CHAPTER V

SIMULATION RESULTS AND DISCUSSION

COMPARISON OF SIMULATION RESULTS WITH EXPERIMENTAL DATA

The experiment were carried out in the fitting of mathematical model with the experimental data. The experiments were taken with the light truck radial tire size 195 R 14., data taken from four tires. The experimental data were measured by thermocouple direct measurement method to determine the temperature - time profiles of three obsered positions as follows tread center , bladder surface and under tread position. (The experimental data see table 5.1, 5.2, and 5.3) Thermocouples were placed at those positions because usually at under tread position (see table 5.1) those known to have the lowest temperature at any time during tire curing process. For bladder surface and tread surface positions were the actual boundary condition. (see tables 5.2 and 5.3 the detail will discuss in subject 2.) The simulation of temperature - time profiles were determined for the following boundary condition :

a.) Using ideal boundary condition of curing service. Its mean that surface temperature kept constant at zero time to infinity.

b.) Using actual boundary condition of curing service and cooling cycle data , the surface temperature variable but known.

The curing service condition were restricted to the temperature of saturated hot water inside the bladder and the super heated steam inside the metal mould. There were temperature equal 193 °C and 163 °C respectively.

From the theoretically, the temperature-time profile could be simulated from the equation below ;

$$T_{(t+\Delta t)} = F_o * [\ T_{r+\Delta r} * (1+\Delta r/r) - T_r * (2+\Delta r/r) + T_{r+\Delta r}\ ] + T_t \qquad (5-1)$$

The simulation results of temperature - time profile at under tread position to be considered were fited by trial and error of the F_o value.

1. DISCUSSION ON IDEAL BOUNDARY CONDITION OF CURING SERVICE

The experimental were set up in order to defind the heating time from the start of the curing cycle until the green tire reached thermal equilibrium (this status was steady state). This was a measuring of the heating time required until the temperature at under tread position was sufficiently close to the impressed temperature that the body could be regarded as being at a uniform temperature. The results were plotted in Fig. 5.1 shown that simulated temperature profiles were close to the heating step.

From Fig. 5.1, it was found that the value F_o was **0.07987**. The mathematical model were fited with the existing data. The results as shown in table 5.4. This model as shown in equation below :

$$T_{(t+\Delta t)} - T_{(t)} = 8.26\text{x}10^{-2}\ T_{(r+\Delta r)} - 1.62\text{x}10^{-1}\ T_{(r)} + 7.19\text{x}10^{-2}\ T_{(r-\Delta r)} \qquad (5\text{-}2)$$

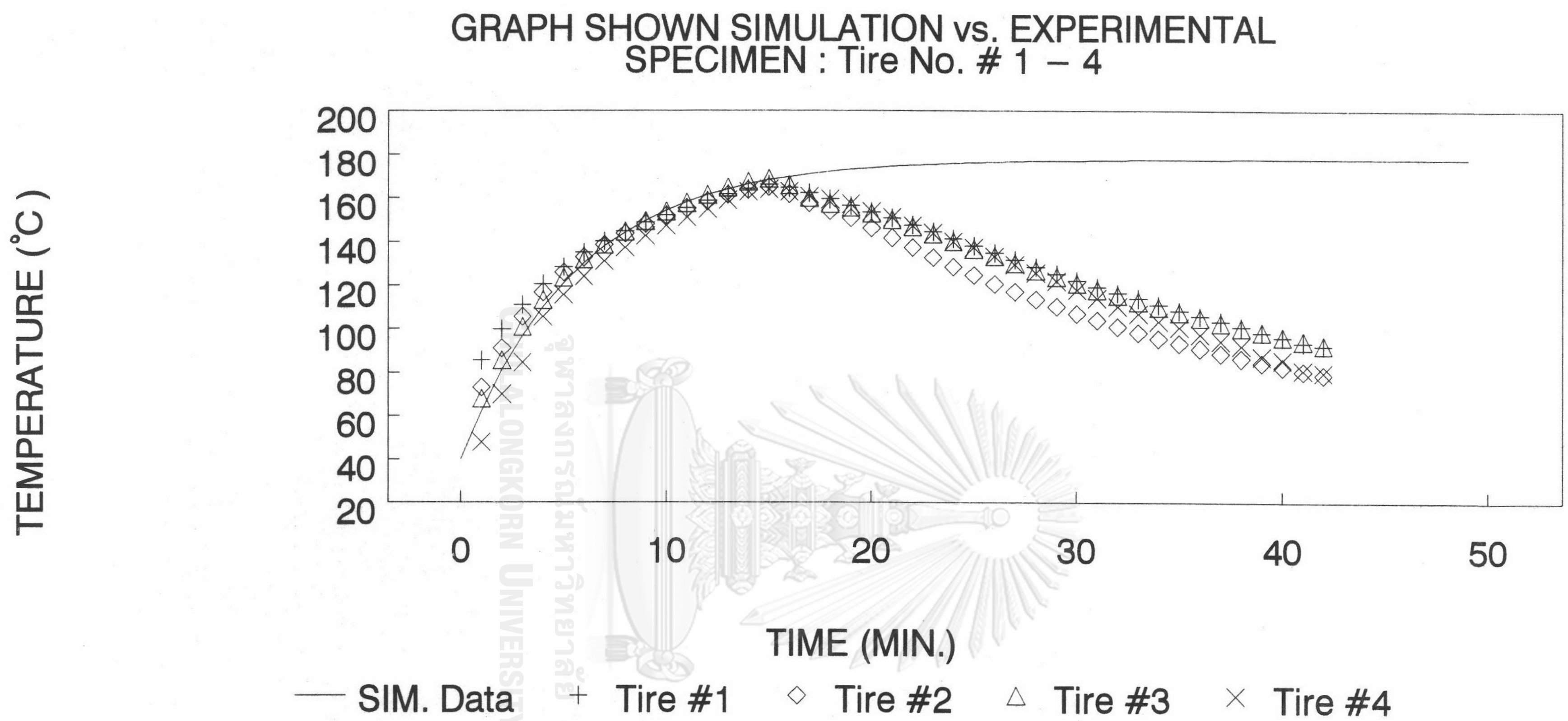

Figure 5.1 Comparison of simulation results with experimental data for ideal boundary condition

2. DISCUSSION ON ACTUAL BOUNDARY CONDITION OF CURING SERVICE AND COOLING CYCLE DATA

For the same method of curve fitting the mathematical model with the experimental data (see table 5.1 - 5.3). There were four tires were measured temperature-time profiles. These profiles shown heating and cooling step during tire curing process, that were specified for actual boundary condition. The results in table 5.2 and 5.3 as shown mean temperature of bladder surface and tread surface position of four tires. Those mean temperatures presented for heating and cooling of tire curing process, that were taken to simulation. The required temperature - time profile was simulated by the value F_o was 0.4175. (see Fig. 5.2) The mathematical model as the equation below ;

$$T_{(t+\Delta t)} - T_{(t)} = 4.32\times10^{-1}\, T_{(r+\Delta r)} - 8.49\times10^{-1}\, T_{(r)} + 4.18\times10^{-1}\, T_{(r-\Delta r)} \qquad (5\text{-}3)$$

The comparison of simulation results with experimental data as shown in table 5.5. The increasing of F_o value was compared with the value that found from previous condition. It could be explained that the actual boundary condition of tire curing process had surface resistance. The actual curing service condition were decreased, when compared with ideal condition. This decreasing affected to surface temperature. The value of thermal diffusivity was increasable to be achived thermal equilibrium.

From experiments, comparing between the simulated data with existing data, it is found that the simulation of temperature - time profile at under tread position were slightly different. However, it was possible to provide the simulation corresponed closely to the theorem. It could be seen that the simulation results were in good agreement with the experimental results. Figure 5.2 shown the measured and simulated cycle for tire curing process.

CALCULATION OF THERMAL DIFFUSIVITY EMPIRICAL AND COMPARE WITH LITERATURE DATA

From the value F_o could be calculated the thermal diffusivity by this equation below :-

$$F_o = D. \Delta t / (\Delta r)^2 \qquad (5-4)$$

The thermal diffusivity was determined from above equation, was call " D-empirical ,(D-Emp.) ". This value was compared with literature data from table 2.2 (page 42). It was found that the D-Emp. had the power order equal literature data. (The calculation results see table 5.6 and 5.7)

The value of D-Emp. as following :

- For ideal boundary condition : 1.73×10^{-7} m^2/sec.
- For actual boundary condition : 9.04×10^{-7} m^2/sec.

The thermal diffusivity empirical value as 9.04×10^{-7} m^2/sec. This value (D-Emp.) could be represented heat flow calculation for 195 R 14 C radial tire. It could be proved by the comparison of simulation results with exisiting data. (see Fig. 5.2)

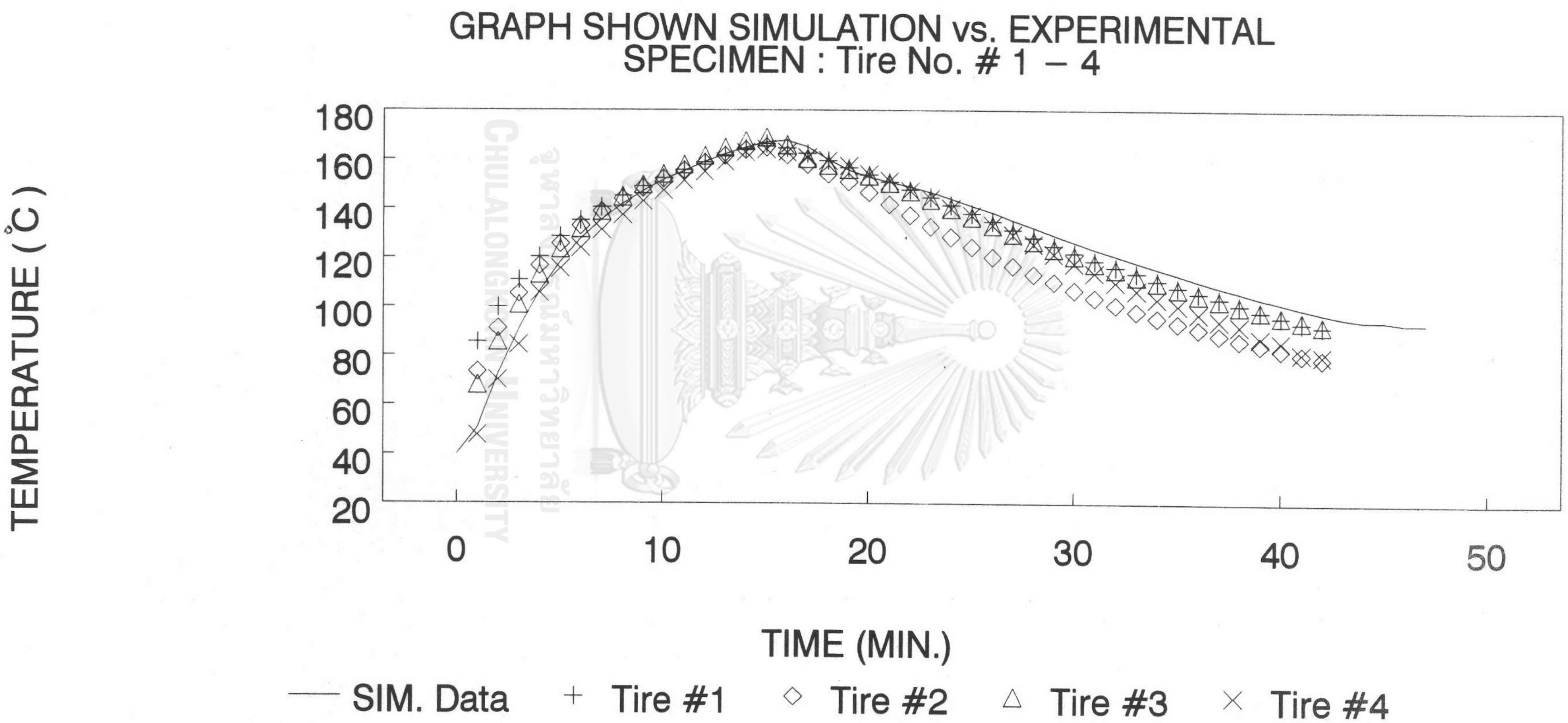

Figure 5.2 Comparison of simulation results with experimental data for actual boundary condition (heating & cooling)

APPLICATION TO TIRE CURING PROCESS

From the experimental discussion, it could be simulated temperature-time profile at under tread position of 195 R 14 C radial tire and shown thermal diffusivity empirical value for this size. All of this results were applied to tire curing process, as presented in case study.

1. CASE STUDY I.

Curing service condition changing affected heating and cooling of tire curing process. In this case, if known the actual data of curing service condition changing occur during tire curing process. Mathematical model was used to simulate temperature - time profile at under tread position and shown differential between regular profile with the case study profile. From the results in Fig. 5.3, as shown the comparison of simulation results for case study I. with regular profile. Case study I. the curing service condition (internal and external temperature) were dropped 5 degree per minute ($^{\circ}$C/min.). (On each time interval was lower than regular condition 5 degree). It was found that simulation results for heating step were lower than regular profile. For tire curing process, meaning was undercure. The temperature at under tread position was lower than specification.

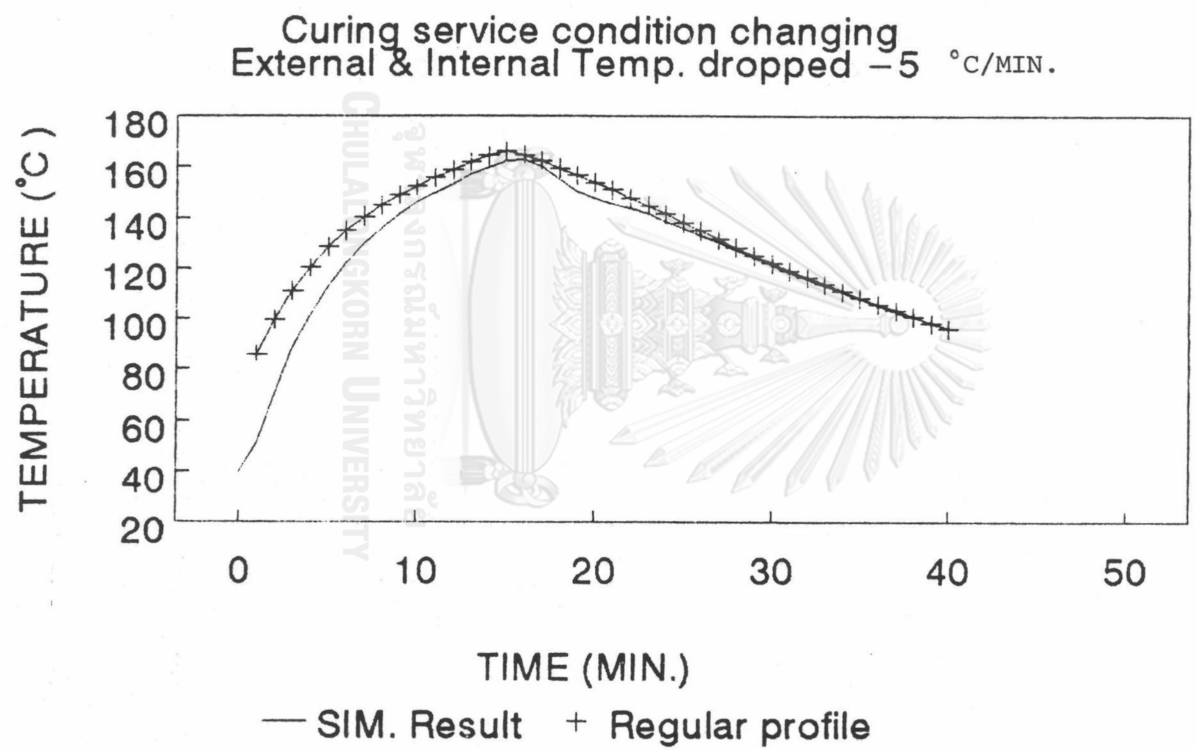

Figure 5.3 The comparison of simulation results for case study I with regular profile

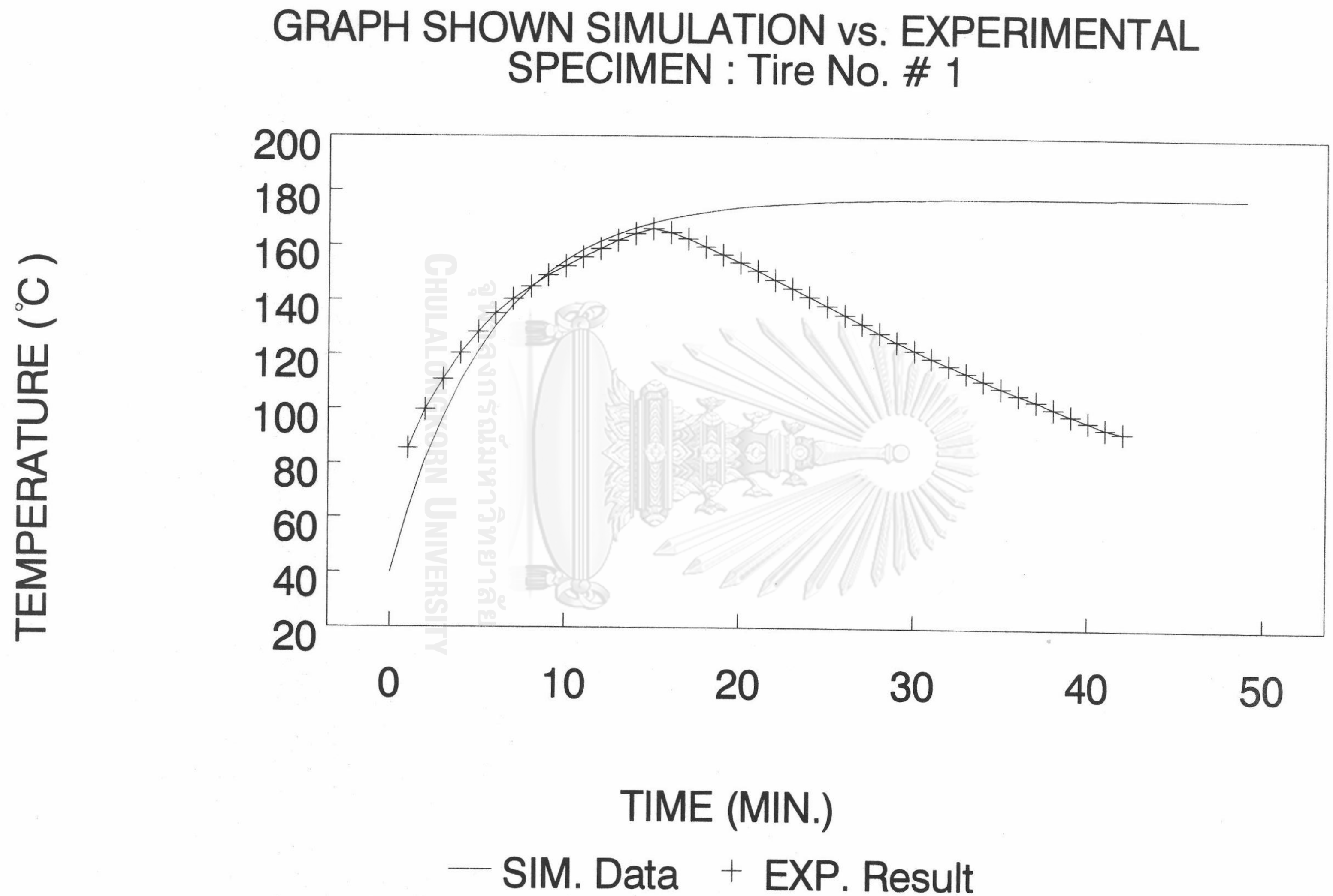

Figure 5.4 Comparison of simulation results with experimental data for ideal boundary condition : specimen Tire #1

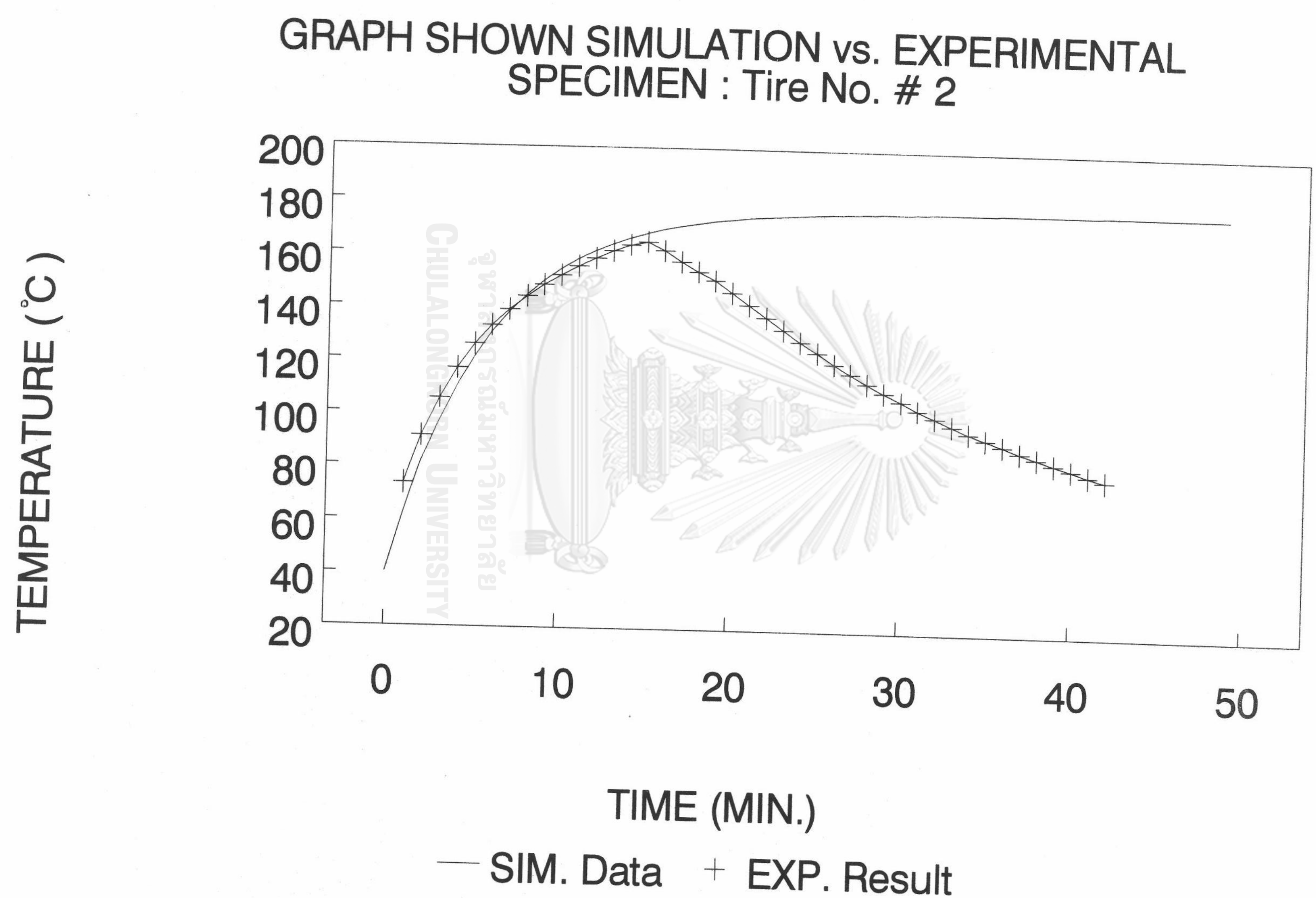

Figure 5.5 Comparison of simulation results with experimental data for ideal boundary condition : specimen Tire #2

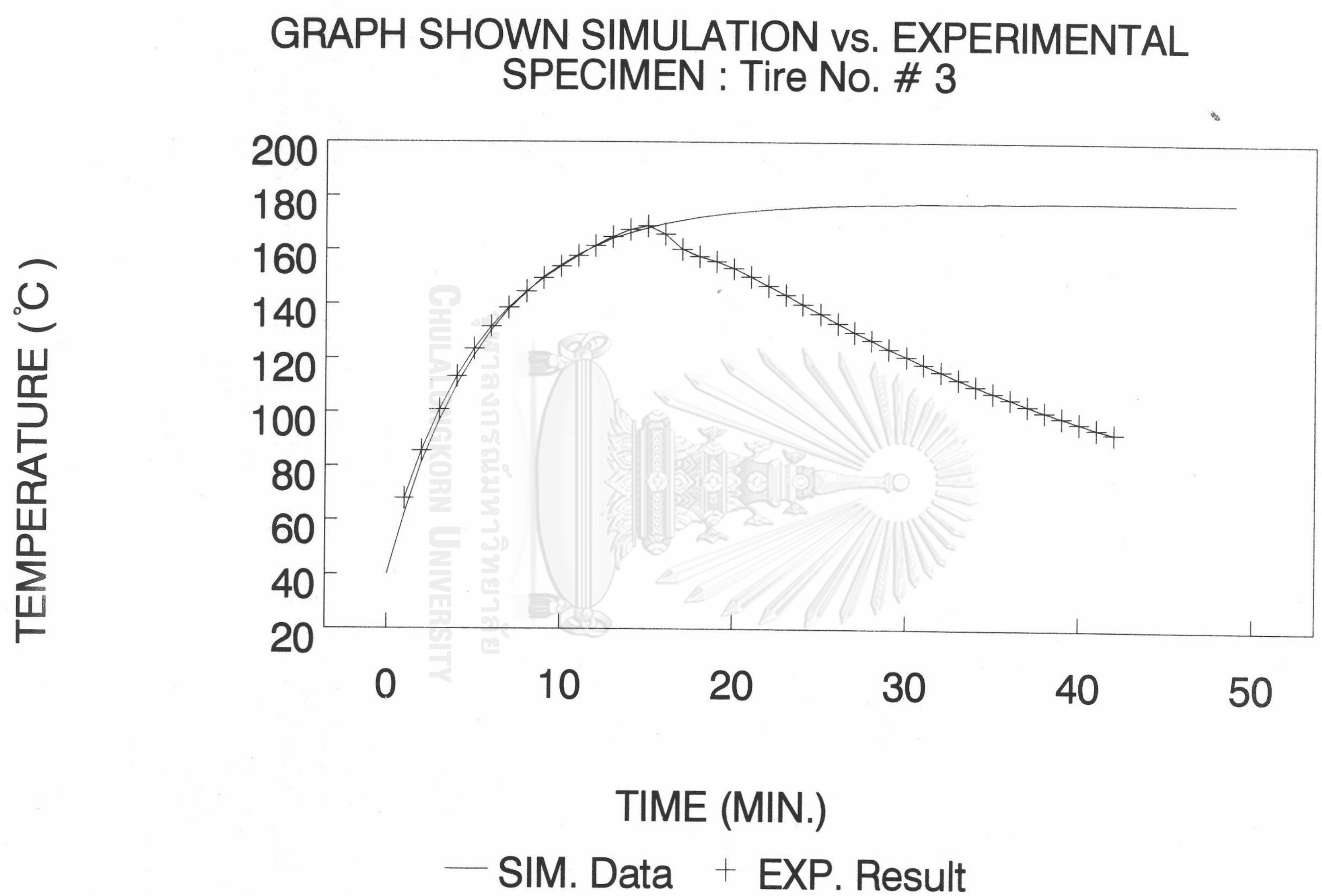

Figure 5.6 Comparison of simulation results with experimental data for ideal boundary condition : specimen Tire #3

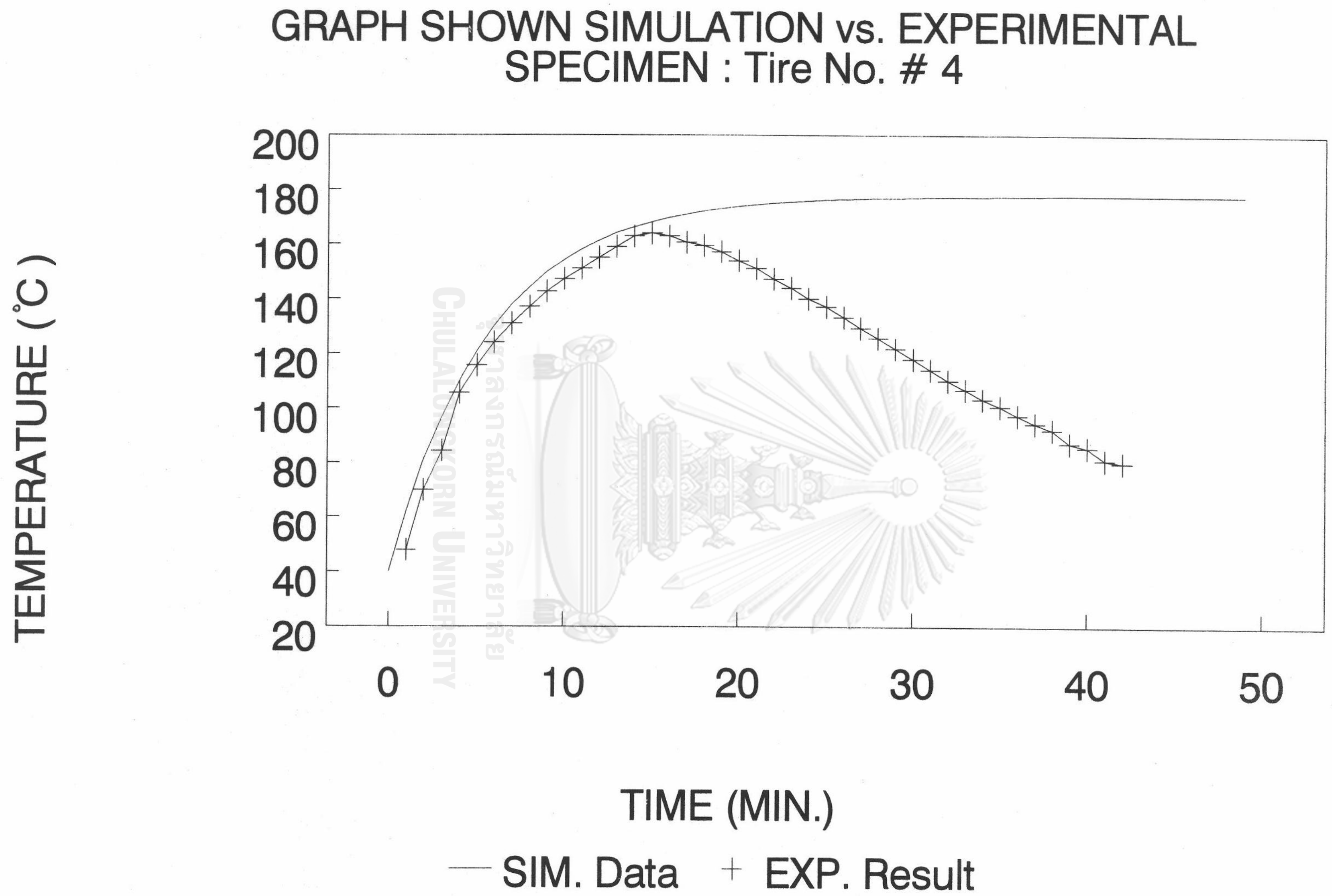

Figure 5.7 Comparison of simulation results with experimental data for ideal boundary condition : specimen Tire #4

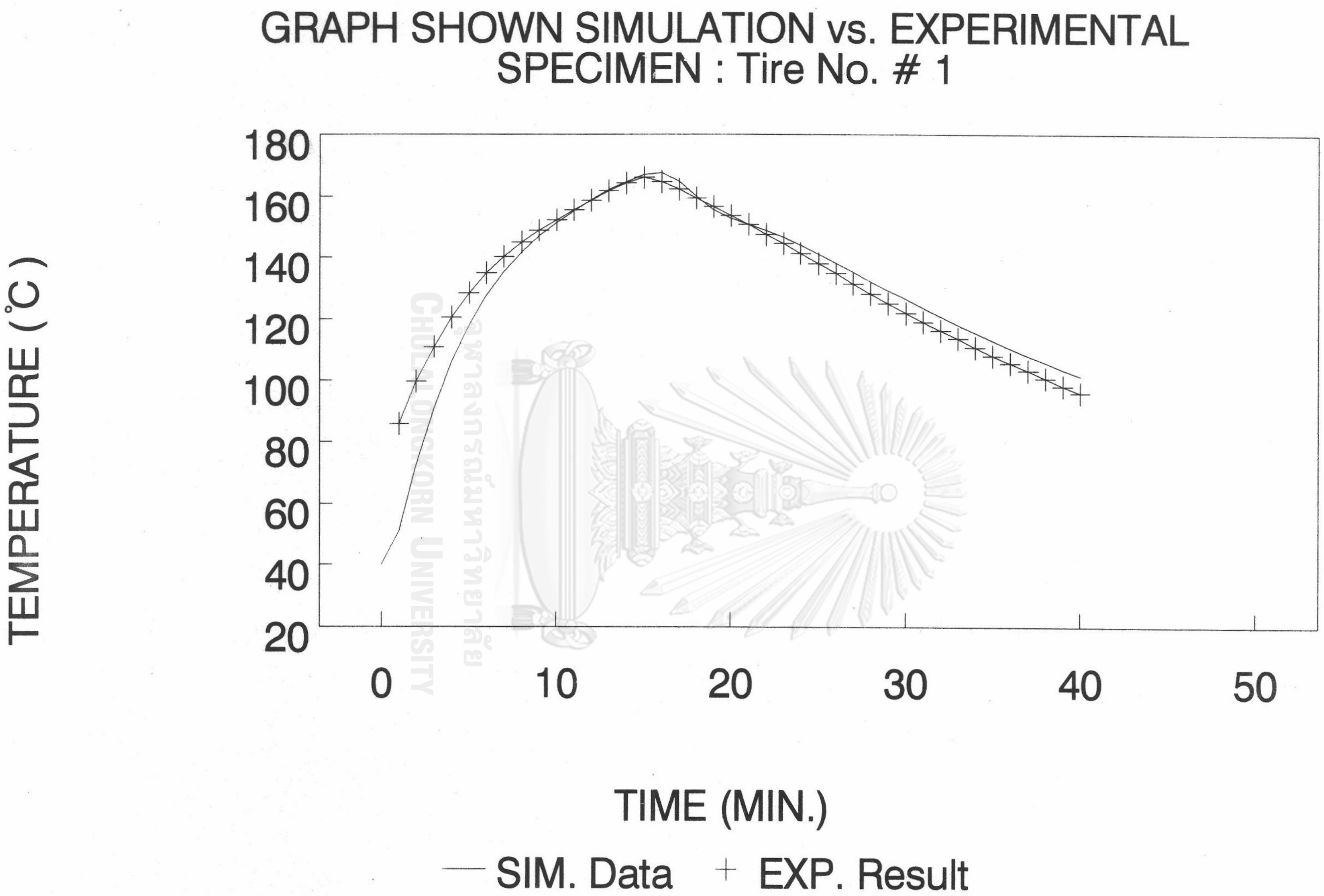

Figure 5.8 Comparison of simulation results with experimental data for actual boundary condition (heating & cooling) specimen : Tire #1

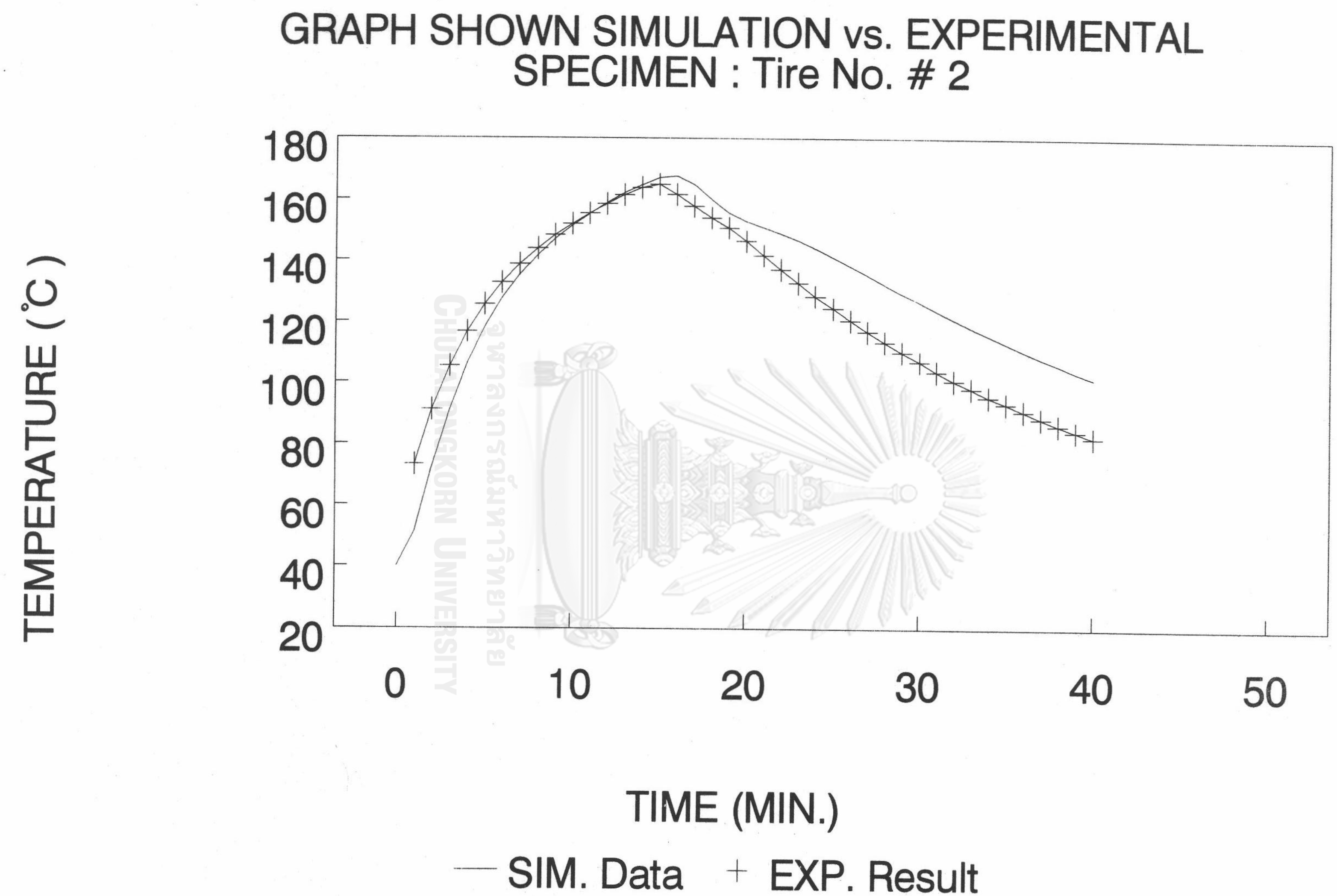

Figure 5.9 Comparison of simulation results with experimental data for actual boundary condition (heating & cooling) specimen : Tire #2

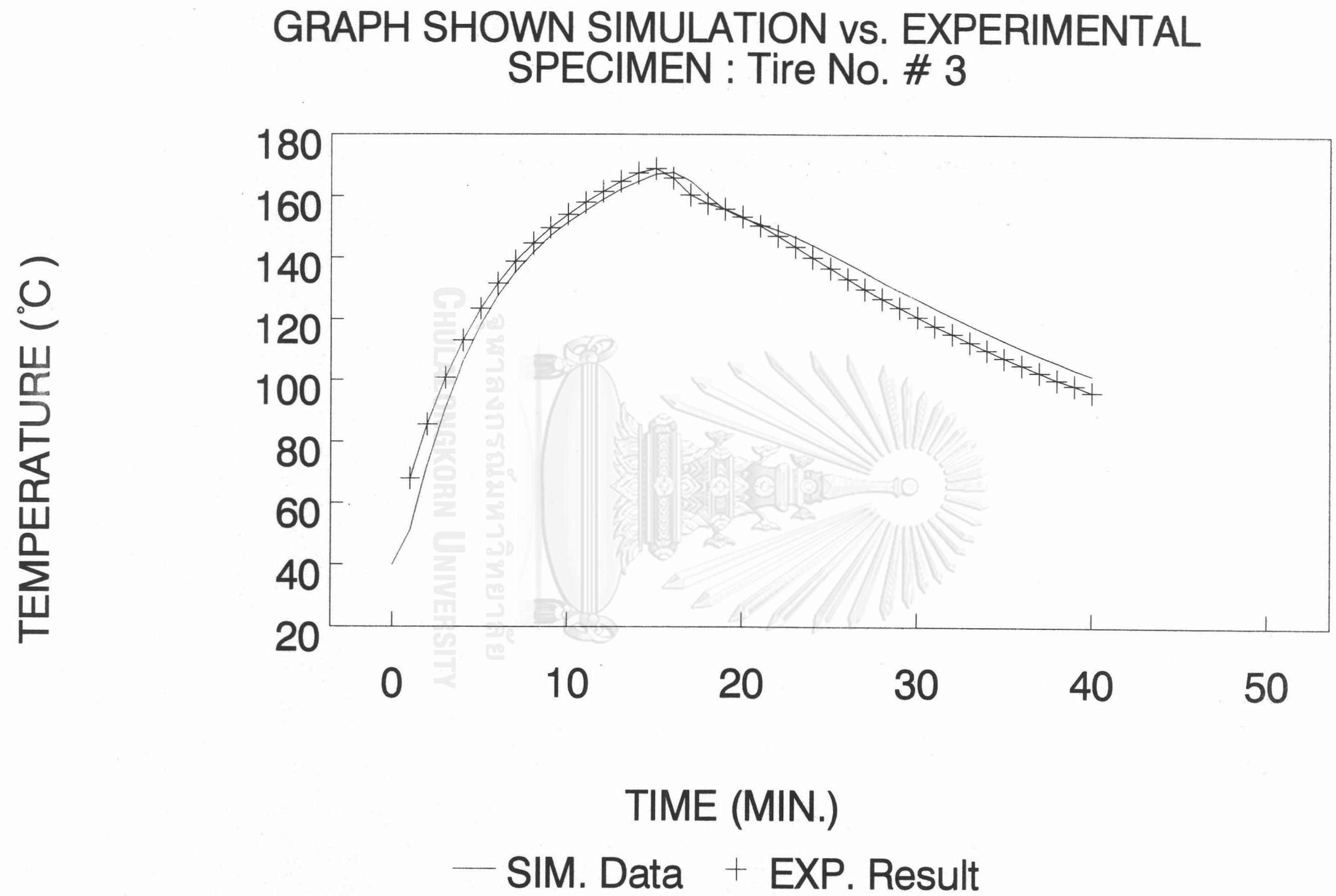

Figure 5.10 Comparison of simulation results with experimental data for actual boundary condition (heating & cooling) specimen : Tire #3

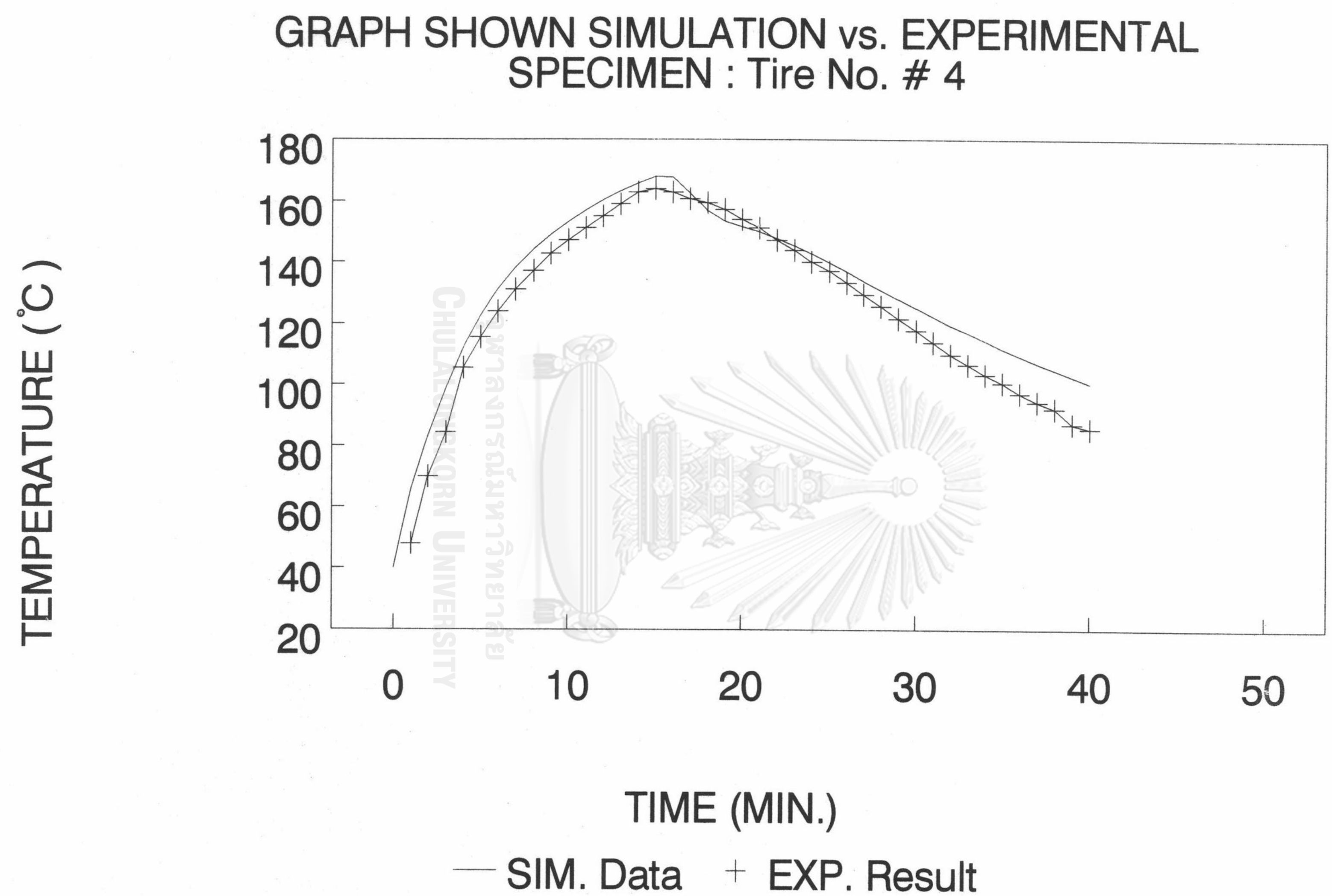

Figure 5.11 Comparison of simulation results with experimental data for actual boundary condition (heating & cooling) specimen : Tire #4

TABLE 5.1 SHOWN EXPERIMENT DATA OF TEMPERATURE UNDER TREAD POSITION

TIME (MINUTE)	UNDER TREAD TEMPERATURE (°C)			
	Tire No.# 1	Tire No.# 2	Tire No.# 3	Tire No.# 4
1.0	–	–	–	47.8
2.0	85.8	73.2	68.0	70.0
3.0	99.7	91.1	85.6	84.4
4.0	110.9	105.4	100.7	105.6
5.0	120.4	116.7	113.1	115.6
6.0	128.4	125.7	123.4	123.9
7.0	135.0	132.8	131.7	131.1
8.0	140.3	138.7	138.7	137.2
9.0	144.9	143.8	144.6	142.8
10.0	148.9	148.2	149.6	147.2
11.0	152.3	151.9	153.9	151.1
12.0	155.6	155.3	157.8	155.0
13.0	158.7	158.5	161.4	158.9
14.0	161.7	161.4	164.7	162.8
15.0	164.3	163.7	167.4	163.9
16.0	166.1	164.9	168.8	162.8
17.0	164.6	161.6	165.8	160.6
18.0	162.3	157.7	160.2	159.4
19.0	159.4	154.0	157.5	157.2
20.0	156.6	150.7	155.7	153.9
21.0	153.7	146.3	153.1	151.1
22.0	150.8	141.7	150.2	147.2
23.0	147.6	137.2	146.9	143.9
24.0	144.6	132.7	143.6	140.0
25.0	141.4	128.4	140.0	137.2
26.0	138.0	124.4	136.5	133.3
27.0	134.8	120.4	133.1	129.4
28.0	131.5	116.8	129.8	125.6
29.0	128.2	113.3	126.8	121.7
30.0	125.0	110.1	123.7	117.8
31.0	122.0	106.9	120.7	113.9
32.0	119.0	103.8	117.8	110.0
33.0	116.3	100.9	115.2	106.7
34.0	113.8	98.2	112.4	103.3
35.0	110.8	95.5	109.9	100.6
36.0	108.1	93.2	107.3	97.2
37.0	105.7	90.9	105.0	94.4
38.0	103.4	88.5	102.6	92.2
39.0	100.7	86.3	100.3	87.2
40.0	98.2	84.3	98.4	85.6
41.0	96.0	82.4	96.2	81.1
42.0	93.9	80.4	94.3	80.0
43.0	92.2	78.8	92.5	77.8
44.0	–	77.0	90.7	76.7
45.0	–	75.3	–	75.6
46.0	–	74.0	–	73.3
47.0	–	–	–	–

TABLE 5.2 SHOWN TREAD SURFACE TEMPERATURE OF SPECIMEN

TIME (MINUTE)	TREAD SURFACE TEMPERATURE (°C)				
	Tire No.# 1	Tire No.# 2	Tire No.# 3	Tire No.# 4	AVERAGE
1.0	–	–	75.3	–	75.3
2.0	95.4	95.1	95.3	96.0	95.5
3.0	110.1	109.5	110.8	111.6	110.5
4.0	121.1	120.6	122.3	125.0	122.2
5.0	129.8	128.9	131.3	133.3	130.8
6.0	137.2	135.6	138.6	139.8	137.8
7.0	143.2	141.3	144.5	145.3	143.6
8.0	147.8	145.9	149.6	150.1	148.3
9.0	151.8	150.1	153.6	153.8	152.3
10.0	155.3	153.6	157.1	157.1	155.8
11.0	158.6	156.8	160.6	160.2	159.1
12.0	161.6	159.8	163.4	163.1	162.0
13.0	163.9	162.3	165.8	165.3	164.3
14.0	166.2	164.3	167.8	167.0	166.3
15.0	168.2	165.9	169.5	168.3	168.0
16.0	167.8	165.8	169.6	168.3	167.9
17.0	162.3	159.9	164.3	163.6	162.5
18.0	155.7	153.8	156.8	158.3	156.2
19.0	150.0	149.7	153.7	155.8	152.3
20.0	147.4	147.6	152.0	154.3	150.3
21.0	145.9	145.3	150.2	152.1	148.4
22.0	144.5	142.9	148.2	149.4	146.3
23.0	142.8	140.5	145.6	146.9	143.9
24.0	140.6	137.7	142.8	144.6	141.4
25.0	137.9	134.9	139.8	142.1	138.7
26.0	135.1	132.1	136.8	139.6	135.9
27.0	131.9	129.2	133.8	137.0	133.0
28.0	129.1	126.3	131.0	134.4	130.2
29.0	126.1	123.7	128.2	131.6	127.4
30.0	123.2	121.1	125.5	129.2	124.7
31.0	120.3	118.4	122.7	126.8	122.1
32.0	117.5	115.7	119.9	124.4	119.4
33.0	115.1	113.2	117.4	122.7	117.1
34.0	112.5	110.8	114.8	120.6	114.7
35.0	109.6	108.4	112.3	118.2	112.1
36.0	106.8	106.2	110.2	115.9	109.8
37.0	104.8	103.9	107.7	113.8	107.6
38.0	102.6	101.8	105.5	111.8	105.4
39.0	99.8	99.8	103.4	110.1	103.3
40.0	97.4	97.7	101.4	108.4	101.2
41.0	95.4	95.6	99.3	106.7	99.3
42.0	93.4	93.8	97.5	105.3	97.5
43.0	91.9	92.1	95.8	103.8	95.9
44.0	–	90.3	94.0	102.5	95.6
45.0	–	88.4	–	101.0	94.7
46.0	–	86.7	–	99.2	92.9
47.0	–	–	–	97.8	97.8

TABLE 5.3 SHOWN BLADDER SURFACE TEMPERATURE OF SPECIMEN

TIME (MINUTE)	BLADDER SURFACE TEMPERATURE (℃)				
	Tire No.# 1	Tire No.# 2	Tire No.# 3	Tire No.# 4	AVERAGE
1.0	–	–	–	65.7	65.7
2.0	82.0	71.1	72.9	80.7	76.7
3.0	99.0	87.5	90.2	95.3	93.0
4.0	112.7	101.7	104.7	108.3	106.9
5.0	123.9	113.5	116.7	118.9	118.3
6.0	133.1	123.3	126.6	127.7	127.7
7.0	140.7	131.3	134.5	134.9	135.3
8.0	146.8	138.1	141.3	141.3	141.9
9.0	151.8	143.8	147.1	146.6	147.3
10.0	156.1	148.7	151.9	151.1	152.0
11.0	160.1	152.9	156.1	155.1	156.0
12.0	163.8	156.8	160.1	158.6	159.8
13.0	166.7	160.6	163.7	162.1	163.3
14.0	169.5	163.6	166.7	165.1	166.2
15.0	171.7	166.2	169.1	167.4	168.6
16.0	167.3	165.2	169.6	167.8	167.5
17.0	158.2	158.8	163.1	163.2	160.8
18.0	151.1	155.2	156.6	158.8	155.4
19.0	147.3	153.4	154.8	157.3	153.2
20.0	146.6	152.0	154.1	155.9	152.1
21.0	146.1	149.8	152.6	153.8	150.6
22.0	145.3	147.1	150.4	151.1	148.5
23.0	143.8	144.4	147.4	148.5	146.0
24.0	140.9	141.1	144.2	146.0	143.1
25.0	137.7	137.8	140.8	143.3	139.9
26.0	134.7	134.7	137.2	140.7	136.8
27.0	131.2	131.3	133.8	137.8	133.5
28.0	128.1	128.1	130.5	135.1	130.4
29.0	125.1	124.9	127.3	132.2	127.4
30.0	122.0	121.9	124.1	129.6	124.4
31.0	119.0	118.8	120.9	126.9	121.4
32.0	116.1	115.8	117.7	124.4	118.5
33.0	113.6	112.9	114.8	122.4	115.9
34.0	110.6	110.3	111.8	120.0	113.2
35.0	107.4	107.7	109.1	117.5	110.4
36.0	104.6	105.3	106.6	115.2	107.9
37.0	102.3	102.9	103.9	113.1	105.5
38.0	99.9	100.6	101.4	110.9	103.2
39.0	97.1	98.3	99.1	109.1	100.9
40.0	94.8	96.1	96.8	107.3	98.8
41.0	92.7	94.0	94.5	105.5	96.7
42.0	90.7	92.1	92.5	103.9	94.8
43.0	89.0	90.3	90.6	102.4	93.1
44.0	–	88.4	88.7	100.9	92.7
45.0	–	86.6	–	99.4	93.0
46.0	–	84.8	–	97.6	91.2
47.0	–	–	–	96.2	96.2

Table 5.4 Comparison of simulation results with experimental data for ideal boundary condition

TIME INTERVAL (Minute)	SIM. RESULTS Temperature (°C)	Experimental data : Temperature (°C)			
		Tire #1	Tire #2	Tire #3	Tire #4
0.0	40.0				
1.0	62.4	85.5	73.2	68.0	47.8
2.0	81.1	99.7	91.1	85.6	70.0
3.0	96.8	110.9	105.4	100.7	84.4
4.0	110.0	120.4	116.7	113.1	105.6
5.0	121.0	128.4	125.7	123.4	115.6
6.0	130.2	135.0	132.8	131.7	123.9
7.0	137.9	140.3	138.7	138.7	131.1
8.0	144.4	144.9	143.8	144.6	137.2
9.0	149.8	148.9	148.2	149.6	142.8
10.0	154.4	152.3	151.9	153.9	147.2
11.0	158.2	155.6	155.3	157.8	151.1
12.0	161.3	158.7	158.5	161.4	155.0
13.0	164.0	161.7	161.4	164.7	158.9
14.0	166.2	164.3	163.7	167.4	162.8
15.0	168.1	166.1	164.9	168.8	163.9
16.0	169.7	164.6	161.6	165.8	162.8
17.0	171.0	162.3	157.7	160.2	160.6
18.0	172.1	159.4	154.0	157.5	159.4
19.0	173.0	156.6	150.7	155.7	157.2
20.0	173.8	153.7	146.3	153.1	153.9
21.0	174.4	150.8	141.7	150.2	151.1
22.0	175.0	147.6	137.2	146.9	147.2
23.0	175.4	144.6	132.7	143.6	143.9
24.0	175.8	141.4	128.4	140.0	140.0
25.0	176.1	138.0	124.4	136.5	137.2
26.0	176.4	134.8	120.4	133.1	133.3
27.0	176.6	131.5	116.8	129.8	129.4
28.0	176.8	128.2	113.3	126.8	125.6
29.0	176.9	125.0	110.1	123.7	121.7
30.0	177.1	122.0	106.9	120.7	117.8
31.0	177.2	119.0	103.8	117.8	113.9
32.0	177.3	116.3	100.9	115.2	110.0
33.0	177.4	113.8	98.2	112.4	106.7
34.0	177.4	110.8	95.5	109.9	103.3
35.0	177.5	108.1	93.2	107.3	100.6
36.0	177.5	105.7	90.9	105.0	97.2
37.0	177.6	103.4	88.5	102.6	94.4
38.0	177.6	100.7	86.3	100.3	92.2
39.0	177.6	98.2	84.3	98.4	87.2
40.0	177.6	96.0	82.4	96.2	85.6
41.0	177.7	93.6	80.4	94.3	81.1
42.0	177.7	92.2	78.8	92.5	80.0
43.0	177.7				
44.0	177.7				
45.0	177.7				
46.0	177.7				
47.0	177.7				
48.0	177.7				
49.0	177.7				

Table 5.5 Comparison of simulation results with experimental data for actual boundary condition (heating & cooling curve)

TIME INTERVAL (Minute)	SIM. RESULTS Temperature (°C)	Experimental data : Temperature (°C)			
		Tire #1	Tire #2	Tire #3	Tire #4
0.0	40.0				
1.0	50.7	85.5	73.2	68.0	47.8
2.0	72.2	99.7	91.1	85.6	70.0
3.0	90.9	110.9	105.4	100.7	84.4
4.0	106.1	120.4	116.7	113.1	105.6
5.0	118.1	128.4	125.7	123.4	115.6
6.0	127.6	135.0	132.8	131.7	123.9
7.0	135.2	140.3	138.7	138.7	131.1
8.0	141.6	144.9	143.8	144.6	137.2
9.0	146.9	148.9	148.2	149.6	142.8
10.0	151.4	152.3	151.9	153.9	147.2
11.0	155.2	155.6	155.3	157.8	151.1
12.0	158.8	158.7	158.5	161.4	155.0
13.0	162.1	161.7	161.4	164.7	158.9
14.0	164.8	164.3	163.7	167.4	162.8
15.0	167.0	166.1	164.9	168.8	163.9
16.0	167.6	164.6	161.6	165.8	162.8
17.0	164.9	162.3	157.7	160.2	160.6
18.0	159.9	159.4	154.0	157.5	159.4
19.0	155.5	156.6	150.7	155.7	157.2
20.0	152.7	153.7	146.3	153.1	153.9
21.0	150.8	150.8	141.7	150.2	151.1
22.0	148.8	147.6	137.2	146.9	147.2
23.0	146.6	144.6	132.7	143.6	143.9
24.0	144.0	141.4	128.4	140.0	140.0
25.0	141.2	138.0	124.4	136.5	137.2
26.0	138.3	134.8	120.4	133.1	133.3
27.0	135.3	131.5	116.8	129.8	129.4
28.0	132.3	128.2	113.3	126.8	125.6
29.0	129.3	125.0	110.1	123.7	121.7
30.0	126.4	122.0	106.9	120.7	117.8
31.0	123.6	119.0	103.8	117.8	113.9
32.0	120.8	116.3	100.9	115.2	110.0
33.0	118.2	113.8	98.2	112.4	106.7
34.0	115.6	110.8	95.5	109.9	103.3
35.0	113.0	108.1	93.2	107.3	100.6
36.0	110.5	105.7	90.9	105.0	97.2
37.0	108.1	103.4	88.5	102.6	94.4
38.0	105.8	100.7	86.3	100.3	92.2
39.0	103.6	98.2	84.3	98.4	87.2
40.0	101.5	96.0	82.4	96.2	85.6
41.0	99.4	93.6	80.4	94.3	81.1
42.0	97.4	92.2	78.8	92.5	80.0
43.0	95.7				
44.0	94.5				
45.0	94.4				
46.0	93.2				
47.0	93.2				
48.0					

TABLE 5.6 SHOWN CALCULATION OF Emp.–THERMAL CONDUCTIVITY & Emp.–THERMAL DIFFUSIVITY USING : IDEAL BOUNDARY CONDITION

Temperature interval (°C)	Fo (curve fitting) dimensionless	Time increment, dt (sec.)	Radial increment, dr (m.)	Density of tread compound (Kg/cu.m)	Specific heat Cp. (J/Kg.°C)	Emp. Thermal conductivity, K (W/m.°C)	Emp Thermal diffusivity, D (sq.m./sec.)
100	0.07987	60	0.0114	1117	410	0.079	1.73E−07
125	0.07987	60	0.0114	1115	1240	0.240	1.73E−07
150	0.07987	60	0.0114	1114	1350	0.261	1.73E−07
175	0.07987	60	0.0114	1108	850	0.164	1.73E−07

THERMAL DIFFUSIVITY – Emp = 1.73 E −07 (sq.m./sec.)

GRAPH SHOWN EFFECT OF TEMPERATURE ON THERMAL CONDUCTIVITY OF TREAD STOCK

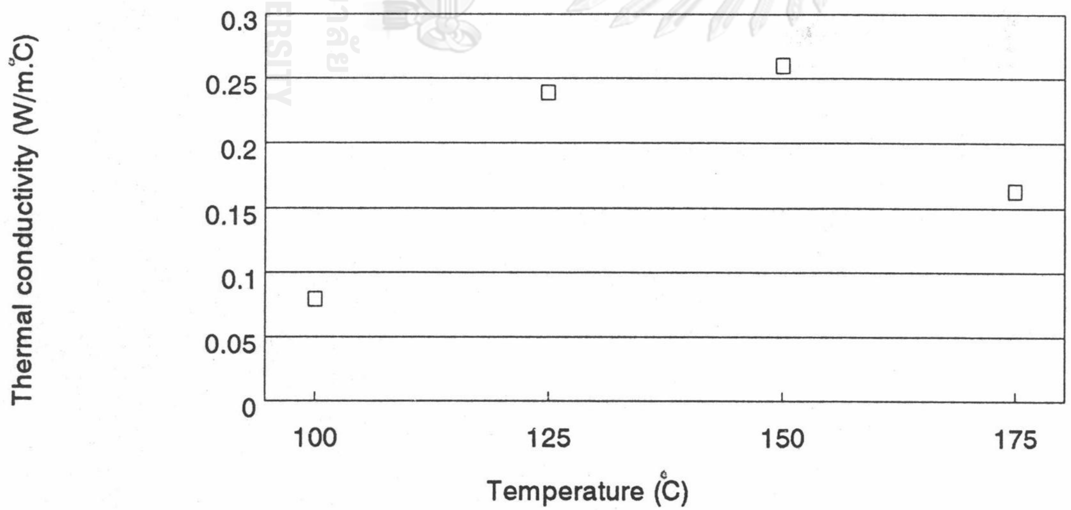

TABLE 5.7 **SHOWN CALCULATION OF Emp –THERMAL CONDUCTIVITY & Emp –THERMAL DIFFUSIVITY USING : ACTUAL BOUNDARY CONDITION**

Temperature interval (°C)	Fo (curved fitting) dimensionless	Time increment,dt (sec.)	Radial increment,dr (m.)	Density of tread compound (Kg/cu.m)	Specific heat Cp. (J/Kg.°C)	Emp Thermal conductivity,K (W/m.°C)	Emp Thermal diffusivity,D (sq.m./sec.)
100	0.4175	60	0.0114	1117	410	0.414	9.04E–07
125	0.4175	60	0.0114	1115	1240	1.250	9.04E–07
150	0.4175	60	0.0114	1114	1350	1.360	9.04E–07
175	0.4175	60	0.0114	1108	850	0.852	9.04E–07

THERMAL DIFFUSIVITY – Emp = 9.04 E –07 (sq.m./sec.)

GRAPH SHOWN EFFECT OF TEMPERATURE
ON THERMAL CONDUCTIVITY OF TREAD STOCK