CHAPTER IV

EXPERIMENTS AND RESULTS

This chapter provides an overview of the experimental procedure and results. Activities performed include breaking down packaging EPS foam, investigating validation of hot box, testing for thermal resistance performance and application of broken-down packaging EPS foam with conventional materials of exterior wall. The experiments were conducted at the Faculty of Architecture at Chiang Mai University.

4.1 Breaking down Packaging EPS Foam

4.1.1 Purpose

Since the target of this research was to use EPS foam pieces to fill in the 10-centimeter-wide cap between regular wall panels but the packaging EPS foam pieces gathered from disposed waste are mostly too large to fill in the gap, therefore, they must be broken down in to small pieces. Considering the size of broken down EPS, large pieces of foam tend to have too much air void between them. Therefore, it is reasonable to use small pieces as much as possible. However, breaking down foam in to small pieces almost always takes time. Thus, it was necessary to try out some breaking down methods and to see how the resultant foam pieces will be. Time and cost to break down is a major factor besides thermal performance to judge which method is appropriate.

4.1.2 Breaking down Methods and their Resultant EPS Foam Particles

One of the main purposes of this research was to find the most appropriate and simplest way for ordinary people to use disposed packaging EPS foam. Therefore, simple manual methods to break down packaging EPS foam into small particles were investigated as described here. Sizes of packaging EPS foam particles were measured via opening of the sieves.

1) *Scratching by Papaya Shredders*

By using a papaya shredder as shown in Figure 4.1, packaging foam was shredded in to very small size of 0.1-3 mm. Using this device took a relatively long time up to 82 hours to produce 1 m^3 of foam particles. Thus, labor cost of obtaining this size will be expensive. EPS particles obtained by this method were called Size 0.1-3 in the experiment.

Figure 4.1 Shredding packaging foam by papaya shredder yields particles size 0.1-3 mm

Another breaking down method was using nail pads to scratch packaging EPS foam. It was the method, which expected to obtain particles faster and cheaper.

2) *Scratching by Nail Pads*

Wooden pads with three different spacing between nails were used. The distances between each nail in the pads are 5-8 mm, 8-10 mm and 10-12 mm. This method can break down packaging EPS foam faster than using papaya shredder. According to scratching process tried out, the pad with nail spacing of 8-10 mm was the most convenient and provided EPS particles faster than the other two.

By using the nail pads spacing 8-10 mm to scratch packaging foam, larger particles sizes were obtained. It was found that to obtain one cubic meter of EPS particles, one worker spent 12 hours to complete 1 m^3. As shown in Figure 4.2, this method gave various sizes of particles mostly smaller than 15 mm. These pieces of foam were called Size 0.1-15 in the experiment.

Figure 4.2 Scratching packaging foam by nail pad yields a mix-particle size 0.1-15 mm

Separation of particle sizes of packaging EPS foam was done by using sieve analysis method. Therefore, the opening of sieves could determine sizes of those particles. Particle Size 0.1-6, Size 6-10 and Size 10-15 as shown in Figure 4.3 were obtained from sieving Size 0.1-15.

Figure 4.3 Packaging EPS particles (from left to right) Size 0.1-6, Size 6-10 and Size 10-15

3) Breaking Down by Hand

To obtain larger EPS particles, packaging foam was picked off by hand. Three different sizes of EPS particles were obtained by this method. The first picking had the size of 15-30 mm (separated into Size 15-20 and Size 20-30), and another picking yielded the size of 50-70 mm (called Size 50-70). To produce 1 m^3 of Size 15-30 by hand picking was slower than scratching for the same amount. Nevertheless, picking larger sizes of EPS chunks of about 50 mm to 70 mm was faster, and therefore, the cost of production was the cheapest to produce larger chunks.

Picking process

Size 15-20

Size 20-30

Size 50-70

Figure 4.4 Breaking down packaging foam by hand picking and particles obtained

4.2 Primary Testing of Hot Box and Construction of Referent Data

4.2.1 Purpose and Approach

The purposes of this test was to evaluate the reliability of the hot box proposed in Chapter III whether it can be used in this research or not, and to construct a reference data on pre-known insulation materials for estimation of R-value of other tested materials.

4.2.2 Specimens

Solid EPS foam of 5cm, 7.5cm, 10cm and 12.5cm thick with R-value of 1.41 ºC•m^2/W (8 ºF•ft^2•h/Btu), 2.11 ºC•m^2/W (12 ºF•ft^2•h/Btu), 2.82 ºC•m^2/W (16 ºF•ft^2•h/Btu) and 3.52 ºC•m^2/W (20 ºF•ft^2•h/Btu), respectively, were installed as partitions between the heating cell and the metering cells. Each solid EPS foam panel was sandwiched between two 0.1mm-thick of galvanized steel sheets and covered all four sides by 10 mm-thick of wooden frame as shown in Figure 4.5. Galvanized steel sheets were used as transmission panels of specimens due to their heat conductivity. The steel sheets should distribute heat all over the panels more evenly.

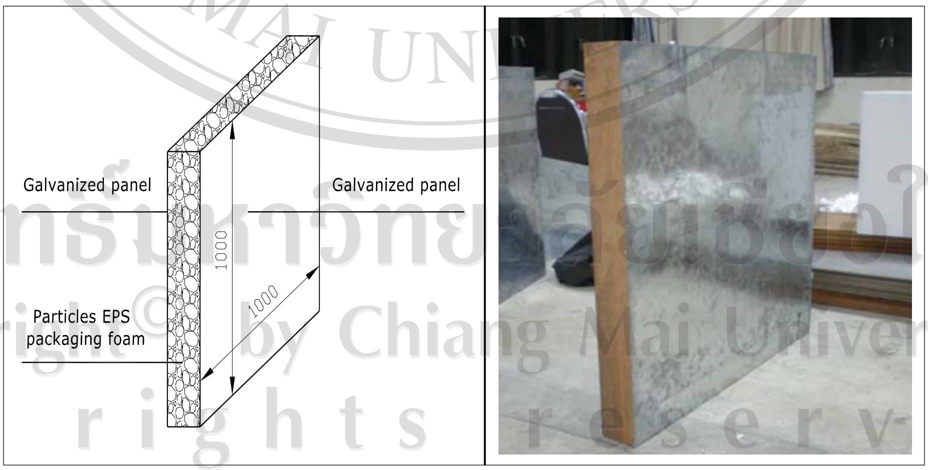

Figure 4.5 Wall panel to be used as the partition between heating and metering cells

4.2.3 Tools and Experimental Procedure

Koch-Nielson (2002) showed that temperature in and around buildings will be affected by the nature of the surrounding surfaces. In a hot climate when air temperature was about 40°C, surface temperatures of concrete can increase up to 52 °C and 65 °C depend on its painted color. Therefore, testing temperatures in this research were set as surface temperatures of concrete.

In this process, test specimens described in Section 4.2.2 were installed in the hot box for testing. The experiments were conducted at three testing temperatures of 50°C, 55°C and 60°C. The first set of experiments was completed in 6 hours. It showed that the results at 4 hours were the same as the results at 6 hours of experiments. Therefore, the latter experiments in this study were conducted in 4 hours to complete.

Temperature Control

A 200-W electric lamp was used as a heater in the heating cell. It was capable to heat up air in the heating cell to increase from temperature of about 26.5°C - 27°C up to 50°C by taking 40 minutes, up to 55°C by taking 60 minutes, and up to 60°C by taking 80 minutes. When the air temperature was raised up to the desired degree, it can be maintained steady by using an electric light dimmer to control. While air in the heating cell was heated up, heat transfer process from heating cell to all 4 metering cells occurred. Air temperatures in all metering cells were increased differently according to thermal resistance of the specimens installed as heat barriers. Five thermometer sensors were used to record the air temperatures increased in those cells.

Data Collection

From the start, when the heating light was turned on, temperatures in the heating cell and in all metering cells were recorded simultaneously by using thermometer sensors. The duration of each experiment was four hours since the starting point until finishing the experiments. Time interval to record air temperatures increased in all cells was five minutes.

The thermometer sensors were placed in the well-sealed metering cells as shown in Figures 3.4 and 3.5. They acquired the output signals from the heat flux sensors and thermocouples. Afterward they digitized, treated the signals and then manually saved the results. After acquiring the data, thermal performance of all samples can be compared.

During the experiments, an infrared thermo-gun was used to record the outside wall surface temperatures of the hot box to observe if there is any heat lost through wall or not. Figure 4.6 shows thermometer sensor and thermo-gun that were used for data acquisition.

Figure 4.6 Thermometer sensor and thermo gun

4.2.4 Result

According to experimental procedure in Section 4.2.3, thermal performances of test specimens were obtained. The following Figure 4.7, 4.8 and 4.9 show temperatures recorded in the metering cells separated from the heating cell by the test specimens when temperatures in the heating cell increased from between 26.5-27°C to 50°C, 55°C and 60°C respectively.

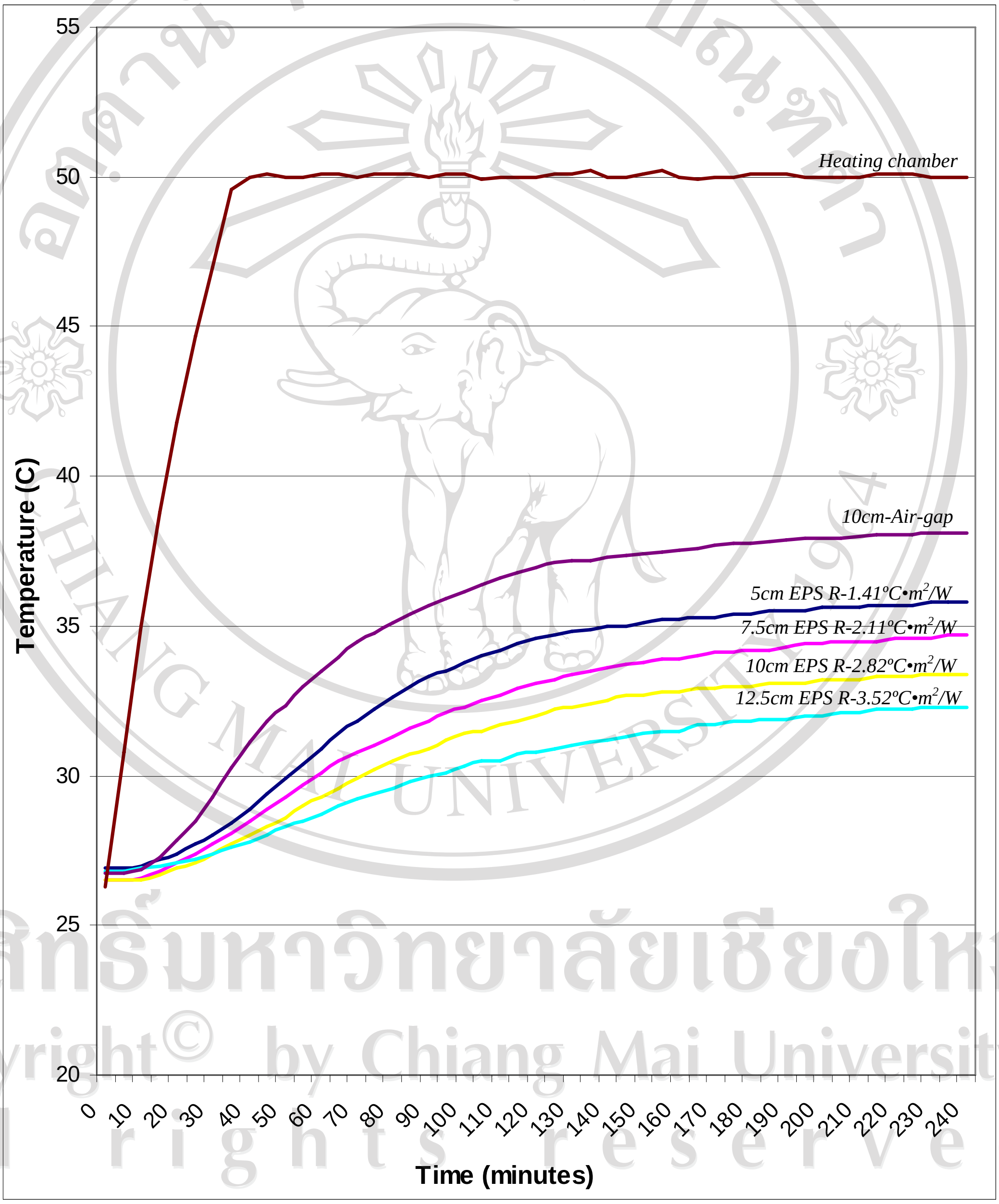

Figure 4.7 Air temperatures in metering cells when heating cell was heated up to 50°C

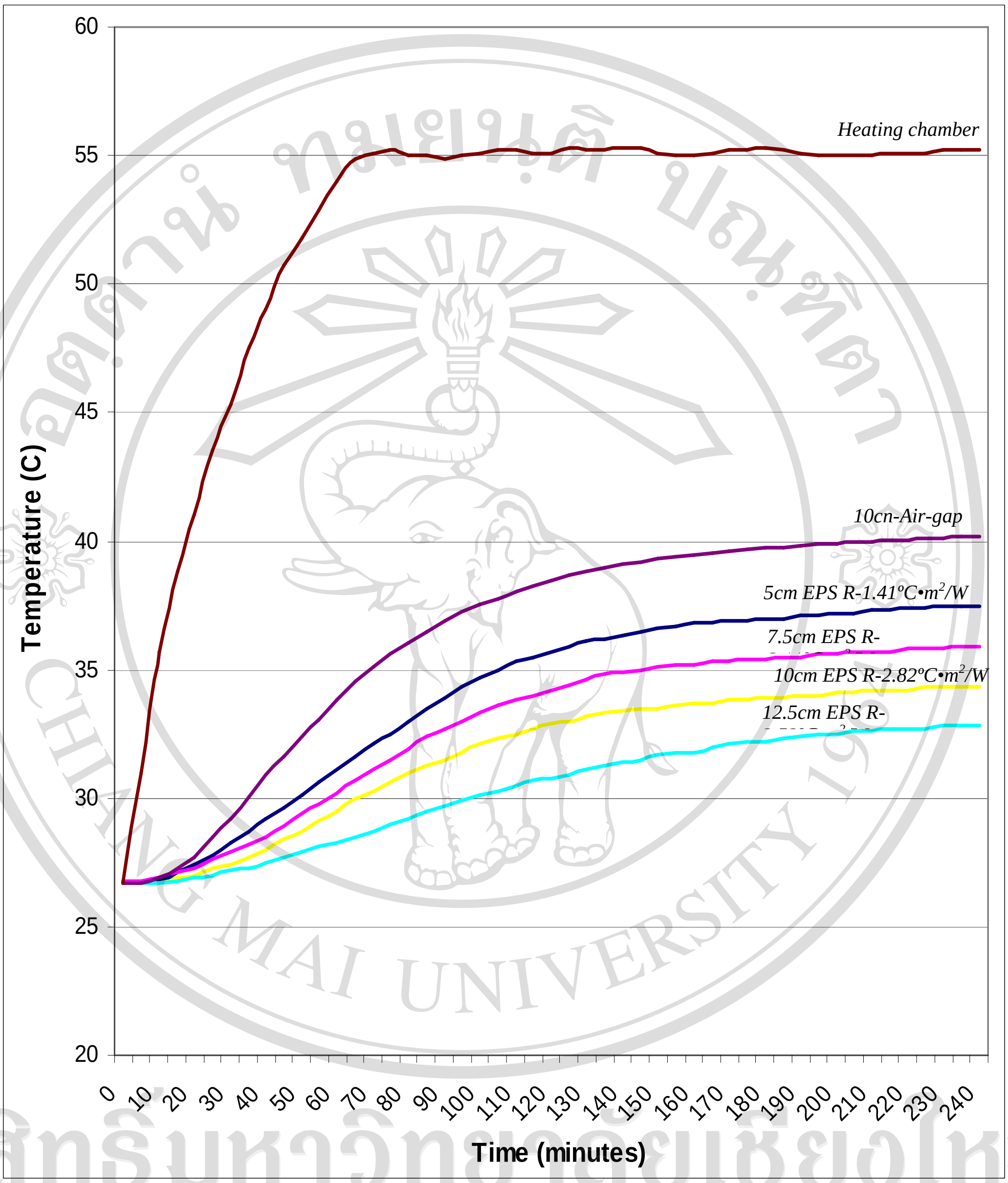

Figure 4.8 Air temperatures in metering cells when heating cell was heated up to 55°C

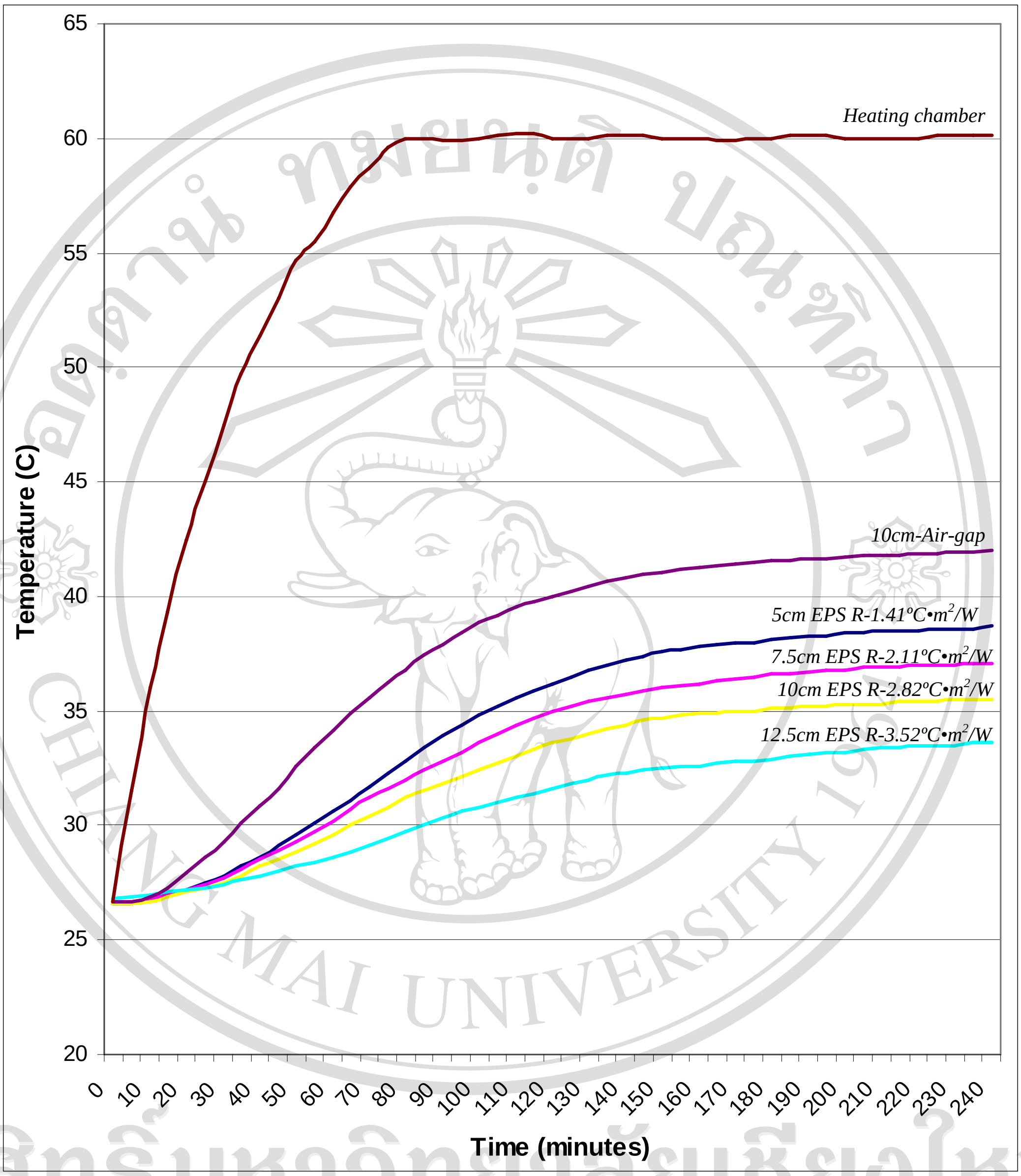

Figure 4.9 Air temperatures in metering cells when heating cell was heated up to 60°C

Figures 4.7, 4.8 and 4.9 show that temperatures increased in metering cells conformed to the thickness of the separating foam: the thicker the foam the lower the temperature in the metering cell. All 3 graphs show that temperature differences between each foam thickness are almost steady. Therefore, it can be concluded that temperatures in the metering cells have a proportional relationship wit R-values of the partition materials. These graphs are very important because they can be used as a reference to approximately find R-values of other materials.

Another issue necessary to investigate was temperatures in metering cells should rise according to the degree of temperatures in the heating cell.

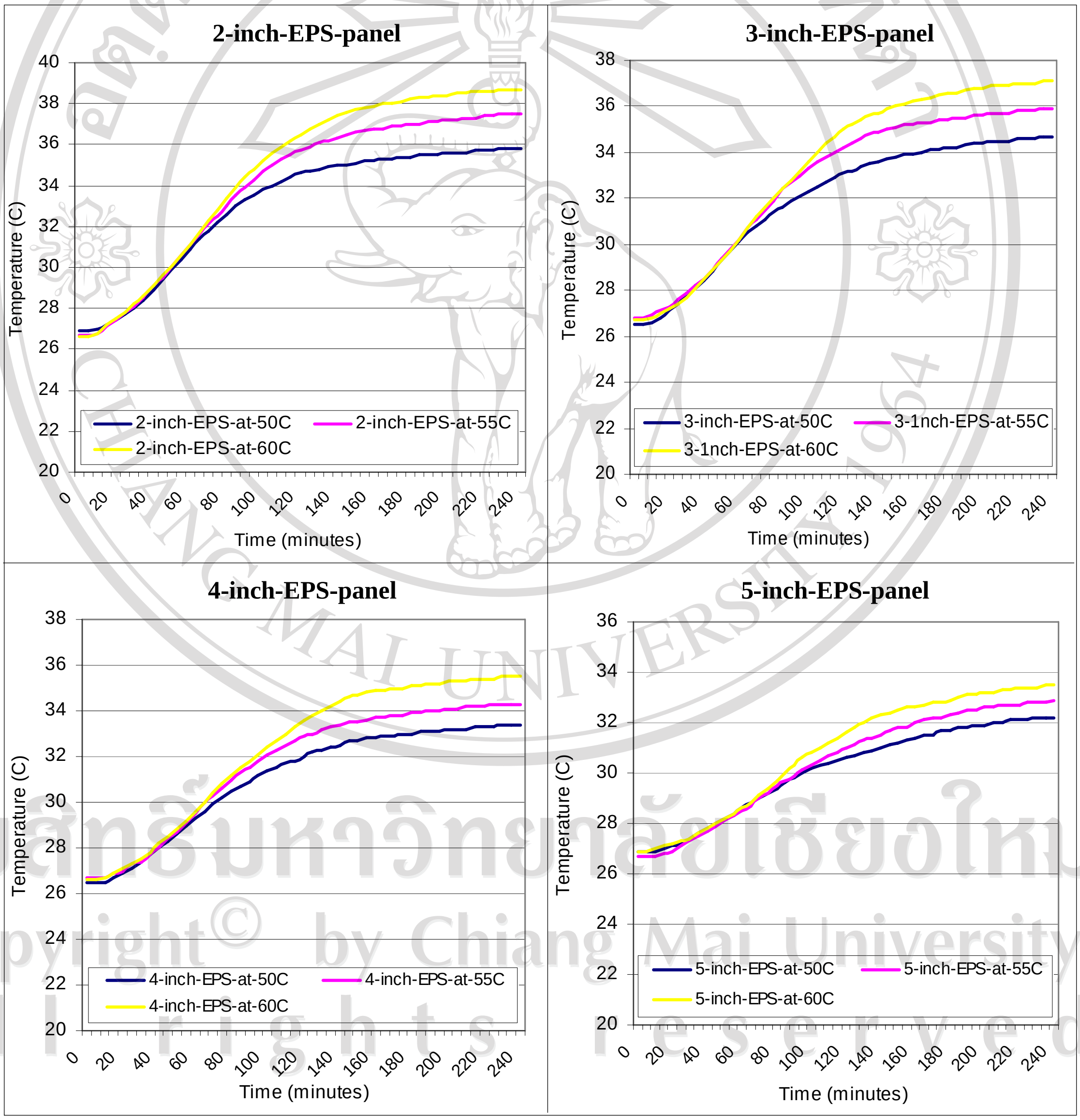

Figure 4.10 Plots of temperatures in metering cells separated by foam with different thickness

Figure 4.10 demonstrates that the result conforms to the assumption. It also show the range of temperatures in heating cell 50, 55 and 60^{o}C, in metering cells that installed the thicker EPS panel can be heated and provided the smaller variation of air temperatures.

4.3 Experiments on the Effect of EPS Particle Sizes and Thermal Resistances

4.3.1 Purpose

The purpose of this experiment was to investigate R-values based on different sizes of EPS particles obtained from the three breaking down methods. The result will be used as a major factor to determine which one should be selected.

4.3.2 Specimens

To investigate size effect on thermal performance of the scratched packaging EPS foam, this research was designed to test on 7 different sizes of EPS particles. They were inserted into the 10 cm width of cavity spaces of specimens for testing thermal performances.

- Size 0.1-3: three specimens of EPS particles size 0.1 up to 3 mm were tested. These specimens were obtained by using papaya shredders.

- Size 0.1-15: three specimens of EPS particles size 0.1 up to 15 mm were tested. These specimens consisted of particles of packaging EPS foam obtained by the scratching using nail pads.

- Size 0.1-6: three specimens of EPS particles size 0.1 up to 6 mm were tested. The specimens were made by sieving EPS particles produced by using nail pads. The opening of the sieve was 6mm. Therefore, particle size of this specimen was 0.1-6 mm, which was 63.3% by volume (loose volume) of the total amount of mixed-size 0.1-15 mm.

- Size 6-10: three specimens of EPS particles size 6 up to 10 mm were tested. The specimens were obtained by sieving the EPS particles larger than 6 mm, which were the remaining particles of the sieving process to produce Size 0.1-6. The opening of the sieve was 10 mm. Therefore, this specimen has particles size between 6-10 mm. Amount 1 m^3 of the mixed-size provided particles size 6-10 mm of 53.3% in volume (loose volume).

- Size 10-15: three specimens of EPS particles size 10 up to 15 mm were tested. They were obtained by sieving the particles remaining from producing Size 6-10. The opening of the sieve was 15mm. Therefore, particle size was10-15 mm. Amount 1 m^3 of the mix-size provided particle size 10-15 mm of 16.7% in volume (loose volume).

  There were very few particles larger than 15 mm still remain from sieving Size 10-15. Those particles are less than 3% in volume (loose volume), and were not used in this research.

- Size 15-20: three specimens of EPS particle size of 15-20 mm obtained by hand picking were tested.

- Size 20-30: three specimens of EPS particle size of 20-30 mm obtained by hand picking were also tested.

4.3.3 Experimental Procedure

The experimental procedure here was conducted similarly to the one previously described in Section 4.2.

a) Specimen construction: all the specimens were constructed and tested in the hot box by filling packaging EPS particles in the 10 cm cavity space between the two galvanized steel sheets in the same configuration as shown in Figure 4.5.

b) Conducting the tests at three temperatures: three specimens were tested at a time along with an empty (air-filled) panel. The latter was used as a control specimen. All of them were tested at three temperatures: 50, 55, and 60ºC.

c) All of the procedure: from start to finish (4-hour period) resembled the hot box performance investigation in Section 4.2. Under the same testing environment, the approximation of R-values of all the specimens using Figures 4.7, 4.8 and 4.9 can be made.

4.3.4 Result

Plots of temperatures in all chambers are shown in Figures 4.11, 4.12 and 4.13. The plots show that at a certain time after the temperatures in the heating cell was raised from 26.5-27°C up to the testing temperatures of 50 or 55 or 60°C, accordingly, temperatures in the metering cells were relatively consistent among the same particle size of specimens. Therefore, result analysis is based on the temperatures beyond 200 minutes after the starts. The consistency of the thermal performance during this testing period allows using the averaging temperatures of the three specimens of each size.

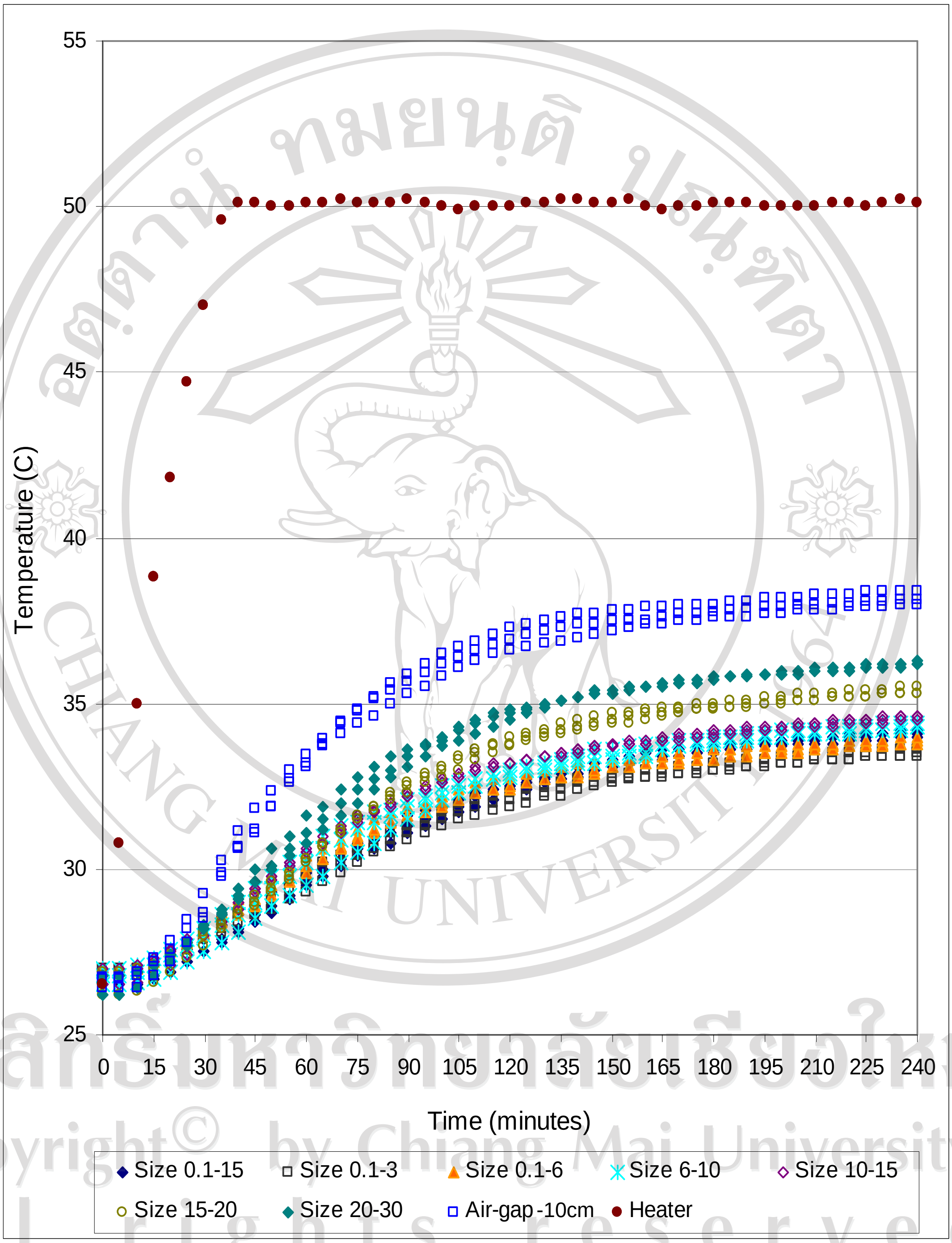

Figure 4.11 Plot of temperatures in all the cells for testing temperature 50°C

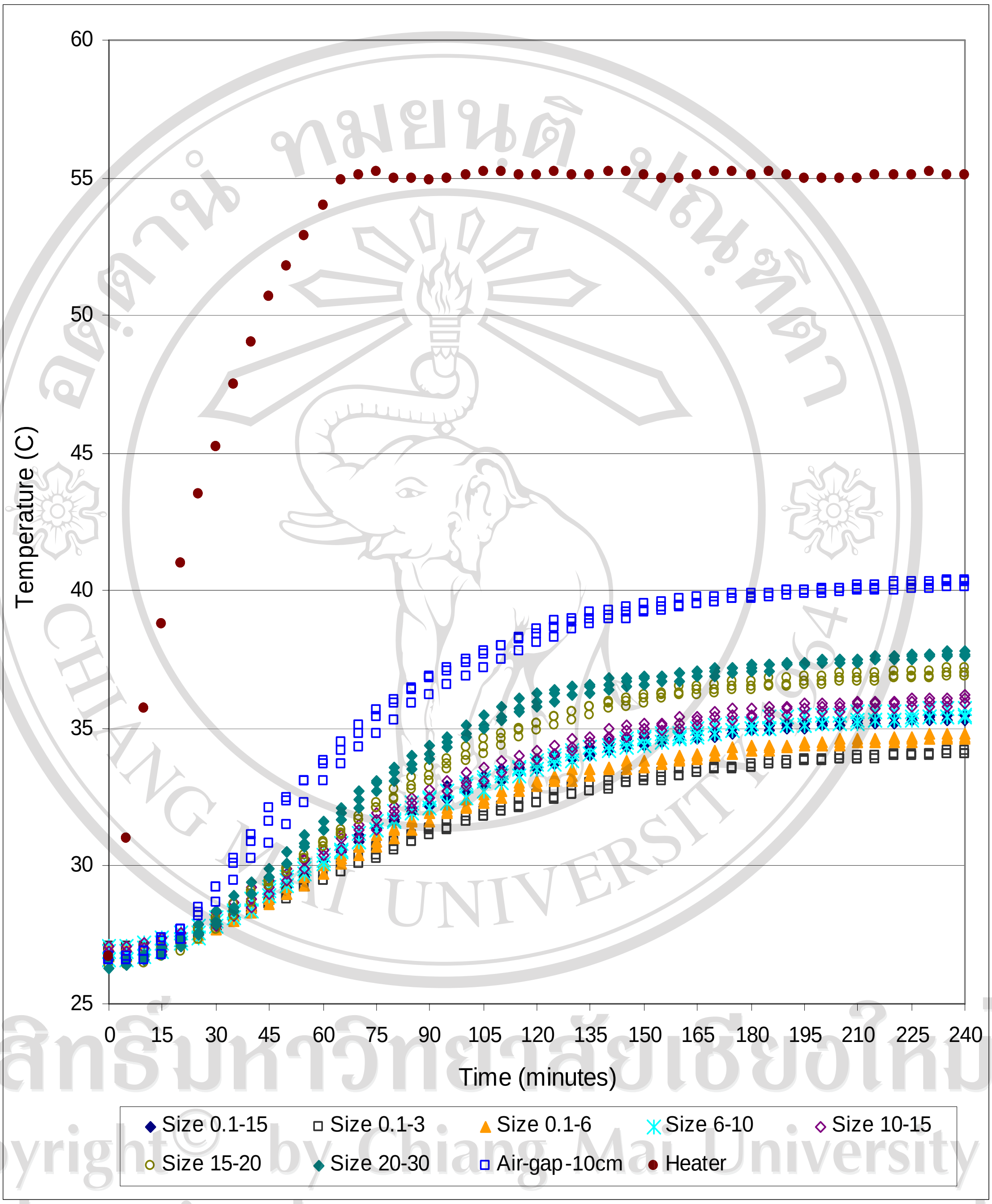

Figure 4.12 Plot of temperatures in all the cells for testing temperature 55°C

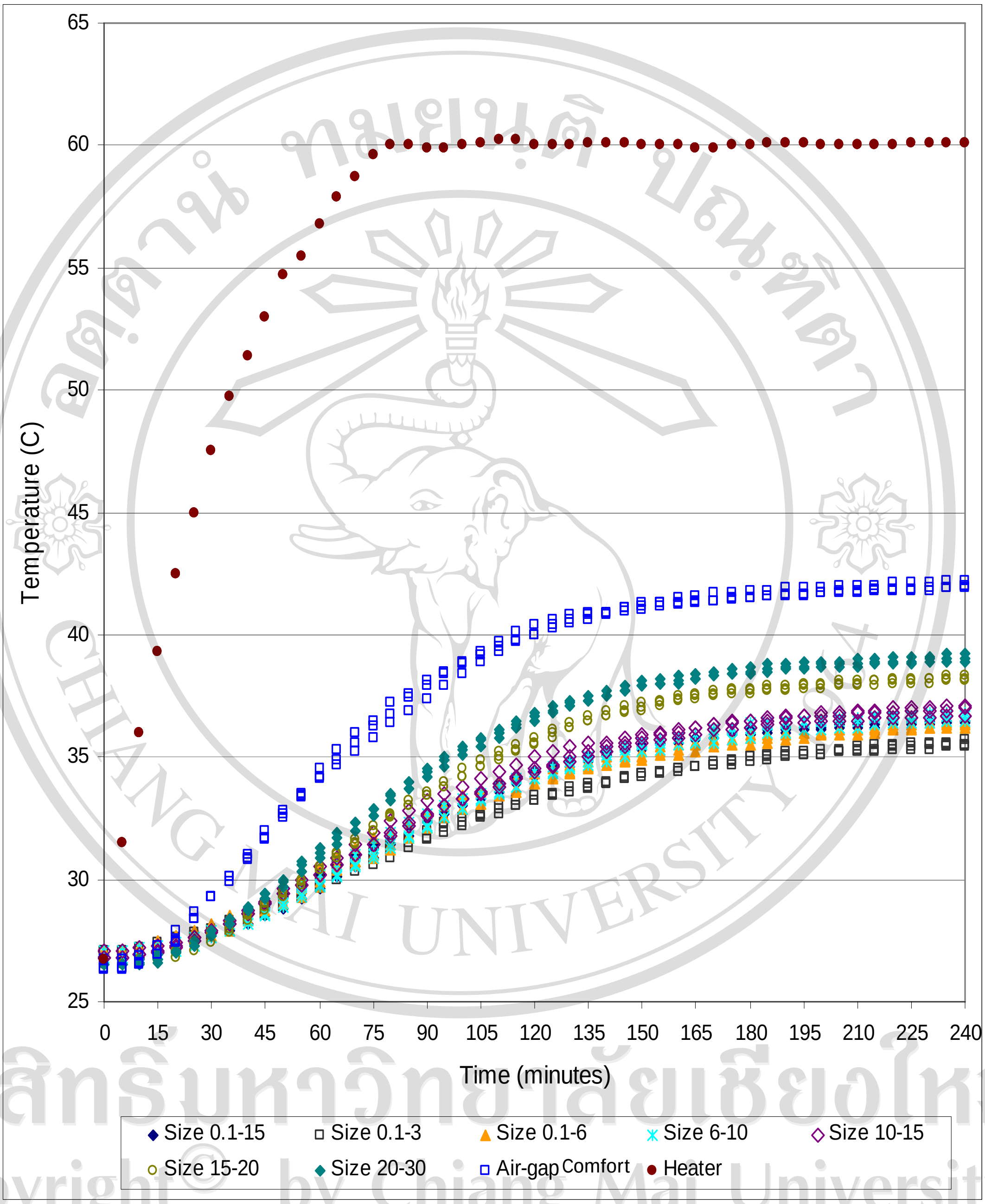

Figure 4.13 Plot of temperatures in all the cells for testing temperature 60°C

The graphs show that the specimen composed from the smaller particle size could resist heat more than the larger. The averaging result obtained from this experiment will be compared with result obtained in Section 4.2 in order to approximate thermal performance resistance.

4.3.5 Approximation of R-values of Particle Sizes of Packaging EPS Foam

In comparison with thermal performances of the test specimens, it is better to use the last straight portion of the curves after the metering cells reach the target testing temperatures. Therefore, in order to find the most reliable results, data at the last 30 minutes of experiments were selected to analyze, compared and approximated for R-values.

In Figures 4.14, 4.15 and 4.16, the average temperatures from Minutes 210-240 (last 30 minutes) of the experiments on EPS particles are plotted along with the reference results from the experiment on EPS panels tested in Section 4.2. R-value of all the tested materials can be interpolated from these plots.

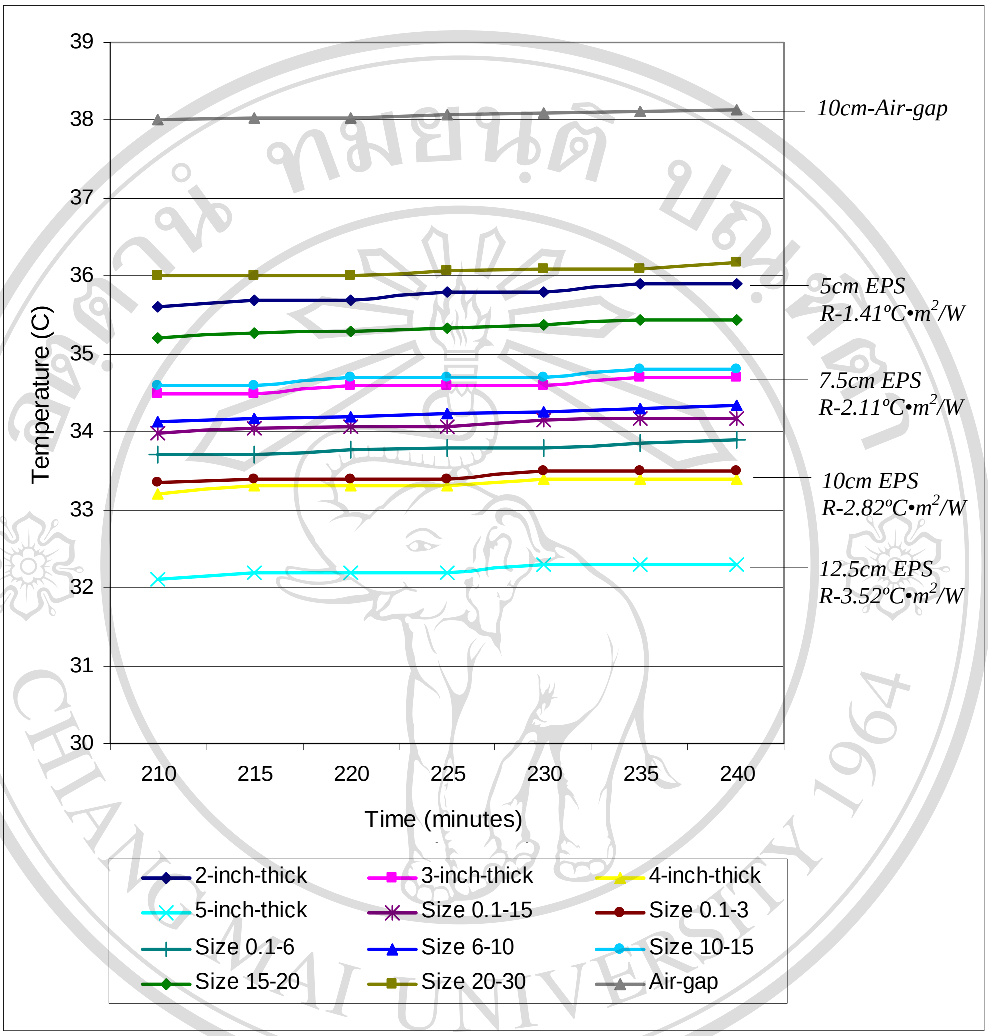

Figure 4.14 Plot of avarage results from the experiments on EPS particles at the testing temperature of 50°C with the reference materials of solid foam panels

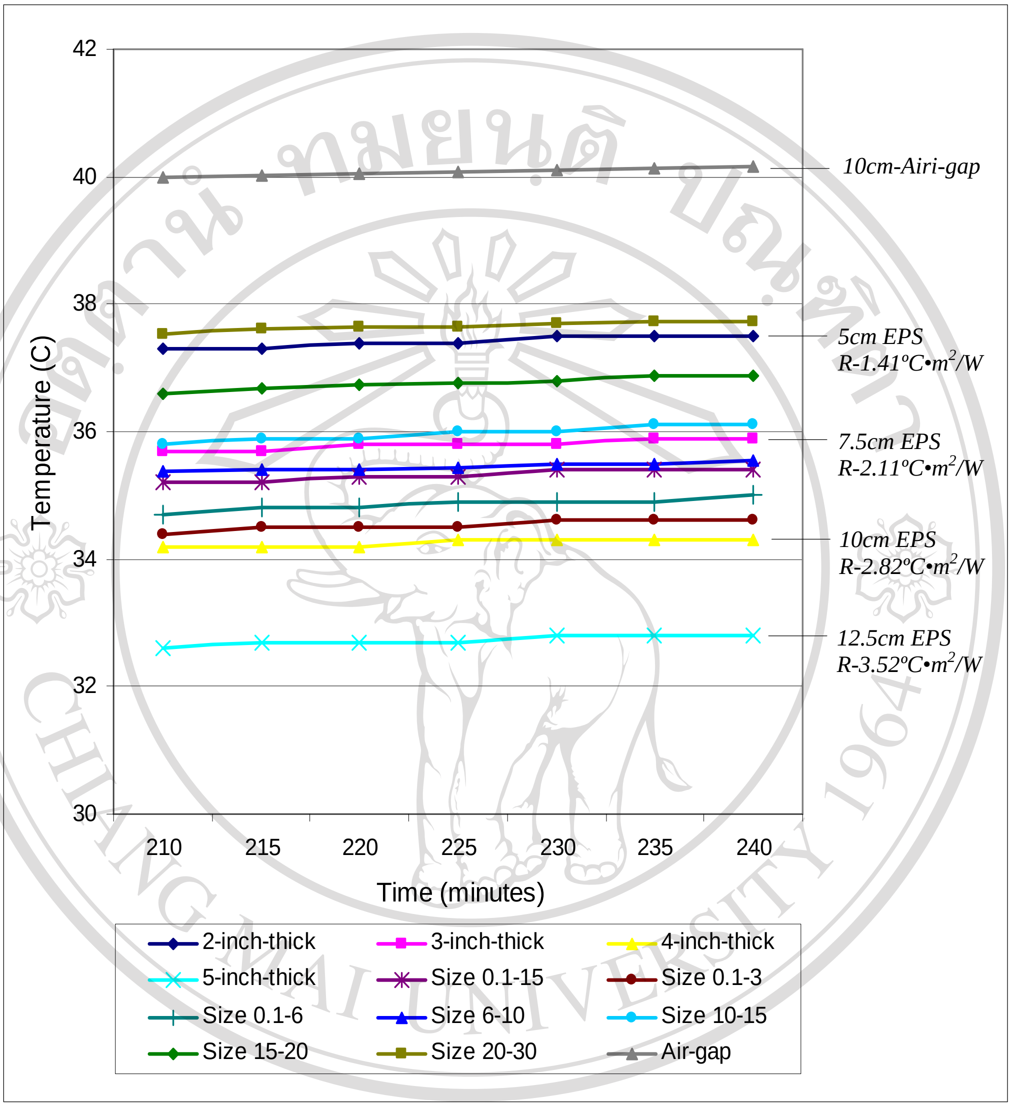

Figure 4.15 Plot of avarage results from the experiments on EPS particls at the testing temperature of 55°C with the reference materials of solid foam panels

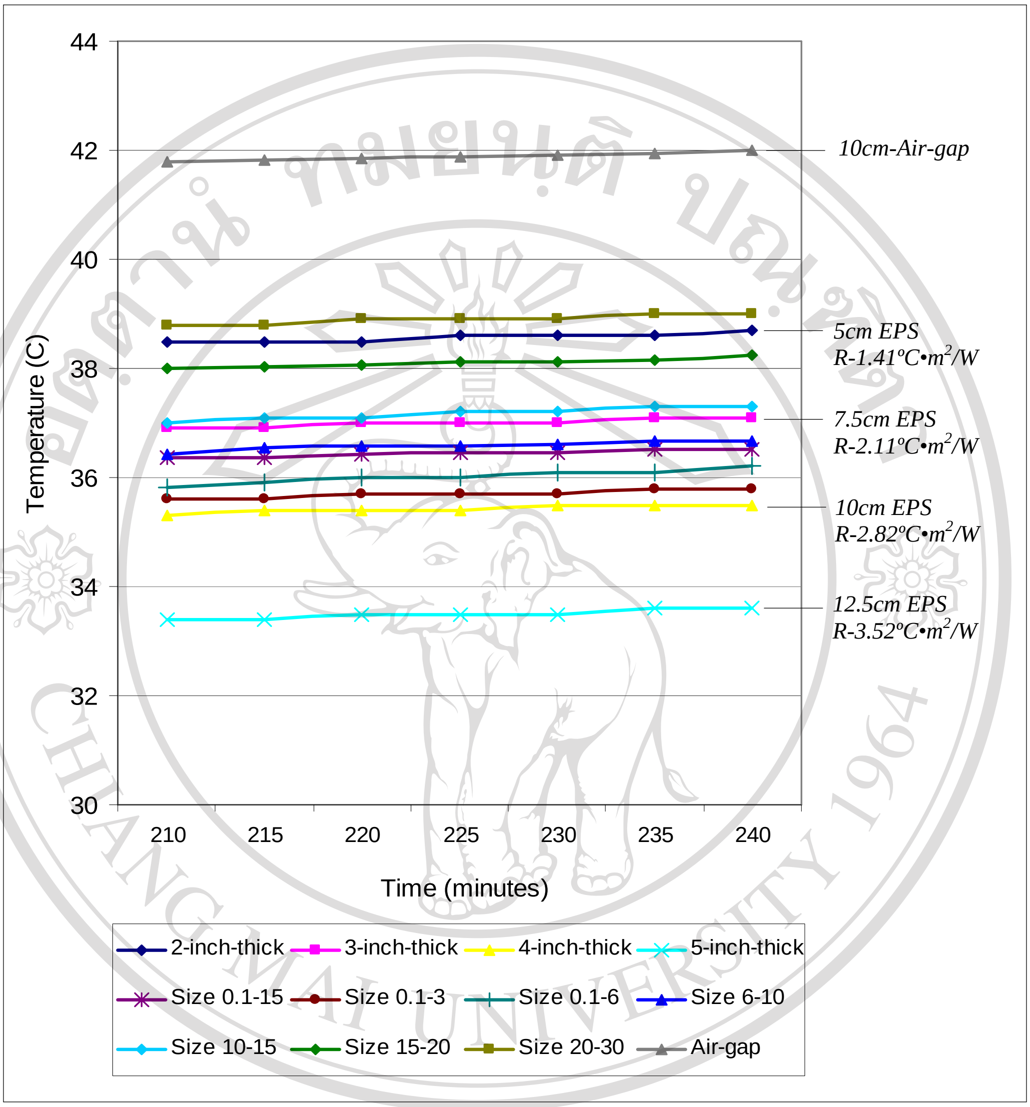

Figure 4.16 Plot of avarage results from the experiments on EPS particls at the testing temperature of 60°C with the reference materials of solid foam panels

From these graphs, the approximated thermal resistances resulted from the experiments on EPS particle sizes could be found. Table 4.1 shows all the approximated thermal resistances of the tested specimens.

Table 4.1 Approximation of thermal resistance of each sample

Test specimens	Approximation of thermal resistances R-values (ºC•m^2/W)			
	50°C	55°C	60°C	Average
Size 0.1-15	2.39	2.34	2.36	2.36
Size 0.1-3	2.76	2.69	2.70	2.72
Size 0.1-6	2.56	2.54	2.55	2.55
Size 6-10	2.32	2.28	2.29	2.30
Size 10-15	1.97	2.04	2.04	2.02
Size 15-20	1.67	1.69	1.62	1.66
Size 20-30	1.23	1.31	1.26	1.27

Table 4.1 shows the test samples, which composed of smaller particle sizes provide higher thermal resistance. The smallest particles, Size 0.1-3, provides the highest result of R-2.72 ºC•m^2/W. If they were used to fill in a wall gap of 10 cm width an R-value of 2.82 ºC•m^2/W can be obtained.

4.4 Thermal Resistance Investigation on EPS Chunks Mixed with Particles

4.4.1 Purpose

As previously mentioned in Section 4.1, large chunks of EPS can be easier and faster produced by hand picking when compared with other methods. However, large chunks, which normally have a lot of air voids between them, may not have a thermal resistance as high as when the voids are filled. Therefore, it was reasonable to investigate thermal performances of EPS chunks mixed with small EPS particles obtained from broken down by nail pads whether they provide high thermal resistances with low costs and easy application.

4.4.2 Specimens

Chunks of EPS packaging foam size between 50-70 mm were mixed with EPS particles obtained by using nail pads to become other specimens as described below.

1) Mix 30-70 was composed of 30% of chunk and 70% by loose volume of the mix sizes EPS particles.

2) Mix 40-60 was composed of 40% of chunk and 60% by loose volume of the mix sizes EPS particles.

3) Mix 50-50 was composed of 50% of chunk and 50% by loose volume of the mix sizes EPS particles.

4) Mix 60-40 was composed of 60% of chunk and 40% by loose volume of the mix sizes EPS particles.

4.4.3 Experimental Procedure

Three specimens of all 4 mixes were tested by the same procedure as the experiments in Section 4.3.

4.4.4 Result

Plots of temperatures in all cells are shown in Figures 4.17, 4.18 and 4.19. The plots show that at a certain time after the temperatures in the heating cell was raised from 26.5-27°C up to the testing temperatures of 50, 55, and 60°C accordingly, temperatures in the metering cells were relatively consistent among the each specimen.

Analysis of the result is based on the temperatures beyond 200 minutes after the starts. The consistency of the thermal performance during this testing period allows using the averaging temperatures of the three specimens of each size.

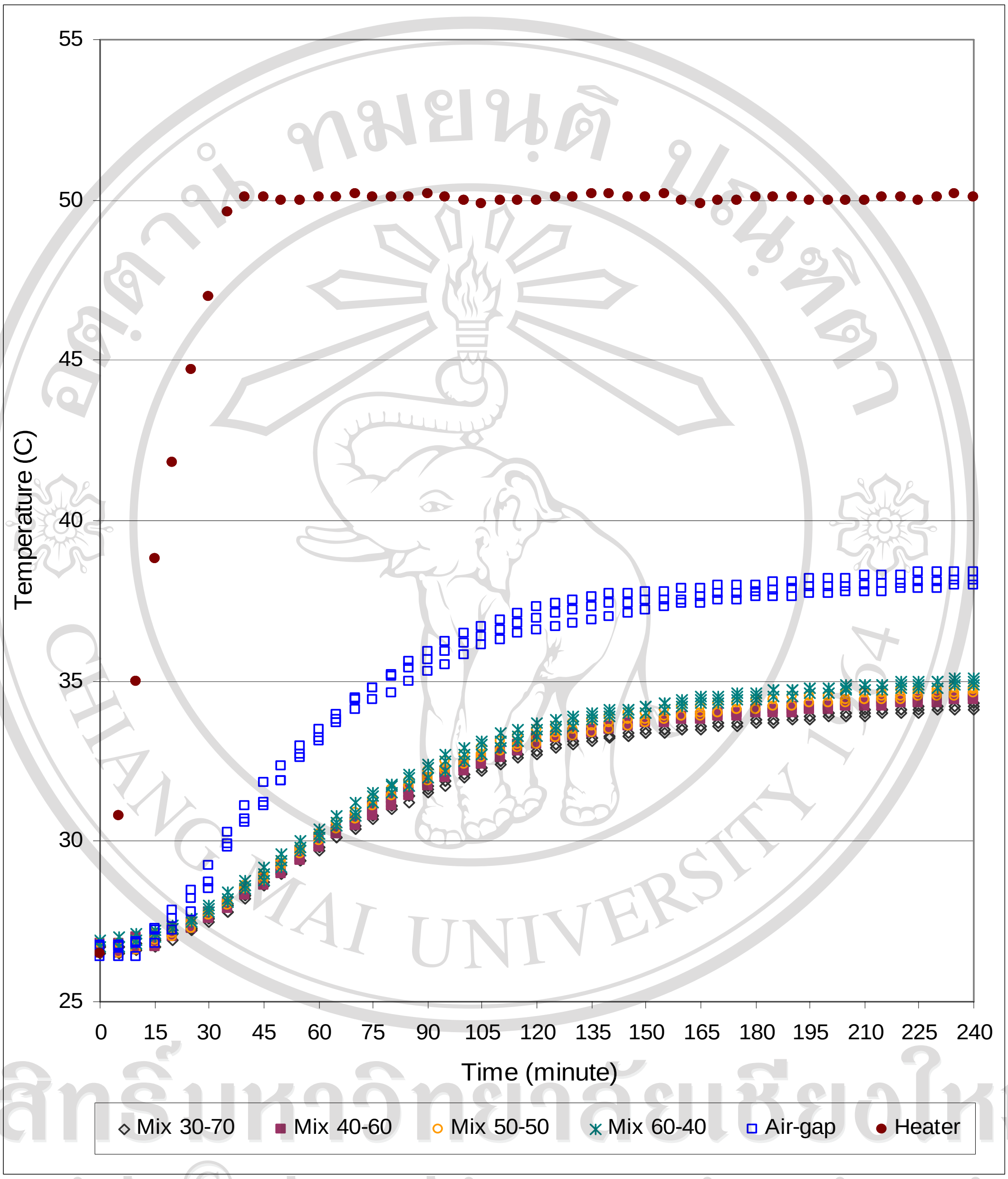

Figure 4.17 Plot of temperatures in all the cells for testing temperature 50ºC

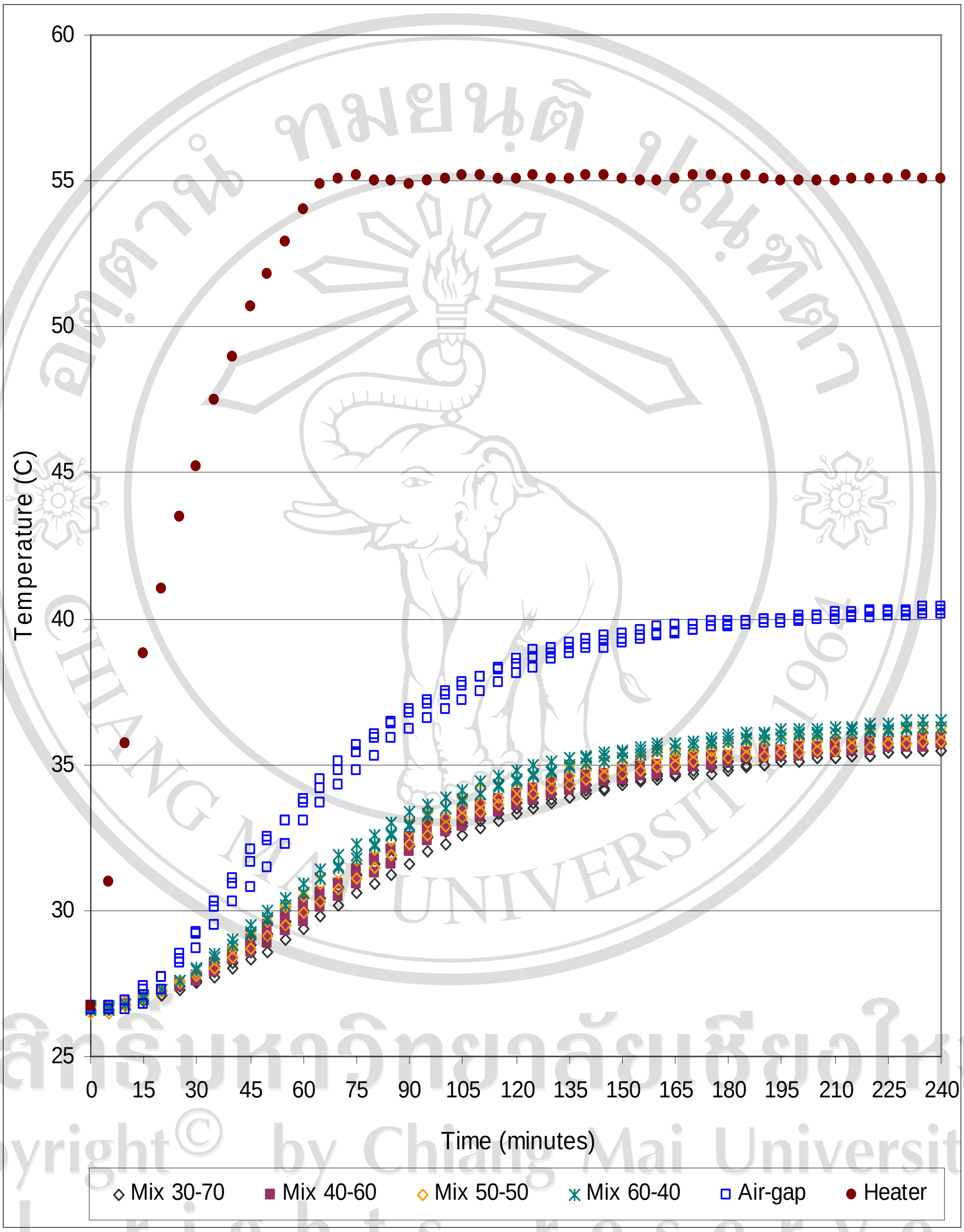

Figure 4.18 Plot of temperatures in all the cells for testing temperature 55ºC

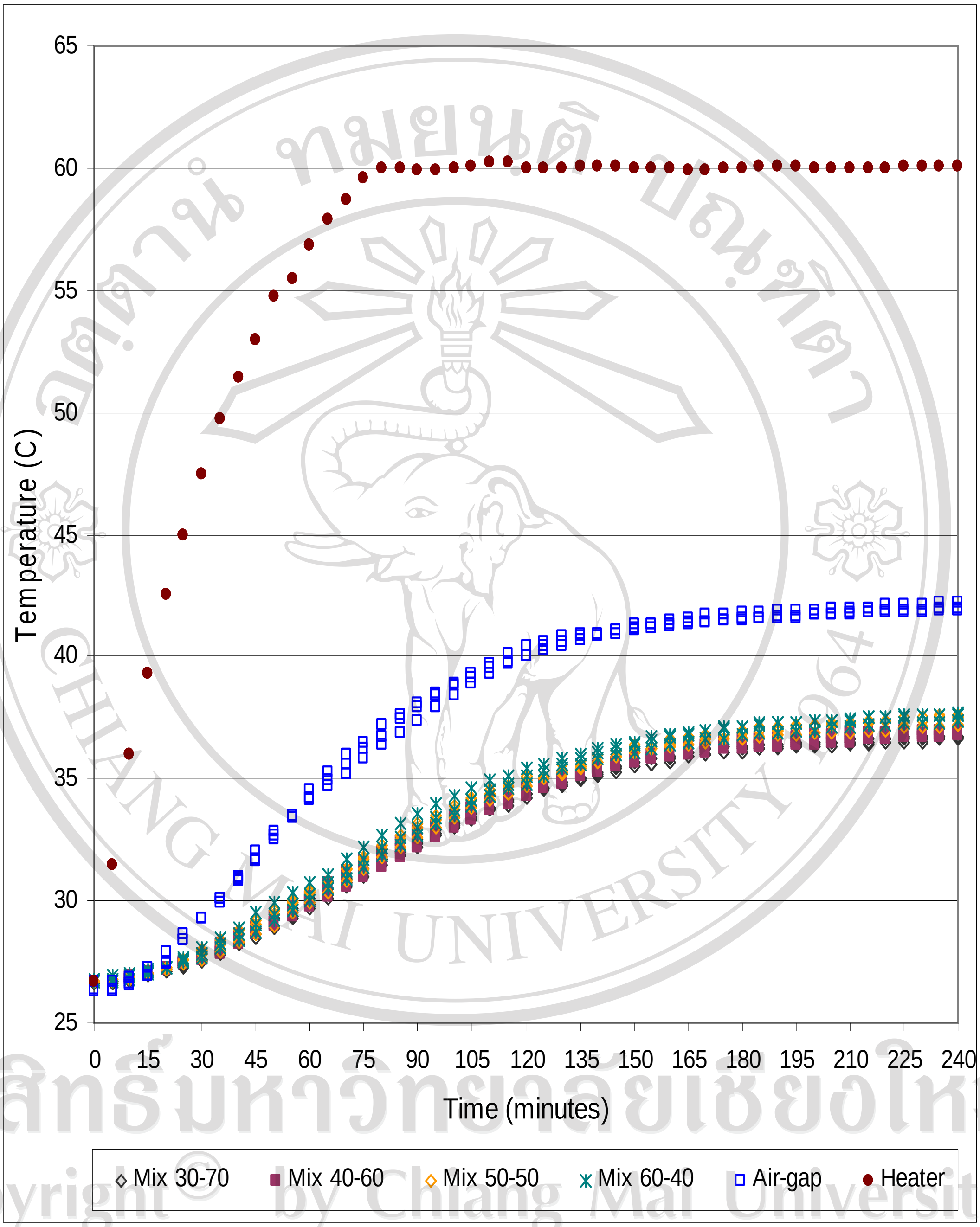

Figure 4.19 Plot of temperatures in all the cells for testing temperature 60°C

Figures 4.17, 4.18, and 4.19 show that the metering cells that separated by the mixed-particles, which has higher portion of EPS chunks, tend to have higher air temperature. This can be a result of air voids between those chunks remained unfilled.

4.4.5 Approximation of R-value of EPS Chunks-Particles Mixes

The process of approximation R-values was similarly to those in Section 4.3. Figures 4.20, 4.21, and 4.22, are averaging results from minutes 210-240 (last 30 minutes) from the experiments on EPS Chunk-Particles Mixes in Section 4.4 are plotted along with the reference results from the experiment on EPS panels tested in Section 4.2. R-values of all the tested materials can be interpolated from these plots.

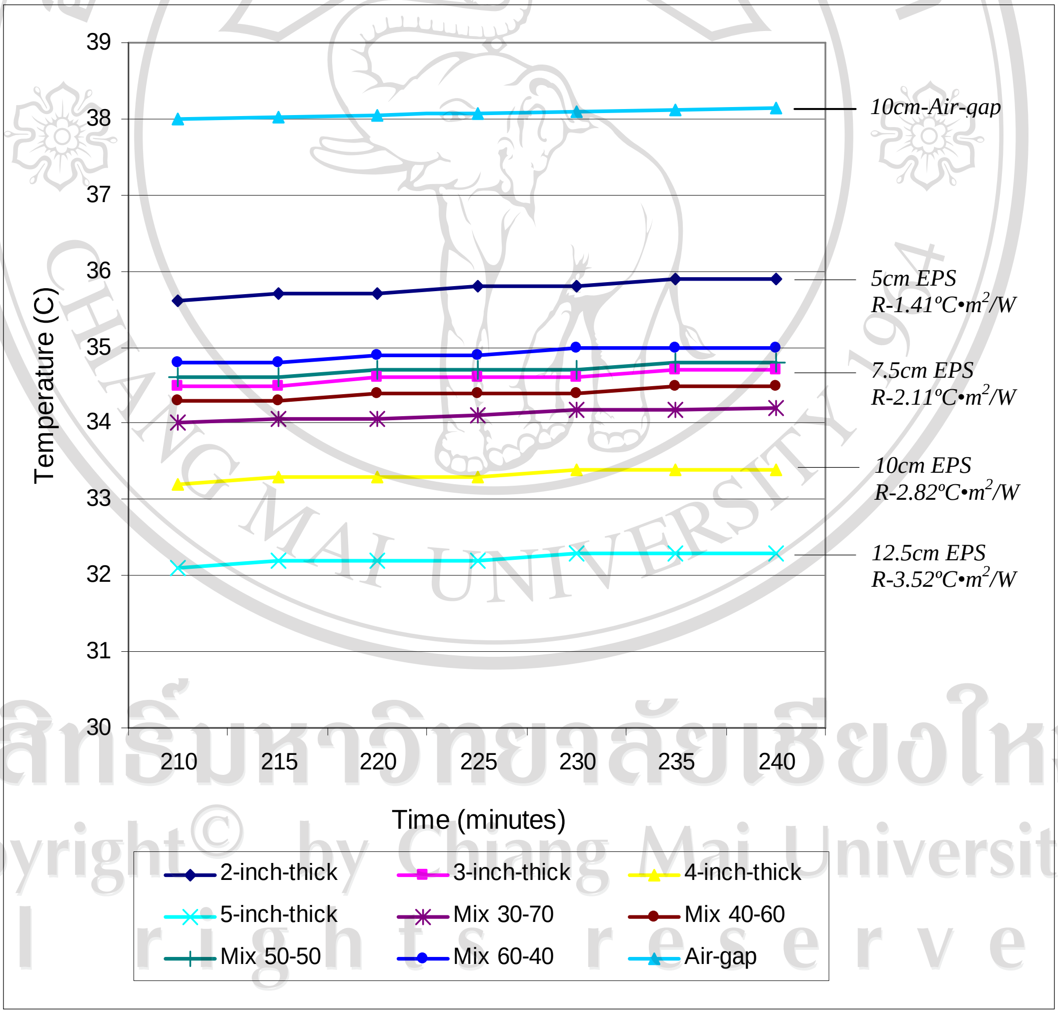

Figure 4.20 Plot of avarage results from the experiments on EPS chunk-particle mixes at the test temperature of 50°C with the reference materials of solid foam panels

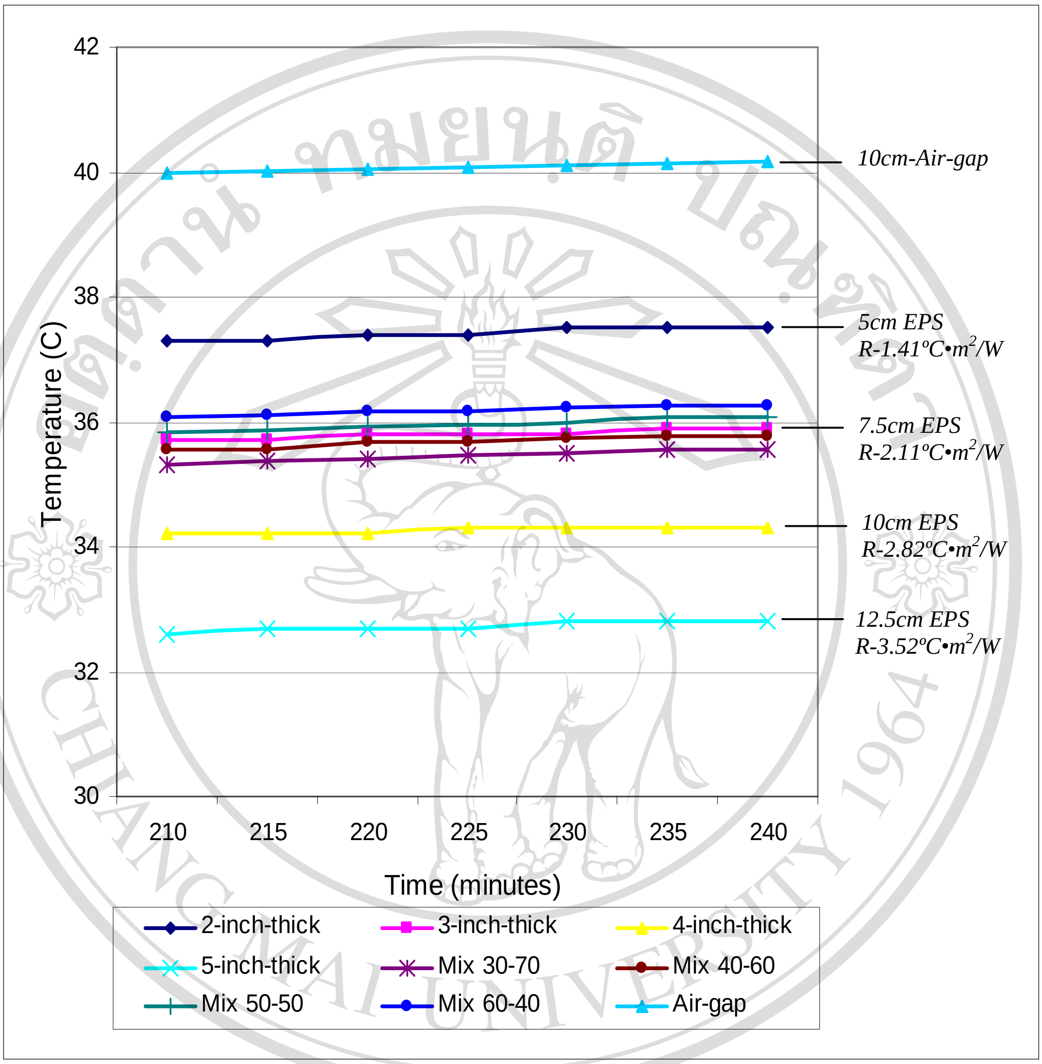

Figure 4.21 Plot of avarage results from the experiments on EPS chunk-particle mixes at the Test temperature of 55°C with the reference materials of solid foam panels

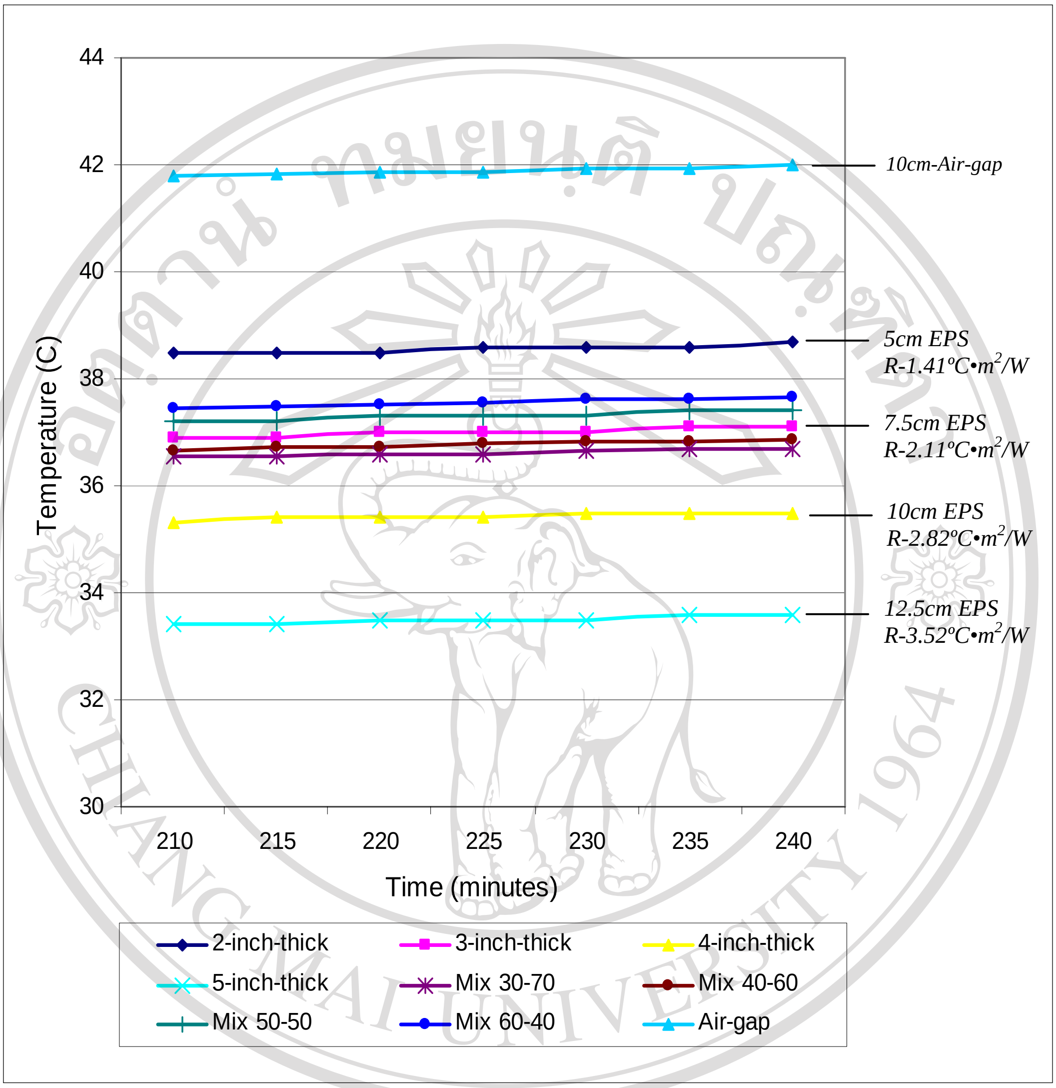

Figure 4.22 Plot of avarage results from the experiments on EPS chunk-particle mixes at the test temperature of 60°C with the reference materials of solid foam panels

From these 3 figures, thermal resistances of specimens tested in this experiment can be approximated, which are summarized in the following table.

Table 4.2 Approximation of thermal resistance of EPS chunks-mixes particles

Test specimens	Approximation of thermal resistances R-values (ºC•m^2/W)			
	50°C	55°C	60°C	Average
Mix 30-70	2.37	2.26	2.28	2.3
Mix 40-60	2.22	2.16	2.22	2.20
Mix 50-50	2.05	2.04	1.98	2.02
Mix 60-40	1.93	1.94	1.86	1.91

Table 4.2 shows R-values of all EPS chunk-particle mixed test in this experiment. It shows that the specimens composed of higher portion of EPS chunks provide lower thermal resistance. As anticipated, this should caused by lacking of EPS particles to fill in the air voids between the chunks.

4.5 Time and Cost Analysis

Assuming that people could obtain disposed packaging EPS foam for free. Thus, they paid for labor cost of production only. Based on the time spent on each breaking down process in Section 4.1, the cost of producing each tested samples can be assessed based on assuming that a labor cost of 200 THB/day. Table 4.2 shows the cost of each EPS particle size per cubic meter.

Table 4.3 Cost of each particle size of packaging EPS foam

Sizes	Size (mm)	Cost THB/m^3
Size 0.1-15	0.1 – 15	300
Size 0.1-3	0.1 – 3	2,050
Size 0.1-6	0.1 – 6	474
Size 6-10	6 – 10	563
Size 10-15	10 – 15	599
Size 15-20	15 – 20	637
Size 20-30	20 – 30	412
Chunk	50 – 70	174

4.6 Selection of Test Specimen and Determination

4.6.1 Selection of Test Specimen

All results show that the tested sample, which composed of smaller particle size, has higher thermal resistance. Therefore, the highest thermal performance among all samples was about *R*-2.72 ºC•m^2/W, which belongs to the EPS particles size 0.1-3mm. The next one is EPS particles size 0.1-6 mm with the R-value of about 2.55 ºC•m^2/W. However, to choose the best size for application in composite wall systems, the cost of production has to be considered.

As shown in Table 4.3, it costs very high to produce EPS particles size 0.1-3 mm. Therefore, even with its high R-value this size has to be neglected. Size 0.1-6 mm with the next highest R-value is still relatively expensive since it needs sieving. It is important to note that the specimens composed of Size 0.1-15 is the easiest and cheapest one to obtain when compared with all other size. Its thermal resistance of about 2.36 ºC•m^2/W is relatively high and acceptable when compared with the rest. EPS chunks mixed with EPS particles were found difficult to fill in the wall panel systems during the experiments. Therefore, they are not recommended.

In conclusion, the most appropriate size of EPS foam particles to fill in composite wall systems is Size 0.1-15 mm, which can be obtained easily by using nail pads to scratch.

4.6.2 Grain Sizes Distribution of EPS Particles Size 0.1-15

Grain size distribution is an important physical characteristic of granulate materials. Granular materials with grain size 0.1-15 mm may have a much larger portion of 0.1-5 mm or may have a larger portion of 10-15 mm. This can cause difference in the thermal resistance property of the material. Therefore, it is important to find the grain size distribution of EPS foam Size 0.1-15 in this research, and use it as a reference. Anyone should not be surprised to see a different R-value of EPS particles size between 0.1-15 mm with grain size distribution different from found in this research.

To find grain size distribution, an amount of EPS particles was weighted and then sieved through a series of nets or sieves with different opening sizes. Then, weighted the particles remaining on each sieve and calculated the percentage of that remaining. This process is called sieve analysis and used widely in the field of Geology and Geotechnical Engineering.

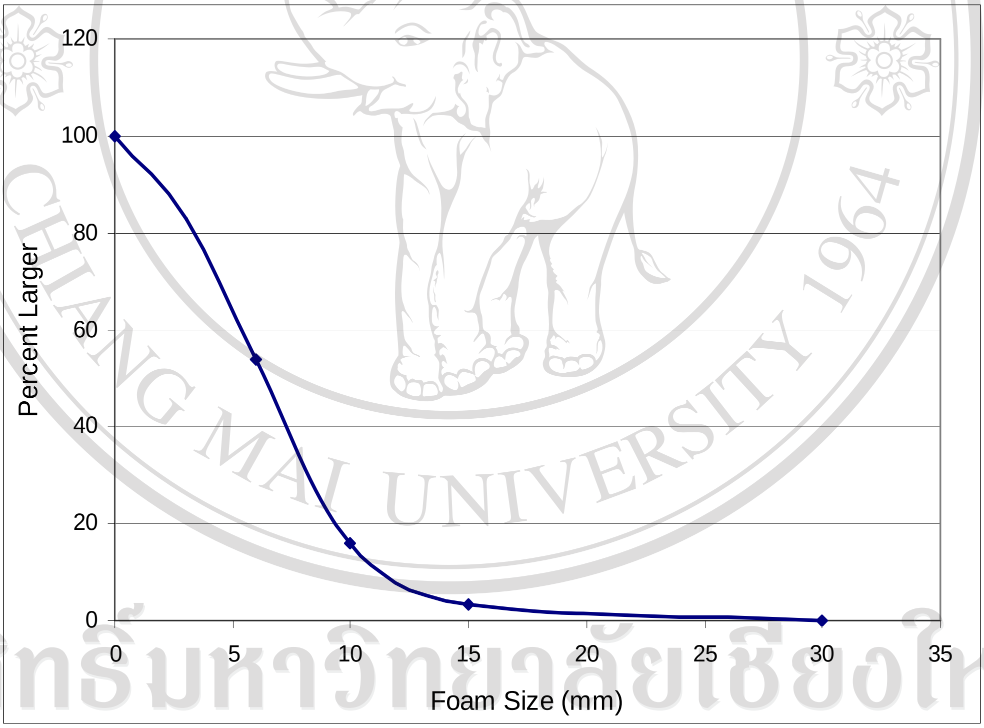

Figure 4.23 Grain size distribution of EPS particles Size 0.1-15 mm