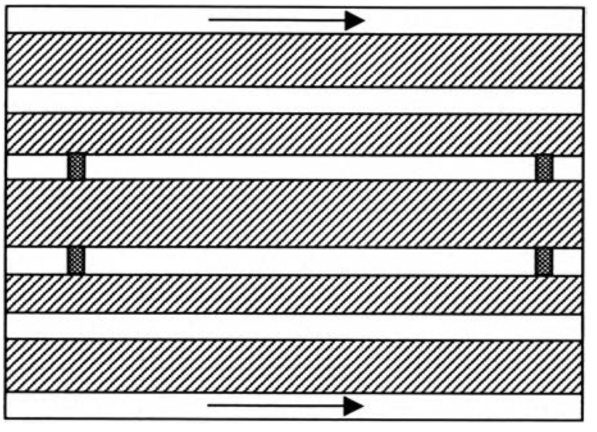


Figure A.3 Representation of VFD for steady state analysis, based on the axial heat transfer

APPENDIX A.4

Two-Dimensional Derivation of Irradiative Heating (Radial)

The two-dimensional derivation in radial direction profile of steady state temperature distribution within flux tube assembly exposed to irradiative heating (gamma cell) is shown.

Figures 3.3 and A.3 represent the detector assembly for the two-dimensional steady state analysis. The two-dimensional steady state energy balances on the three zones are given by

Outside tube

$$\frac{\partial}{\partial r}\left(\frac{r\partial T_3}{\partial r}\right)+r\frac{\partial^2 T_3}{\partial x^2}=\frac{q_1 r}{k} \qquad \text{(A.4-1)}$$

Inner tube

$$\frac{\partial}{\partial r}\left(\frac{r\partial T_2}{\partial r}\right)+r\frac{\partial^2 T_2}{\partial x^2}=\frac{q_2 r}{k} \qquad \text{(A.4-2)}$$

Center cylinder

$$\frac{\partial}{\partial r}\left(\frac{r\partial T_1}{\partial r}\right)+r\frac{\partial^2 T_1}{\partial x^2}=\frac{q_1 r}{k} \qquad \text{(A.4-3)}$$

The boundary conditions for the two dimensional case are

$$x = 0\ ;\ 0 \le r \le R_5;\ \frac{\partial T_3}{\partial x} = 0$$

$$\frac{\partial T_2}{\partial x} = 0$$

$$\frac{\partial T_1}{\partial x} = 0$$

$$x = l\ ;\ 0 \le r \le R_5;\ \frac{\partial T_3}{\partial x} = 0$$

$$\frac{\partial T_2}{\partial x} = 0$$

$$\frac{\partial T_1}{\partial x} = 0$$

$$r = 0\ ;\ 0 \le r \le l;\quad \frac{\partial T_1}{\partial r} = 0$$

$0 \le r \le l - s;$

$$r = R_1 \qquad h_1(T_1 - T_2) = -k\left(\frac{dT_1}{dr}\right)$$

$$r = R_2 \qquad h_1(T_1 - T_2) = -k\left(\frac{dT_2}{dr}\right)$$

$$r = R_3 \qquad h_2(T_2 - T_3) = -k\left(\frac{dT_2}{dr}\right)$$

$$r = R_4 \qquad h_2(T_2 - T_3) = -k\left(\frac{dT_3}{dr}\right)$$

$$r = R_5 \qquad h_3(T_3 - T_s) = -k\left(\frac{dT_3}{dr}\right)$$

$l - s \le r \le l$;

$$r = R_1 \qquad h'_1(T_1 - T_2) = -k\left(\frac{dT_1}{dr}\right)$$

$$r = R_2 \qquad h'_1(T_1 - T_2) = -k\left(\frac{dT_2}{dr}\right)$$

$$r = R_3 \qquad h_2(T_2 - T_3) = -k\left(\frac{dT_2}{dr}\right)$$

$$r = R_4 \qquad h_2(T_2 - T_3) = -k\left(\frac{dT_3}{dr}\right)$$

$$r = R_5 \qquad h_3(T_3 - T_s) = -k\left(\frac{dT_3}{dr}\right)$$

where: h'_1 is the heat transfer coefficient between the center cylinder and inner tube at thee strap, W/cm^{2}°C.

s is the width of the strap, cm.

l is the distance between one strap to another strap, cm.

For the two cases, irradiative heating and electrical heating, h_1 is less than h_1' due to the strap having enhanced the good heat transfer due to direct contact.

APPENDIX A.5

Two-Dimensional Derivation of Electrical Heating (Radial)

The two-dimensional derivation in radial direction profile of steady state temperature distribution within flux tube assembly exposed to electrical heating is shown.

Figures 3.3 and A.3 represent the detector assembly for the two-dimensional steady state analysis. The two-dimensional steady state energy balances on the three zones are given by

Outside tube

$$\frac{\partial}{\partial r}\left(\frac{r\partial T_3}{\partial r}\right)+r\frac{\partial^2 T_3}{\partial x^2}=0 \qquad \text{(A.5-1)}$$

Inner tube

$$\frac{\partial}{\partial r}\left(\frac{r\partial T_2}{\partial r}\right)+r\frac{\partial^2 T_2}{\partial x^2}=0 \qquad \text{(A.5-2)}$$

Center cylinder

$$\frac{\partial}{\partial r}\left(\frac{r\partial T_1}{\partial r}\right)+r\frac{\partial^2 T_1}{\partial x^2}=\frac{q_1 r}{k} \qquad \text{(A.5-3)}$$

The boundary conditions for the two dimensional case are

$$x = 0\ ;\ 0 \le r \le R_5;\ \frac{\partial T_3}{\partial x} = 0$$

$$\frac{\partial T_2}{\partial x} = 0$$

$$\frac{\partial T_1}{\partial x} = 0$$

$$x = 1\ ;\ 0 \le r \le R_5;\ \frac{\partial T_3}{\partial x} = 0$$

$$\frac{\partial T_2}{\partial x} = 0$$

$$\frac{\partial T_1}{\partial x} = 0$$

$$r = 0\ ;\ 0 \le r \le 1;\quad \frac{\partial T_1}{\partial r} = 0$$

$0 \le r \le 1 - s;$

$$r = R_1 \qquad h_1(T_1 - T_2) = -k\left(\frac{dT_1}{dr}\right)$$

$$r = R_2 \qquad h_1(T_1 - T_2) = -k\left(\frac{dT_2}{dr}\right)$$

$$r = R_3 \qquad h_2(T_2 - T_3) = -k\left(\frac{dT_2}{dr}\right)$$

$$r = R_4 \qquad h_2(T_2 - T_3) = -k\left(\frac{dT_3}{dr}\right)$$

$$r = R_5 \qquad h_3(T_3 - T_s) = -k\left(\frac{dT_3}{dr}\right)$$

$l - s \leq r \leq l$;

$r = R_1 \qquad h'_1(T_1 - T_2) = -k\left(\frac{dT_1}{dr}\right)$

$r = R_2 \qquad h'_1(T_1 - T_2) = -k\left(\frac{dT_2}{dr}\right)$

$r = R_3 \qquad h_2(T_2 - T_3) = -k\left(\frac{dT_2}{dr}\right)$

$r = R_4 \qquad h_2(T_2 - T_3) = -k\left(\frac{dT_3}{dr}\right)$

$r = R_5 \qquad h_3(T_3 - T_s) = -k\left(\frac{dT_3}{dr}\right)$

where: h'_1 is the heat transfer coefficient between the center cylinder and inner tube at thee strap, W/cm^2°C.

s is the width of the strap, cm.

l is the distance between one strap to another strap, cm.

For the two cases, irradiative heating and electrical heating, h_1 is less than h_1' due to the strap having enhanced the good heat transfer due to direct contact.

APPENDIX B

Description of the Previous Experiments

In the previous study, the test cell was design to be a model of the Vertical Flux Detector Assembly to simulate the means of the temperature distribution measurement. the irradiative heating by gamma cell, which had Cobalt-60 as the fuel, was used to simulate the irradiative heating within the nuclear reactor. In the experiments, the test cell was operated in steady state outside and inside the gamma cell.

As shown in Figure B.1, the steady-state processes were operated in the following manner.

Water from the water reservoir at a set temperature was allowed to circulate through the test cell by a pump until the thermal equilibrium was achieved throughout the test cell while it was outside the gamma cell. Then, the test cell was lowed down into the gamma cell irradiative hole by the elevator. The test cell stayed within the gamma cell until the thermal equilibrium was achieved again. After reaching the equilibrium, the test cell was removed from the gamma cell by the elevator and operated in the same manner outside the gamma cell until thermal equilibrium was achieved. The water still constantly flew at the constant flow rate all along the process.

All runs in the gamma cell were operated with the helium flowing through the cavity containing the detector wells at 2ml/min as its flow rate.

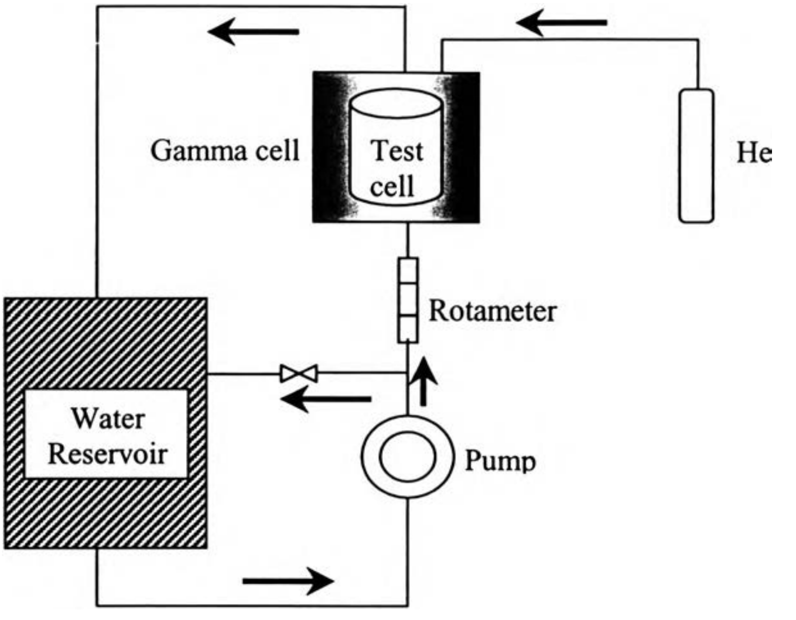


Figure B.1 Experimental arrangement for steady state processes

APPENDIX C.1

Experimental Data

Table C.1.1 The data of test cell with electrical heating, electrical heaters at the bottom of the test cell

Power (W)	Position of strap from top of cap (cm)	Position of T/C from top of cap (cm)	Distance away from strap (cm)	Temperature difference (°C) Velocity = 0.14 m/s			
				T/C2	T/C3	S1	S2
2.8	2.5	2.5	0	0.32	0.23	15.81	12.20
		3.5	1	0.61	0.56	23.27	18.00
		4.5	2	0.35	0.54	29.20	21.16
		5.5	3	0.51	0.32	32.78	24.17
		6.5	4	0.28	0.05	32.74	24.28
	3.5	2.5	1	0.21	0.27	16.08	12.40
		3.5	0	0.15	0.1	29.99	28.71
		4.5	1	0.49	0.25	29.90	28.11
		5.5	2	0.86	0.63	31.02	29.57
		6.5	3	0.34	0.51	28.03	27.38

T/C is thermocouple.

S is straw of test cell.

Table C.1.2 The data of test cell with electrical heating, electrical heaters at the bottom of the test cell and using pumped water

Power (W)	Position of strap from top of	Position of T/C from top of cap	Distance away from strap	Temperature difference (°C)					
				T/C2			T/C3		
				Velocity (m/s)			Velocity (m/s)		
				0.14	0.27	0.69	0.14	0.27	0.69
4.5	2.5	4.5	2	0.55	-	0.14	0.12	-	0.56
	3.5	4.5	1	0.69	0.66	1.06	0.51	0.78	1.01
17.5	2.5	4.5	1	0.30	-	1.03	1.16	-	1.22
	3.5	4.5	1	0.34	-	1.59	1.25	-	1.90

Table C.1.2 (Cont.)

Power (W)	Position of strap from top of	Position of T/C from top of cap	Distance away from strap*	Temperature difference (°C)					
				S1			S2		
				Velocity (m/s)			Velocity (m/s)		
				0.14	0.27	0.69	0.14	0.27	0.69
4.5	2.5	4.5	2	44.74	-	46.27	41.05	-	40.86
	3.5	4.5	1	44.17	46.14	44.32	37.83	39.73	37.50
17.5	2.5	4.5	1	158.7	-	160.2	148.2	-	146.5
	3.5	4.5	1	162.2	-	159.5	143.5	-	137.6

* unit is cm.

T/C is thermocouple.

S is straw of test cell.

Table C.1.3 The data of test cell with electrical heating, electrical heaters, strap at the center of the test cell

Power (W)	Position of T/C from top of cap (cm)	Distance away from strap (cm)	Temperature difference (°C)				
			Velocity = 0.14 m/s				
			T/C2	T/C3	S1	S2	S3
1.08	1.5	2	0.63	0.55	6.25	5.06	4.89
	2.5	1	0.60	0.90	8.76	6.89	7.20
	3.5	0	0.90	1.16	10.29	8.71	8.55
	4.5	1	0.19	0.30	12.03	10.39	10.10
	5.5	2	0.19	0.27	10.48	8.80	8.61
2.8	1.5	2	0.25	0.03	17.43	14.54	14.44
	2.5	1	0.36	0.51	24.35	20.37	20.50
	3.5	0	0.49	0.58	29.86	26.25	25.69
	4.5	1	0.55	0.52	31.82	27.28	27.18
	5.5	2	0.28	0.51	28.80	26.12	23.60
4.5	1.5	2	0.41	0.05	26.88	22.64	21.83
	2.5	1	0.52	0.06	39.07	32.59	32.55
	3.5	0	0.45	0.40	46.41	40.88	40.02
	4.5	1	0.34	0.73	49.04	42.26	41.56
	5.5	2	0.16	0.08	43.52	38.77	38.48
5.04	1.5	2	0.54	0.61	30.50	25.21	23.97
	2.5	1	0.74	0.95	42.26	34.67	35.32
	3.5	0	0.44	0.06	52.62	45.90	43.98
	4.5	1	0.63	0.74	55.07	48.10	46.70
	5.5	2	0.49	0.37	48.84	44.21	43.02

Table C.1.3 (Cont.)

Power (W)	Position of T/C from top of cap (cm)	Distance away from strap (cm)	Temperature difference (°C)				
			Velocity = 0.14 m/s				
			T/C2	T/C3	S1	S2	S3
8.04	1.5	2	0.42	0.85	45.86	38.51	37.04
	2.5	1	0.36	0.71	66.39	54.19	56.38
	3.5	0	0.19	0.10	81.69	72.42	70.80
	4.5	1	0.08	0.07	85.37	75.81	72.78
	5.5	2	1.02	0.76	75.57	68.14	64.83
10.21	1.5	2	0.17	0.67	58.13	50.11	48.18
	2.5	1	0.46	0.80	83.32	69.71	70.08
	3.5	0	0.58	0.74	102.4	90.40	88.61
	4.5	1	0.33	0.19	106.6	96.42	92.38
	5.5	2	0.03	0.05	94.69	87.97	82.60
12.04	1.5	2	0.21	0.29	67.55	58.11	57.05
	2.5	1	0.46	0.49	99.16	81.93	83.84
	3.5	0	0.14	0.24	123.9	106.2	106.0
	4.5	1	0.10	0.03	132.7	118.0	109.9
	5.5	2	0.26	0.68	111.8	104.3	100.3
15.38	1.5	2	0.70	0.19	85.36	72.66	72.35
	2.5	1	0.49	0.56	121.9	101.1	102.3
	3.5	0	0.52	0.38	149.5	136.3	131.1
	4.5	1	0.37	0.49	155.1	145.2	136.6
	5.5	2	0.79	1.07	139.3	131.6	123.2

Table C.1.3 (Cont.)

Power (W)	Position of T/C from top of cap (cm)	Distance away from strap (cm)	Temperature difference (°C)				
			Velocity = 0.14 m/s				
			T/C2	T/C3	S1	S2	S3
17.5	1.5	2	0.79	1.05	93.63	83.30	78.61
	2.5	1	0.15	0.51	137.1	117.0	117.2
	3.5	0	0.81	0.83	170.1	149.4	147.4
	4.5	1	0.62	0.87	180.3	159.1	151.8
	5.5	2	0.26	0.23	155.7	137.9	134.8

T/C is thermocouple.

S is straw of test cell.

Table C.1.4 The data of test cell with electrical heating, electrical heaters, strap at the center of the test cell, and using pumped water

Power (W)	Position of T/C from top of cap	Distance away from strap*	Temperature difference (°C)							
			T/C2				T/C3			
			Velocity (m/s)				Velocity (m/s)			
			0.14	0.27	0.42	0.69	0.14	0.27	0.42	0.69
4.5	3.5	0	0.31	0.34	0.10	0.65	0.61	0.52	0.33	0.88
17.5	3.5	0	0.50	0.24	0.44	1.13	1.45	0.83	0.74	1.26

Table C.1.4 (Cont.)

Power (W)	Position of T/C from top of cap	Distance away from strap*	Temperature difference (°C)							
			S1				S2			
			Velocity (m/s)				Velocity (m/s)			
			0.14	0.27	0.42	0.69	0.14	0.27	0.42	0.69
4.5	3.5	0	42.5	42.6	42.0	42.9	38.8	37.7	37.5	39.0
17.5	3.5	0	151	150	149	150	145	148	148	149

* unit is cm.

T/C is thermocouple.

S is straw of test cell.

Table C.1.5 The data of test cell with electrical heating, electrical heaters and strap at the center of the test cell,thermocouples at 1 cm from top of test cell

Power (W)	Velocity (m/s)	Temperature difference (°C)				
		T/C2	T/C3	T/C5	S1	S2
4.5	0.14	0.23	0.68	16.65	16.65	13.32
	0.27	0.39	1.08	18.01	18.01	14.17
	0.42	0.89	1.00	17.78	17.78	13.77
	0.69	0.78	0.50	16.95	16.95	13.91
17.5	0.14	1.00	1.10	5.66	62.11	19.65
	0.27	0.70	1.22	5.78	61.61	18.91
	0.42	0.75	1.29	5.37	61.65	18.36
	0.69	0.25	0.93	4.29	61.48	48.48

T/C is thermocouple.

S is straw of test cell.

APPENDIX C.2

Numerical Data

In Figures C.2.1 and C.2.2, the temperature profile of the electrical heating case using air as the fluid 2 with the heat generation rate of 0.555 W/g are presented. The maximum temperature in the model was 405.95 K.

In Figures C.2.3 and C.2.4, the temperature profile of the gamma heating case using air as the fluid 2 with the heat generation rate of 0.555 W/g are presented. The maximum temperature in the model was 412.21 K.

In Figures C.2.5 and C.2.6, the temperature profile of the electrical heating case using helium as the fluid 2 with the heat generation rate of 0.555 W/g are presented. The maximum temperature in the model was 322.74 K.

In Figures C.2.7 and C.2.8, the temperature profile of the gamma heating case using helium as the fluid 2 with the heat generation rate of 0.555 W/g are presented. The maximum temperature in the model was 330.79 K.

Figure C.2.9 and C.2.10 are the temperature along the inside and outer tube of center tube for electrical heating at 5 W with using air.

Figure C.2.11 and C.2.12 are the temperature along the inside and outside surface of the outer tube for gamma heating at 5 W with using air.

Figure C.2.13 and C.2.14 are the temperature along the inside and outer tube of center tube for electrical heating at 5 W with using helium.

Figure C.2.15 and C.2.16 are the temperature along the inside and outside surface of the outer tube for gamma heating at 5 W with using helium.

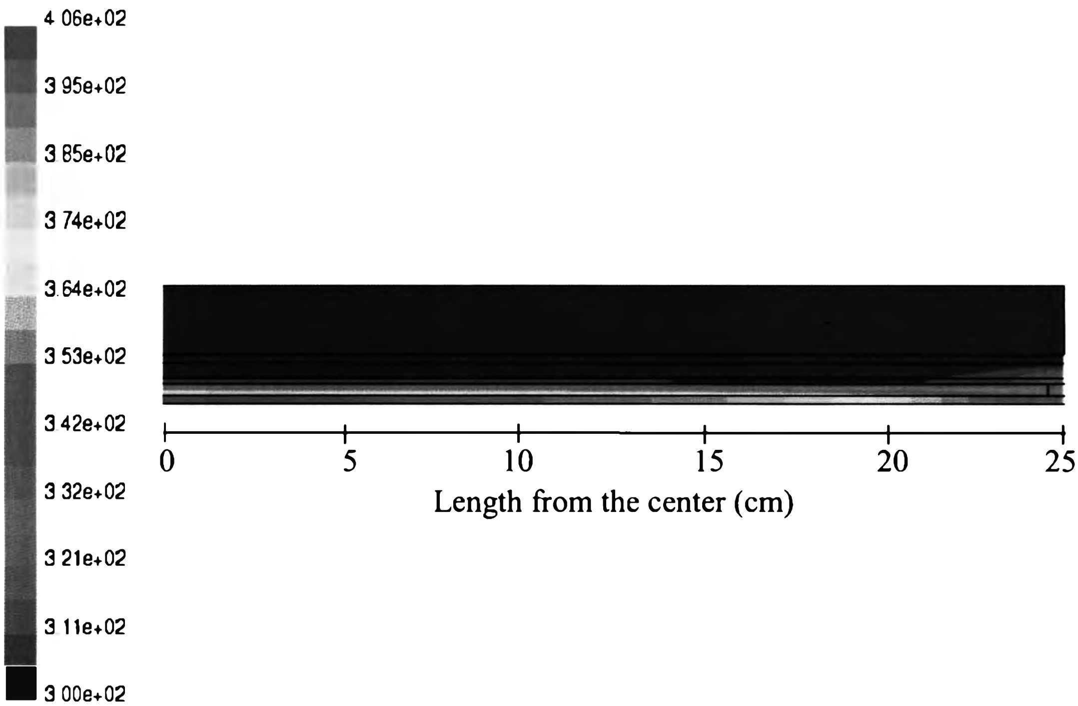


Figure C.2.1 Temperature profile for the small part of the test cell with electrical heating at 0.555 W/g and using air

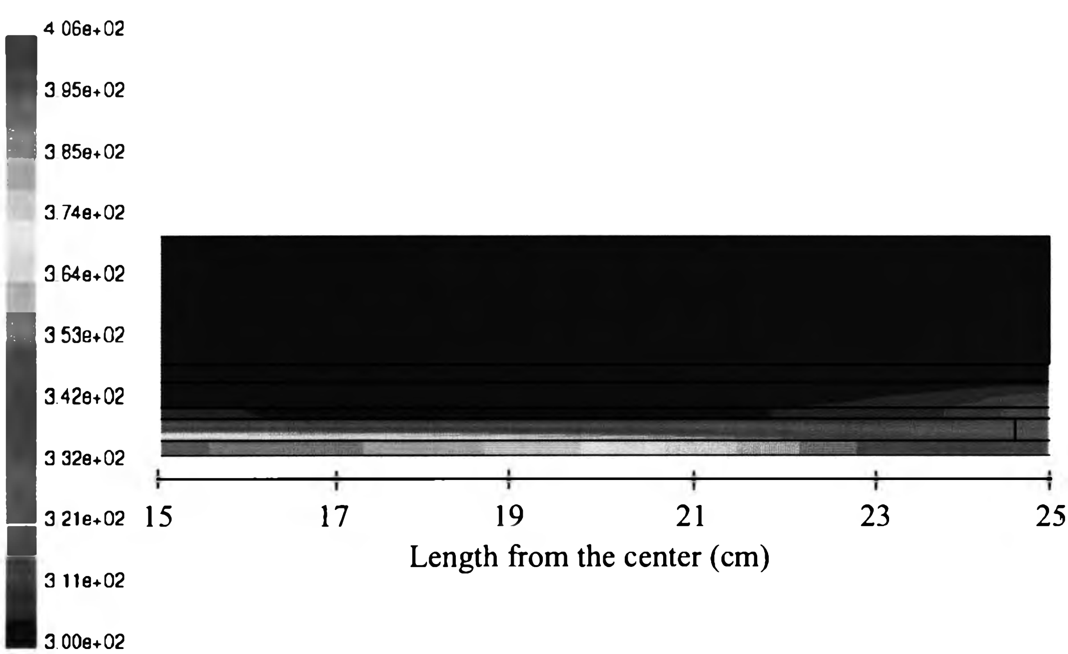


Figure C.2.2 Temperature profile for specifying at the strap of the test cell with electrical heating at 0.555 W/g and using air

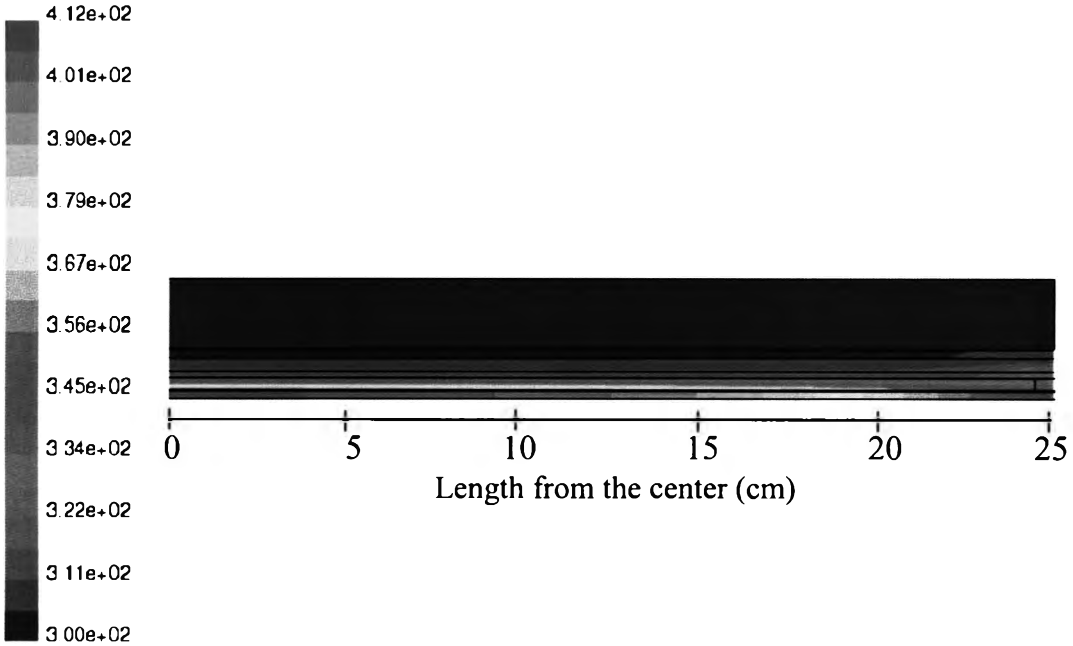


Figure C.2.3 Temperature profile for the small part of the test cell with gamma heating at 0.555 W/g and using air

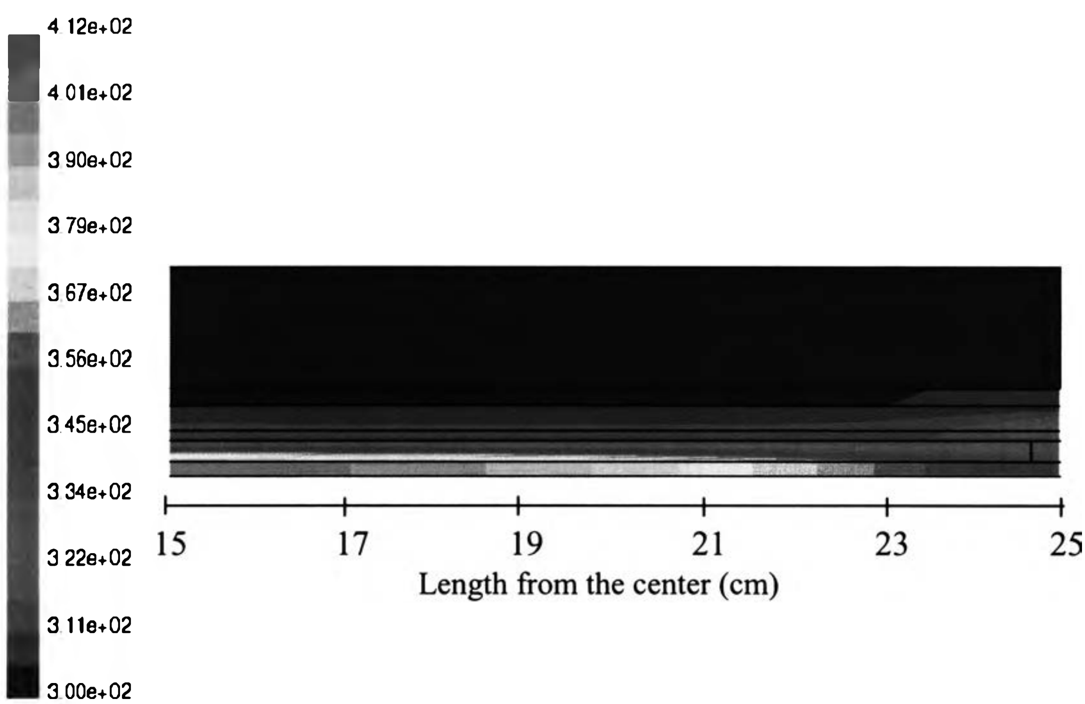


Figure C.2.4 Temperature profile specifying at the strap of the test cell with gamma heating at 0.555 W/g and using air

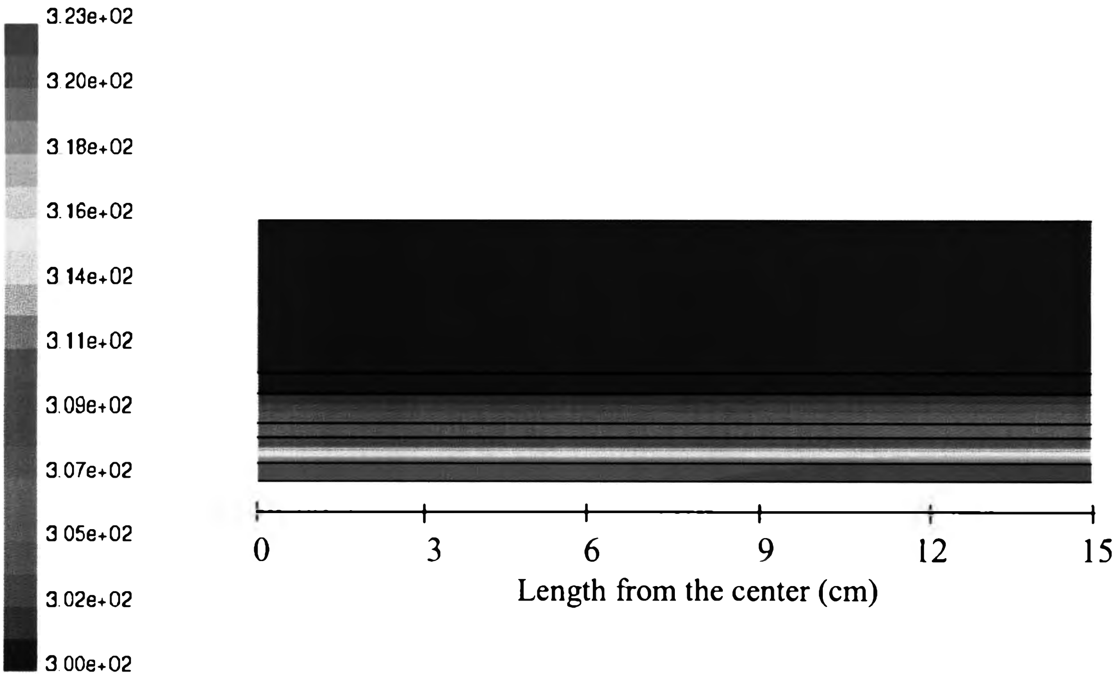


Figure C.2.5 Temperature profile for the end part of the test cell with electrical heating at 0.555 W/g and using helium

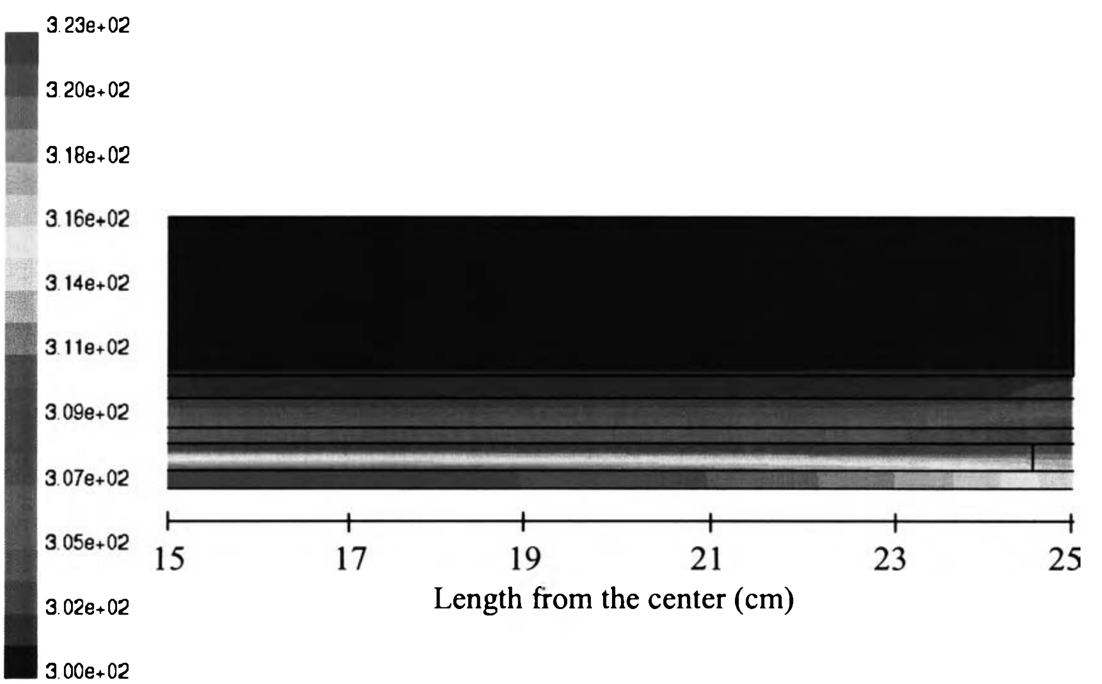


Figure C.2.6 Temperature profile for specifying at the strap of the test cell with electrical heating at 0.555 W/g and using helium

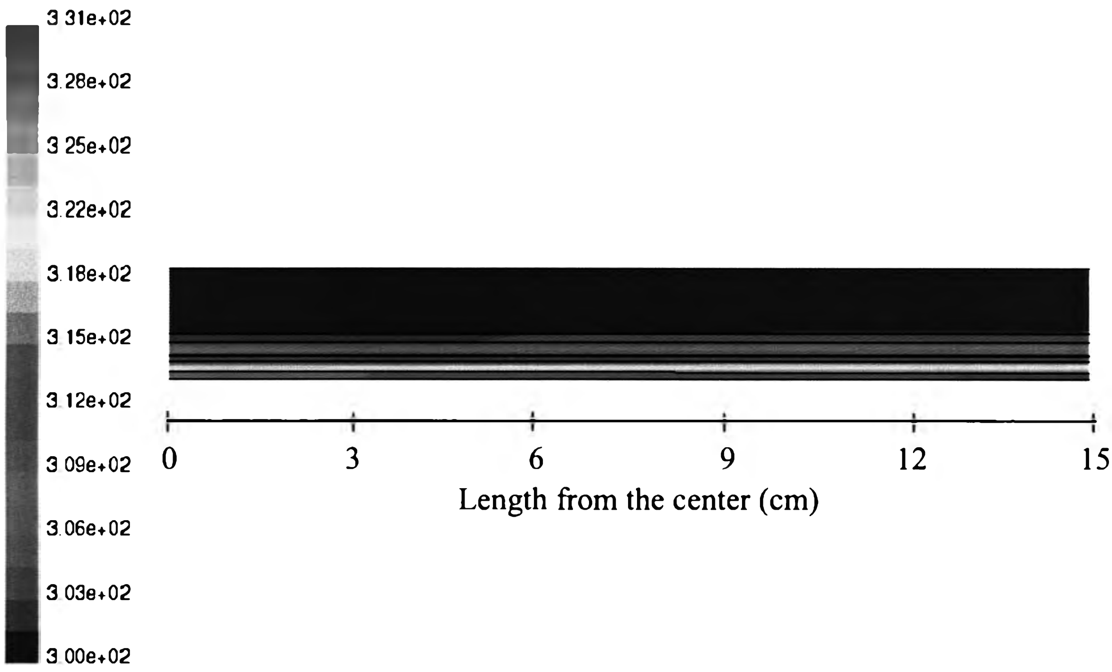


Figure C.2.7 Temperature profile for the end part of the test cell with gamma heating at 0.555 W/g and using helium

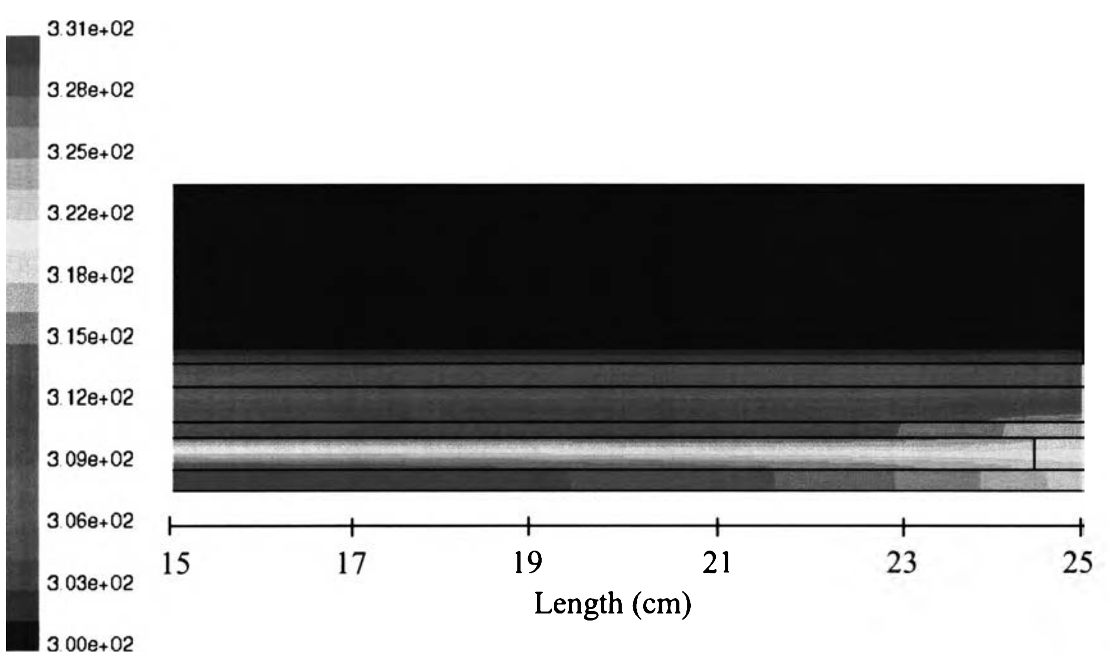


Figure C.2.8 Temperature profile for specifying at the strap of the test cell with gamma heating at 0.555 W/g and using helium

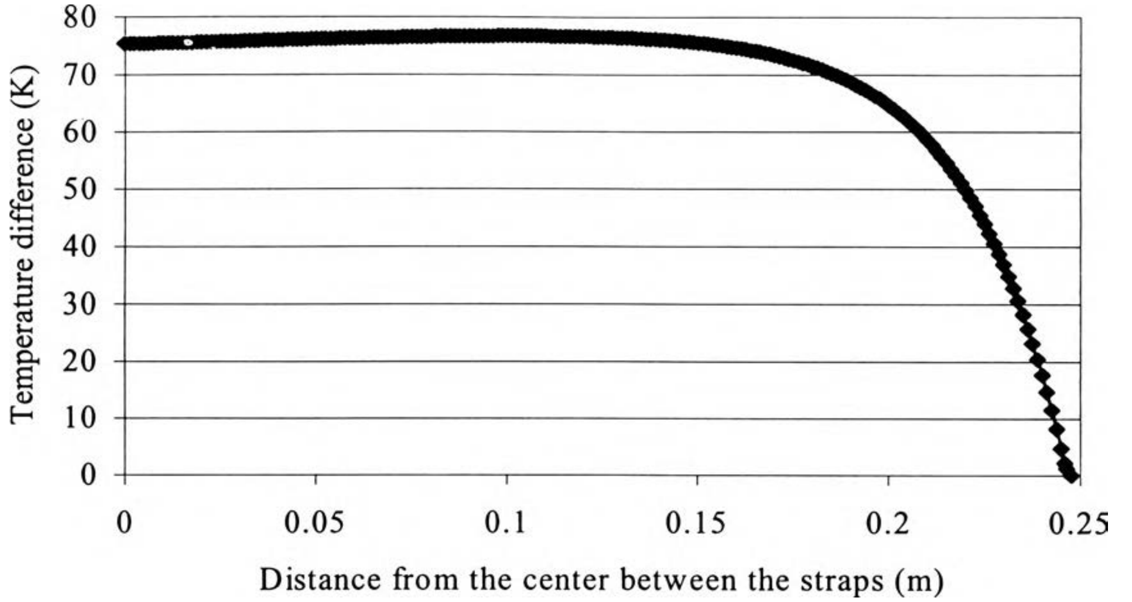


Figure C.2.9 The temperature along the inside surface of the center tube, (R_1) for electrical heating at 5 W with using air

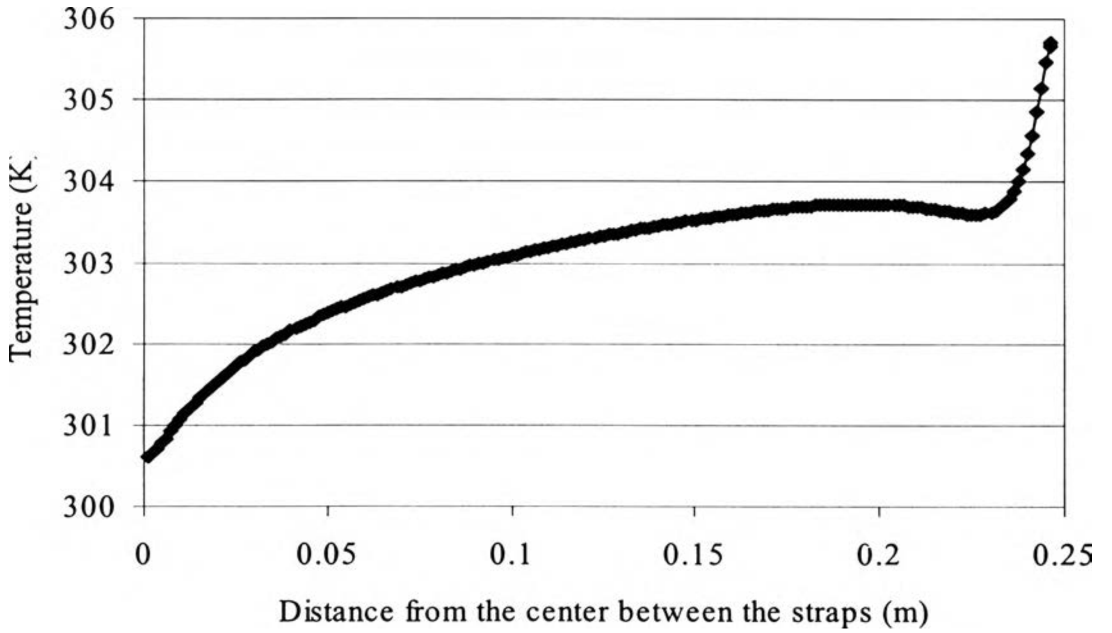


Figure C.2.10 The temperature along the outside surface of the outer tube, (R_6) for electrical heating at 5 W with using air

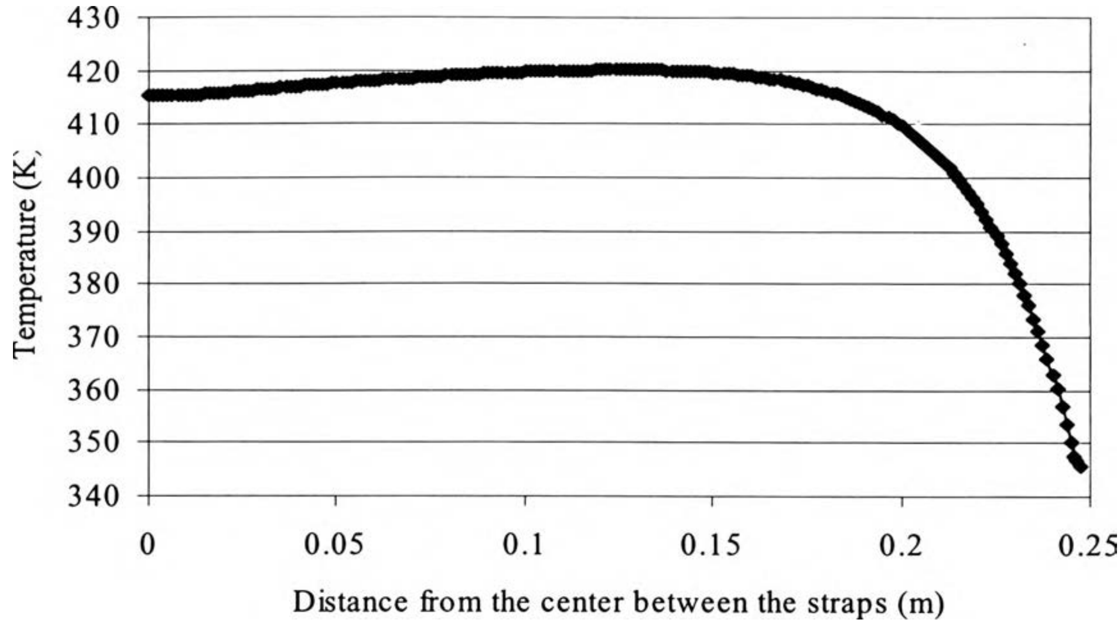


Figure C.2.11 The temperature along the inside surface of the center tube, (R_1) for gamma heating at 5 W with using air

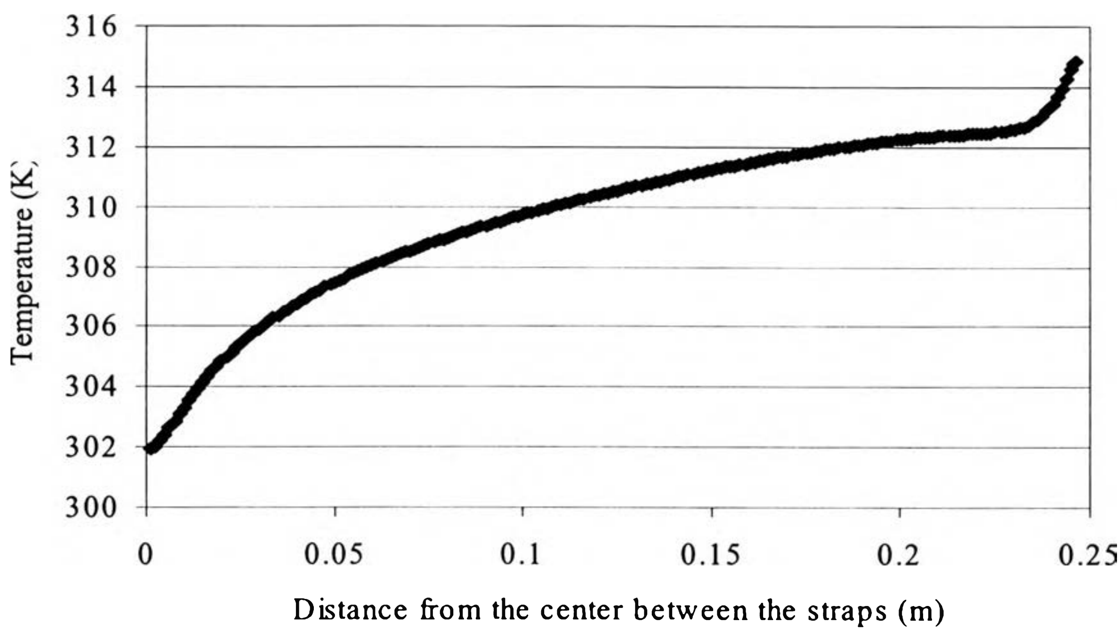


Figure C.2.12 The temperature along the outside surface of the outer tube, (R_6) for gamma heating at 5 W with using air

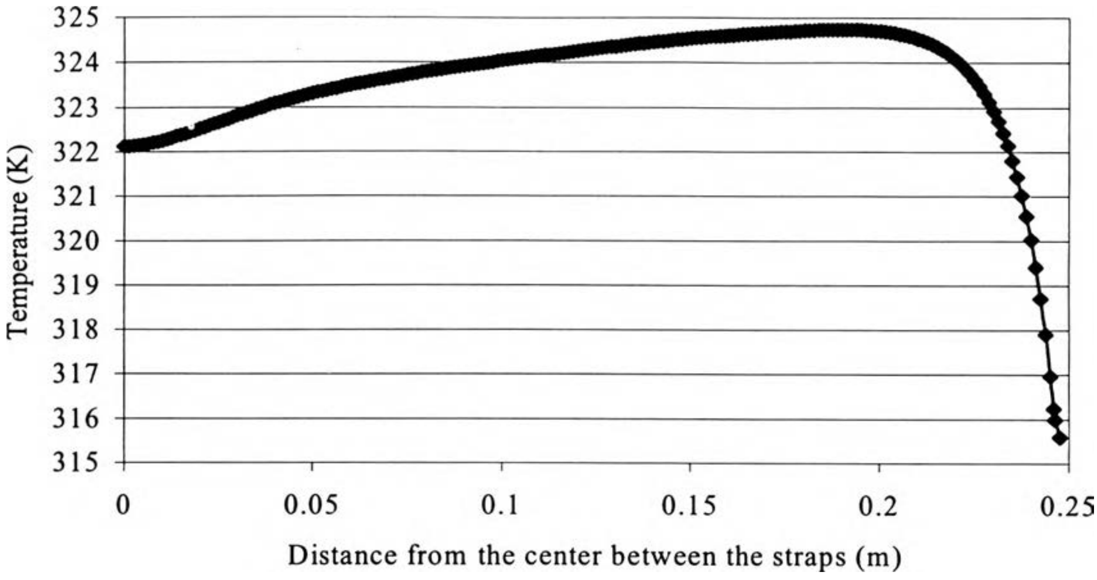


Figure C.2.13 The temperature along the inside surface of the center tube, (R_1) for electrical heating at 5 W with using helium

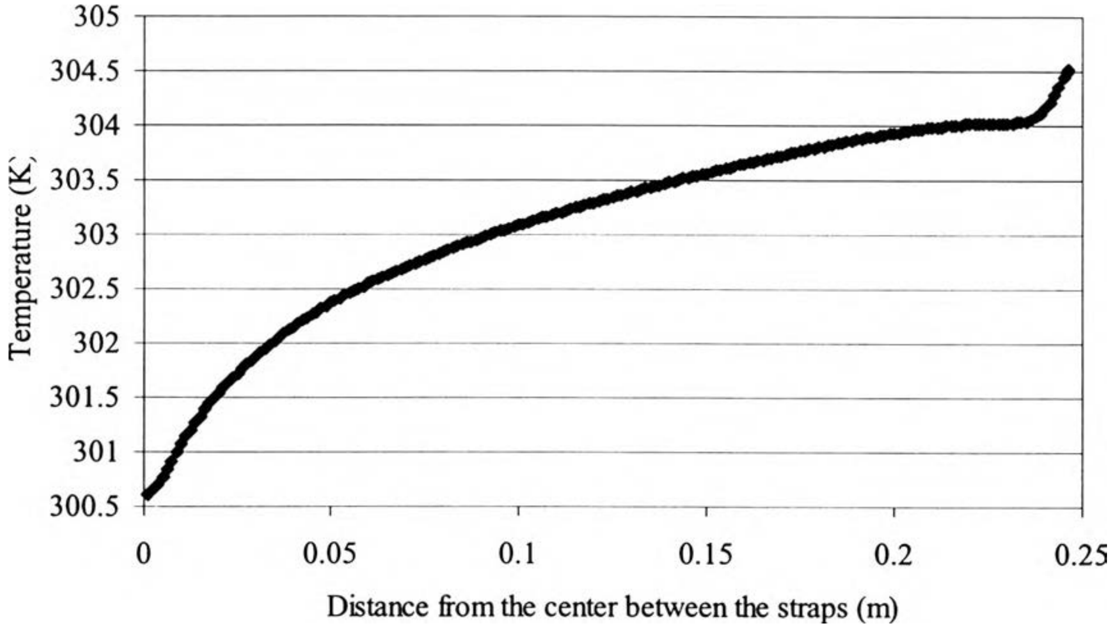


Figure C.2.14 The temperature along the outside surface of the outer tube, (R_6)for electrical heating at 5 W with using helium

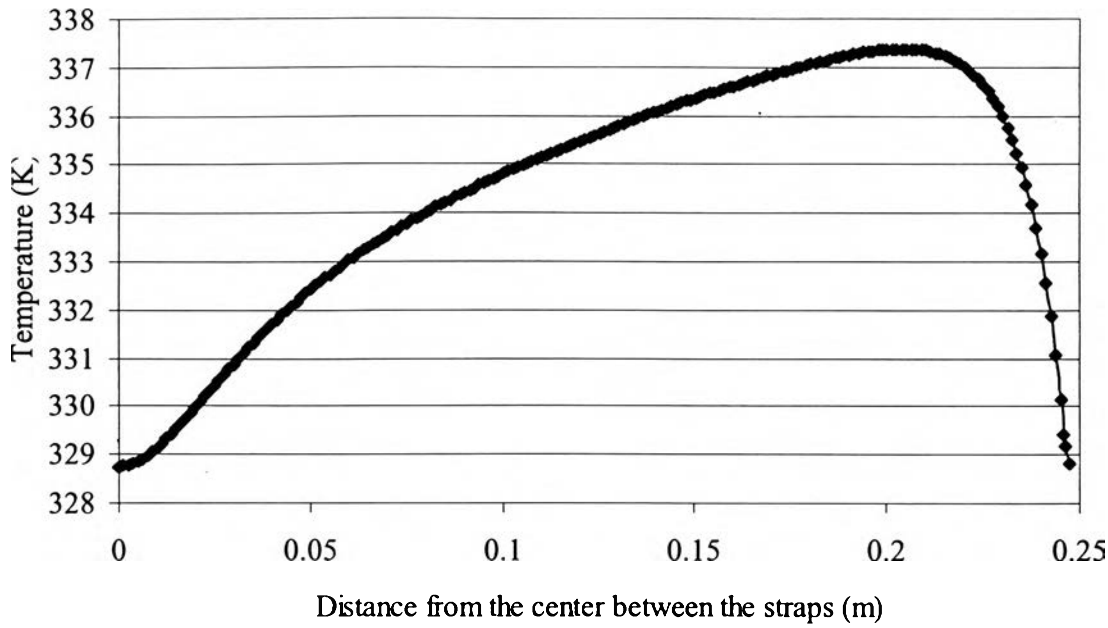
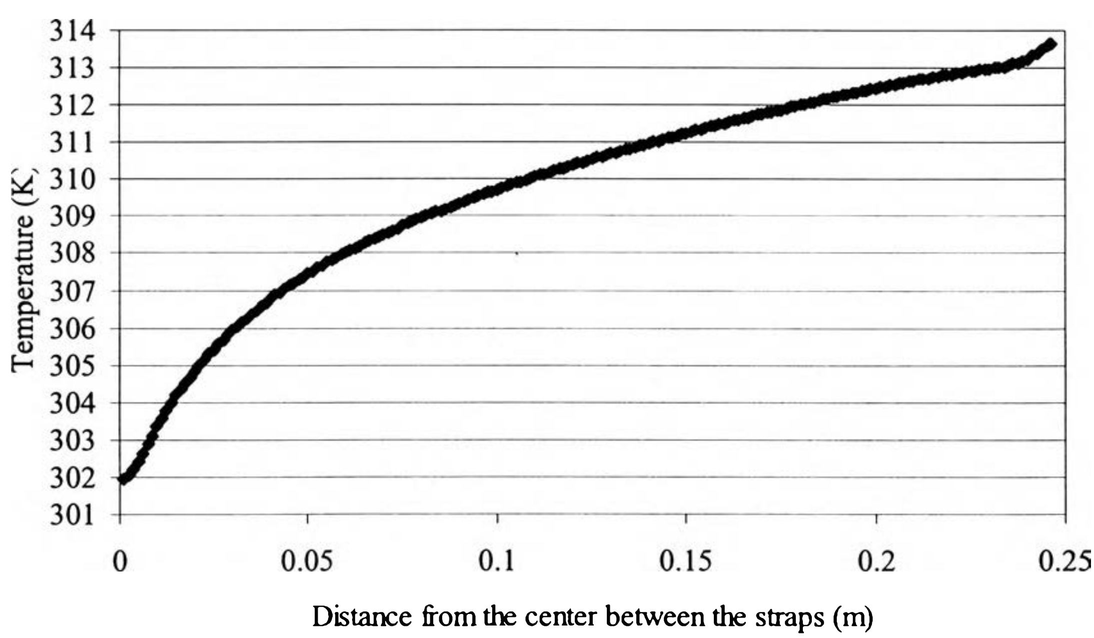


Figure C.2.15 The temperature along the inside surface of the center tube, (R_1)



For gamma heating at 5 W with using helium

Figure C.2.16 The temperature along the outside surface of the outer tube, (R_6)

For gamma heating at 5 W with using helium

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