CHAPTER II

THEORY AND LITERATURE REVIEW

By focusing on the research topic, information about the existing of expanded polystyrene (EPS) in the forms of packaging foam, a review of literatures about physical properties of EPS, concept of human comfort, quality of insulation, and principles of heat transfer are described in this chapter.

2.1 Packaging Foam

Many products sold worldwide are fragile and/or sensitive to heat and thus, protection is required. Several types of packaging foam are generally made from polystyrene, polyurethane and polyethylene. One of those types is expanded polystyrene, which is made from polystyrene beads. It is mostly used for protecting, cushioning, and insulating various kinds of products especially appliances.

EPS has been used in thousands of different ways by individuals and businesses worldwide. Base on the report of Plastic Product (2001), in Thailand alone, there were approximately 2,500 plastic factories that also produce EPS located nationwide, of which 90% are small sizes, producing for local demand only. The remaining 10 % were acquired by Big Mills, supporting their investment in overseas markets. The productions capacities of polystyrene were 445,000 tones per year and EPS were 44,000 tones per year, e.g. Thai Modern Packaging and Insulation Factory alone has capacity to produce EPS up to 3,000 tons per year (TMPI, 2007).

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2.2 Expanded Polystyrene

EPS is a durable material. It does not shrink, can be molded and cut to any shapes, and can be applied to many applications (Yucel, et al, 2003). EPS's thermal properties are stable. It does not experience any thermal drift and does not lose heat resistance value over its life. EPS also provides an environmentally sustainable structure with long-term thermal resistance and does not contribute to the greenhouse effect.

2.2.1 Materials and Manufacturing

EPS foam is created by blowing a gas into polystyrene material. The gas, called as blowing agent, expands inside the polystyrene, creates a large number of small, closed cells. In some cases, the blowing agent may be introduced into a pile of polystyrene beads and subsequently expand, while in other cases, the mixture expands in single stage (BASF, 1997). Manufacturing process starts with small polystyrene beads of 0.2 to 3 mm diameter (known as expandable polystyrene, beads or resin) being mixed with blowing agent (pentane, a low boiling point hydrocarbon). These beads have a bulk density approximately 650 kg/m^3 (BASF, 1997).

The next stage is pre-expansion of the beads. Although any form of heat can be used (including hot air, hot water, and infrared radiation), steam is used almost exclusively (BASF, 1997). Steam (at approximately 100°C) is fed into the pre-expander machine containing the beads. The high temperature both softens the polystyrene and causes the pentane to expand, causing the beads to expand up to 60 times of their initial size. The bulk density of expanded beads (call pre-puff) depends on the duration (2 to 5 minutes) and temperature of the steaming. The final density of the EPS block depends largely on the bulk density of the pre-puff.

Following the steaming, the pre-puff must be aged. This process allows the pre-puff, to cool and equalizes the pressures inside the beads caused by condensation of the pentane. The pressure equalization occurs as air diffuses into the beads, stabilizing them and allowing the following process stage.

The pre-puff is then placed into a metal mold. In a process similar to the pre-expender, steam is blown into the mold, causing the pre-puff to expand and fill the mold. Following a brief cooling period, the homogenous block is ready to be removed from the mold and, after another aging period of several days, is ready to be used or process

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further. The aging period is required to allow stabilization of the foam (due to slight shrinkage following processing), and to allow residual pentane to diffuse from the block.

After the above process, manufactured EPS blocks are often large in size. In order to create panel or smaller block sizes, EPS blocks can be either sawn or cut using hot wire equipment. For some applications, EPS molds are of customized shapes. However, for shapes other than rectangular prisms, significant variations in EPS density may occur within the shape.

Because newly made EPS is normally soft, it may be elasticized. This is a physical process involving rapid compression of the EPS block to approximately 60 to 70 percent strain in one axis followed by rapid unloading. After this treatment, the compressed EPS blocks rebound to approximately 85 percent of the original block height. This process alters the physical properties of the EPS, and has important implications to the use of EPS board as a yielding compressible inclusion in the context of current research.

In order to produce different EPS properties, several options are possible. If improved fire resistance is required, an additive can be incorporated with the polystyrene before it is made into the small beads. This bromine-based flame radiation makes the EPS self-extinguishing. Polystyrene beads with additive are called modified expandable polystyrene.

2.2.2 Properties of EPS

Density

EPS density varies from 10 and 35 kg/m^3 and more than 95% air in volume. Density is the most common property used to classify EPS foam. However, manufacturing standards must be maintained in order to ensure a constant quantitative relationship between density and thermal properties (Horvath, 1995).

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Thermal Properties

Generally, in North America, EPS is manufactured according to ASTM standard C578 as shown in Table 2.1.

Table 2.1 EPS properties based on ASTM Standard C578

EPS Properties							
Property			Type XI	Type I	Type VIII	Type II	Type IX
Nominal Density		lb/ft^3 (kg/m^3)	0.75 (12)	1.00 (16)	1.25 (20)	1.50 (24)	2.00 (32)
Density[1], min.		lb/ft ^{3} (kg/m^3)	0.70 (12)	0.90 (15)	1.15 (18)	1.35 (22)	1.80 (29)
Thermal Resistance[1],min., per 1.0 in. thickness	75ºF 24ºC	ºF•ft^2•h/Btu (ºC•m^2/W)	3.10 (0.55)	3.60 (0.63)	3.80 (0.67)	4.00 (0.70)	4.20 (0.74)
	40ºF 4.4ºC	ºF•ft^2•h/Btu (ºC•m^2/W)	3.30 (0.58)	4.00 (0.70)	4.20 (0.74)	4.40 (0.77)	4.60 (0.81)
Compressive strength[1] @10% def., min.		Psi (kPa)	5.0 (35)	10.0 (69)	13.0 (90)	15.0 (104)	25.0 (173)
Flexural strength[1], min.		Psi (kPa)	10.0 (69)	25.0 (173)	30.0 (208)	35.0 (276)	50.0 (345)
Water Vapor Permeance[1] of 1.0 in. thickness, max., perm			5.0	5.0	3.5	3.5	2.0
Water Absorption[1] by total immersion, max., volume %			4.0	4.0	3.0	3.0	2.0
Oxygen Index[1], min., volume %			24.0	24.0	24.0	24.0	24.0
Flame Spread[2]			20	20	20	20	20
Smoke Developed[2]			150-300	150-300	150-300	150-300	150-300

[1] ASTM C-578 Standard Specification for complete information

[2] UL Certificate AFM-1 available from R-Control Building Systems

Source: R-Control of Expanded Polystyrene EPS Foam
(http://www.r-control.com/EPS/properties.asp)

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Moisture Resistance of EPS

EPS foam is moisture resistant and retains its thermal properties (Ostrogorsky and Glicksman., 1986). It is rot proof and durable when installed as recommended, and will remain effective as insulation for the life of buildings and structures. The superior moisture resistance of EPS insulation provides outstanding benefits for most construction and engineering applications.

Flammability

The base material of EPS has an oxygen index of 9 and 18% depending on density compared with the natural oxygen content of 23%, thus; EPS can be burn (Horvath, 1995, and Collier, 2005). Before being ignited, the expanded polystyrene must first be melt at temperature between 150°C and 260°C. Then it must be ignited at temperature between 316°C and 343°C for the gasses to be given off (Horvath, 1995). Therefore, EPS foam insulation is a relatively easy subject to ignition but when ignited, they emit a dense, black, toxic smoke containing and in some cases deadly hydrogen cyanide gas. Because of the dangers described above, most EPS foam used in interior building construction requires an adequate fire barrier. Half-inch (1.26 cm) gypsum wallboard is one of the most common fire barriers (HG, 2007). Not only EPS foam but also many other insulation materials are combustible and may constitute a fire hazard if improperly installed. These products should not be left exposed in the interior of buildings where people reside, work or assemble. An approved thermal barrier, such as one-half inch (1.26 cm) gypsum board or its equivalent, should be mechanically attached over the EPS foam in interior applications (King and Meyer, 1999).

According to Murphy, (1988), the barrier should prevent the insulation from heating to more than 120°C (250°F) above ambient temperature for at least 15 minutes after the fire ignites. One-half inch of gypsum board, fire retardant plywood, asbestos cement board or cement based mixture (gypsum-sand or gypsum-vermiculite) should be used as nailed in place over the insulation. In refer to WIKIPEDIA (2007), some

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sandwich insulation panels (SIPs) used fiber-cement or plywood for the panels, and agricultural fiber, such as wheat straw, for the core. Fiber-cement several benefits that can last longer and require less maintenance, will not rot, burn, or corrode, typically do not require drywall, are vermin-resistant and do not support black mold growth.

2.3 Thermal Comfort Condition

The environmental conditions that are considered comfortable for human vary with the impact ratio of the thermal environment factors of temperature, humidity, wind, etc, as well as clothing and level of activities (Koch-Nielsen, 2002). A combination of certain values of the four factors (air temperature, relative humidity, air velocity and mean radiation temperature) result in what called thermal comfort, which can be represented by the comfort zone on various charts. When one or more of four factors of environment is somewhat outside the in-comfort range, the remaining factors can be adjusted up or down to compensate, thereby restoring thermal comfort (Lechner, 2001).

Design strategies to achieve thermal comfort were suggested by Givoni (1998). His diagram is based on thermal comfort inside a building, where not only air movement, but also the thermal properties of building envelope and other passive cooling means can be used to counteract high temperatures. The diagram also shows that, for combination of very high humidity and temperatures found in warm and humid regions, passive means other than natural ventilation, thermal mass and evaporative cooling will be required to arrive at an acceptable comfort level. Figure 2.1 shows the diagram of thermal comfort zone by Givoni (1998).

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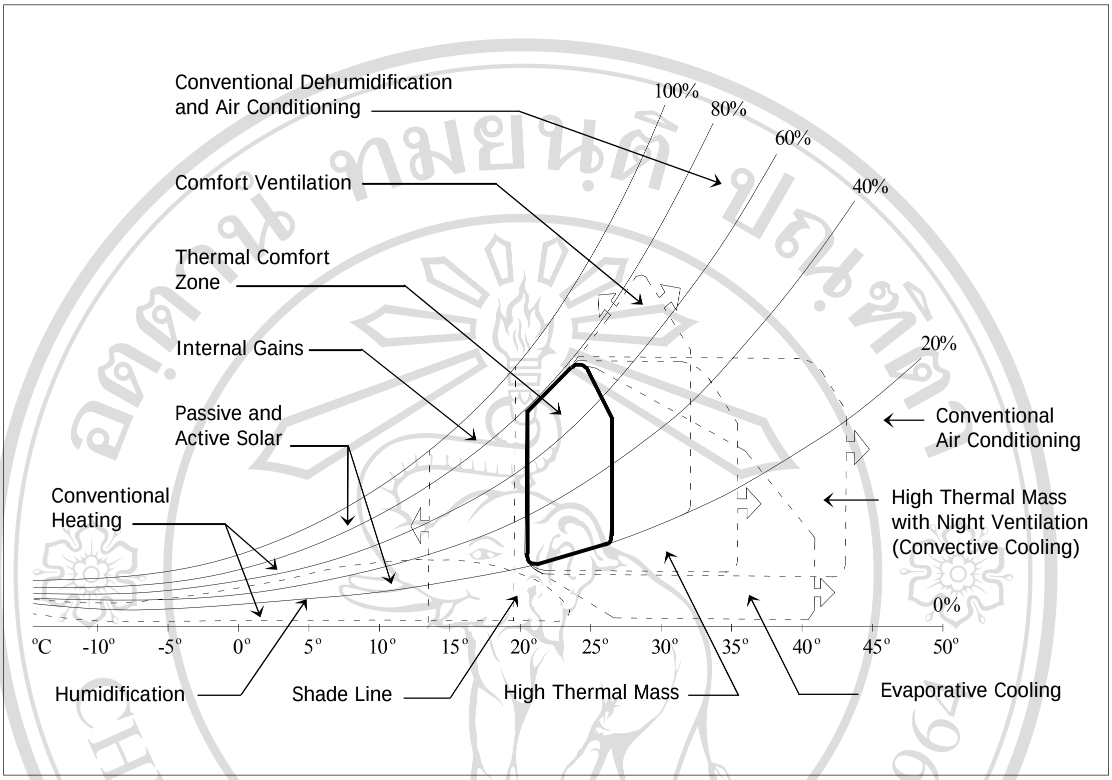

Figure 2.1 Diagram showing strategies to achieve thermal comfort in buildings in hot and humid climate (Givoni, 1998)

The comfort zone has been the subject of many studies. Lechner (2001) demonstrated a large range of thermal comfort that mean radiation temperature should in between 20°C and 27°C and relative humidity of between 20% and 80%. According to Koch-Nielsen (2002), a common standard for air-conditioned indoor today is temperatures of between 21°C and 26°C and relative humidity of between 30% and 70%, with air changes related to the use of each single room.

In Southeast Asia region, climate is very humid and sticky because it is surrounded by oceans. The average outdoor humidity is from 70 to 90 % (Lydia, 2002). For indoor conditions in Thailand, temperatures varied from 26-36°C (dry bulb temperature) and 50-80% relative humidity (Khedari et al, 2000). Thus, using insulation for exterior wall is significance.

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2.4 Insulating Values and Energy Saving

Thermal insulation retards conductive, convection and radiation heat transfer (ASHRAE, 2001). Providing adequate insulation in the building envelope is critical for energy efficiency. ORNL (2002) provided guidelines for selecting the type and level of insulation for different envelope components in residences in different climates. For a wood frame house with a slab-on-grade floor in a hot and humid climate, it is recommended that insulations with thermal resistance range from R-11 to R-15 ºF•ft^2•h/Btu (R-1.94 to R-2.64 ºC•m^2/W) be provided for wall cavities, R-38 ºF•ft^2•h/Btu (R-6.69 ºC•m^2/W) for attics and cathedral ceilings. These values exceed the minimum levels required by the ICC (1999), which are based on the glazing area and the location of the house.

Many studies have also quantified the energy savings from improved insulation. Ternes et al. (1994) showed 9% energy use reduction and 15% average peak demand reduction in Arizona, by retrofitting exterior masonry wall insulation from R-3 to R-13 ºF•ft^2•h/Btu (R-0.53 to R-2.29 ºC•m^2/W). A study of a typical un-insulated masonry house in Bangkok, Thailand, by Rasisutta and Haberl (2004), showed 8% of total energy reduction from light-weight concrete block walls with R-10 ºF•ft^2•h/Btu (1.76 ºC•m^2/W) exterior insulation, and 9% reduction from similar wall construction with R-10 interior insulation. A similar study of a Habitat for Humanity house in the hot-humid climate of Central Texas by Kootin-Sanwu (2004) showed a small annual electricity savings, but a high cooling energy savings in the summer from improved insulation in light-weight walls. These studies suggest that high R-values and low air infiltration loss could be achieved with advanced construction techniques, which can result in significant energy savings. However, high cooling energy savings are expected in residences in hot and humid climates.

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Besides insulation, all the materials used for wall and roof assemblies have some insulating value, and thus, also contribute to the thermal performance of the building envelope. Therefore, the choice of construction type and materials can also have a significant effect on building energy use. Malhotra (2005) demonstrated that thermal mass and insulation provides significant benefit in shifting peak load conditions and reducing overall indoor heat gain or loss, provided that average outside temperature is moderate. Therefore, energy and cost are operating HVAC system. However, these benefits depend on the configuration of the wall assembly (i.e., insulation inside or outside thermal mass relative to the interior building) and the climatic conditions.

2.5 Building Wall Materials and Thermal Properties

2.5.1 Conventional Materials and their Thermal Properties

Numerous residential buildings came up across Southeast Asia countries were constructed of conventional and local materials. External finishes of the wall systems are wood, fiber-cement, concrete, masonry, rendered and painted with coatings are commonly used. In addition, aluminum and steel are also a part of wall systems as well. Thermal conductivities of some construction materials are showed in the Table 2.2.

Table 2.2 Construction materials and their thermal properties (Koch-Nielsen, H., 2002)

Material	Density (kg/m^3)	K-value (W/°C•m)
Aluminum	2,700	200
Steel	7,850	60
Stone	2,600-2,800	2.3-3.5
Concrete: dense light	 2,400 1,000-1,700	 1.8 0.3- 1.0
Timber heavy weight light weight	 600-800 400-500	 0.20 1.50
Viva board	1,100-1,300	0.125
Clay	1,600-2,840	0.45-1.8
River sand	1,700-2,000	1.3-1.5
Compressed earth block	1,700-1,800	1.0-1.2

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The use of these materials results in undesired conducted heat gain into buildings, which creates discomfort indoor and leads to consume electricity for air conditioning purpose. There are many ways to reduce indoor heat gain, but the best way is using thermal insulation because it does not affect indoor lighting, natural ventilation and scenic view. Therefore, designers and builders should aware of outdoor-to-indoor heat gain and thermal insulation. Some thermal properties of insulation materials in Thailand are provided as shown in Table 2.3.

Table 2.3 Glass wool insulation based on SFG (2007)

Insulation	Glass wool insulation: Un-Face Board Blanket (UBB)					
Description size (M)	Density (kg/m^3)	Thickness (mm)	Weight (kg)	Price/unit (Baht)	Price/m^2 (Baht)	R-Value (m^2 °C/W)
UBB 1625 1.22 x 30.50	16	25	14.9	2,250	60	0.658
UBB 1650 1.22 x 30.50	16	50	14.9	2,180	117	1.316
UBB 2425 1.22 x 30.50	24	25	22.3	3,270	88	0.714
UBB 2450 1.22 x 30.50	24	50	22.3	3,170	170	1.429
UBB 3225 1.22 x 30.50	32	25	14.9	2,180	117	0.756
UBB 4913 1.22 x 30.50	40	13	19.3	2,840	76	0.406
Insulation	Glass wool insulation: Un-Face Board (UB)					
UBB 3250 1.22 x 2.44	32	50	4.8	690	232	1.471
UBB 4825 1.22 x 2.44	48	25	3.6	510	171	0.758
UBB 4850 1.22 x 2.44	48	50	7.1	980	329	1.515

Although insulation materials as shown in Table 2.3 become more popular they are still expensive for low-income people in Thailand. This reason causes people hesitate to install these insulation to walls of their homes.

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2.5.2 <u>Previous Researches on Development of Exterior Wall Systems Incorporating EPS</u>

Increasing of indoor temperature is the main reason of increasing electrical consumption for air-conditioning, causing researchers to conduct research projects. There are many ways to create low thermal conductivity of exterior composite wall systems.

In order to obtain low thermal conductivity of exterior wall, a study of concrete made with EPS beads as aggregate was carried out by Park and Chisholm (1999). They investigated the effect of adding fly ash in to foam beads of three different densities. Thermal conductivity testing showed that the lighter the concrete, the lower the thermal conductivity. Bicini et al., (2005), conducted experiment on fiber reinforced mud bricks. These materials fulfilled the compressive strength and heat conductivity requirements of ASTM and Turkish standards. Several materials such as plastic fiber, gypsum, cement, basaltic pumice, polystyrene fabric, straw and water were mixed with clay by studying the graduation and particle size. The composition of fiber reinforced mud brick; a mixture between clay, polystyrene, basaltic pumice and water, has low thermal conductivity. To simplify the composition, Gaggino (2005) conducted a research of light concrete brick for housing external closure by mixing between concrete and EPS foam of 5-7 mm diameter. Many tests were made to find the most adequate procedure to manufacture bricks varying as material dosage, material mixture and time, manual or mechanical pressure and application or non-application adherence-promoting substances between the EPS spheres and the cement mixture. Thermal conductivity of 0.15 W/m ºC was obtained when the density of brick is 600 kg/m^3.

2.6 Heat Transfer Theory

Generally, heat always flows from warmer to cooler regions. This flow does not stop until the temperatures of the two surfaces are equal. Whenever there is a temperature difference in a medium or between media, heat transfer occurs. Conduction is transfer of heat through an object. When one part of an object is heated, the molecules within begin to move faster and more vigorously. These molecules hit other molecules within the object; which conducts heat throughout the object. They cause heat to be transferred through the entire object. In contrast, the term of convection refers to heat transfer that will occur between a surface and a moving fluid passing by that surface when there are difference temperatures. The third mode of heat transfer is term of thermal radiation. Any object will radiate heat to cooler objects around it by giving off “heat waves”. This is a

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direct transfer of heat from one object to another, without heating the air in between (Incropera and De Witt., 1990). Insulations used to reduce heat transfer through wall, ceiling and roof can prevent heat transfer by the way of conduction only (Stein, 1997). They do nothing for the heat transfer by ways of convection and radiation.

2.6.1 Principle of Heat Conduction

Heat conduction requires a relatively dense material to be effective, and solid are most common for this phenomena (Rolle, 2000). Even then, there are causes other than density that allow or retard conduction, such as readiness for molecules to share energy with neighboring molecules. The mathematical model for the steady state of conduction heat transfer Fourier's Law at the area A, thermal conductivity K, temperature gradient ΔT and material thickness Δx is

$$Q_x = -KA\,\Delta T / \Delta x \qquad \text{……….(1).}$$

K can be found by

$$K = -\,Qx\,\Delta x / A\,\Delta T \qquad \text{……….(2).}$$

Thermal resistance can be calculated from

$$R = A\,\Delta T / Qx\,\Delta x \qquad \text{……….(3).}$$

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2.6.2 Thermal Resistance of Multilayer Wall

In some cases walls may be constructed as a multilayer system in vertical direction as shown in Figure 2.2. Calculations of thermal resistance and coefficients are different from the ones described previously.

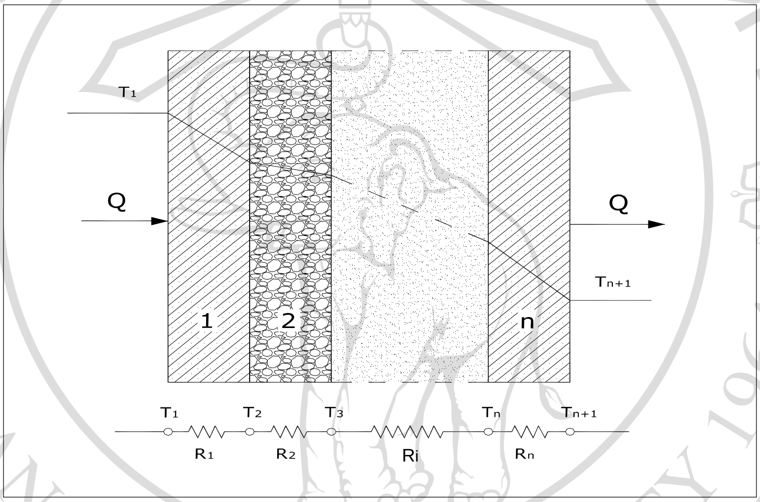

Figure 2.2 Schematic of heat flow in multi-layers of wall

Its total thermal resistance can be found by

$$R_T = R_1 + R_2 + ... + R_n \qquad \text{……….(4),}$$

And its thermal coefficient

$$U = 1/R_T \qquad \text{……….(5)}$$

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2.6.3 Heat Conduction in Porous Media

Heat conduction in porous materials is usually described macroscopically by averaging the microscopic heat transfer processes over a representative element volume (REV). Traditional treatment of heat conduction of porous materials is based largely on the mixture theory (Cenry et al,1995), assuming local equilibrium within the solid and fluid phases, so that the heat transfer processes in two phases can be lumped into a process described by a single heat conduction equation. The problem then becomes the construction of an appropriate composite model for the effective stagnant thermal conductivity mixture.

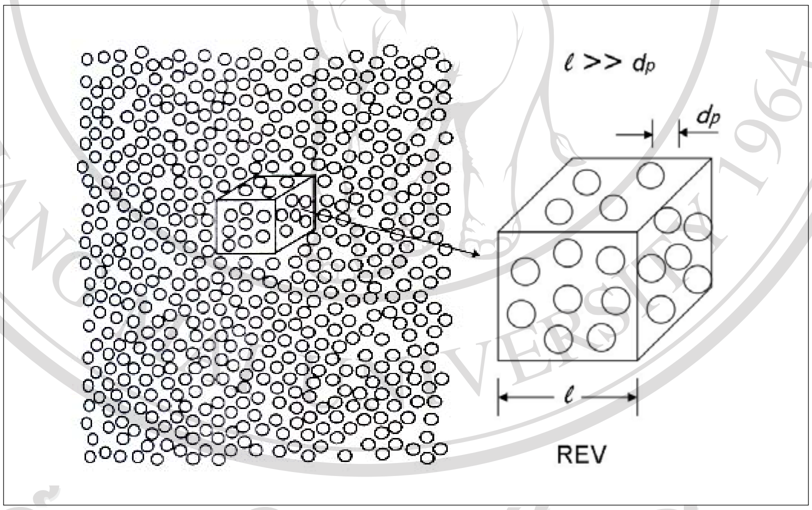

Figure 2.3 Schematic of porous media and representative element volume (REV) (Cenry et al,1995)

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Assuming that the porous materials consist of a packed solid particles surrounded by fluids, as depicted in Figure 2.3. For simplicity, but without loss generally, we should consider the spherical particles to be of uniform size. The diameter *dp* of the spheres then presents the microscopic scale of the media. Also assume that *dp* is much higher than the typical size of molecules, so that fluid and solid are regarded microscopically as continuous. Hence, the microscopic transient heat conduction equations for the fluid and solid are described by:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x}\right) \qquad \ldots\ldots\ldots(6)$$

Where K is thermal conductivity, ρ is the density and c is the specific heat, T is temperature, t is time, and x is space variable.

2.7 The Proposed Idea to Use EPS Packaging Foam

Though the methods of producing EPS-based mixtures as mentioned in Section 2.5.2 were effective, but they were still difficult and complicated for ordinary people to follow. Therefore, a research to find easier way to reuse packaging EPS foam with low cost production should be carried out.

EPS foam is abundantly used as packaging, cushioning, and insulating various kinds of products at everywhere. There is not market available for disposed EPS foam, thus, people can gather and reuse it for free. Therefore, an idea of breaking down packaging EPS foam into small particles, then use them as a sandwiched layer as exterior wall was proposed in this study. The external layer of wall made from conventional materials and internal layer made from gypsum to prevent flame catching in case of fire. This idea must be researched into what possible size of packaging EPS foam is the best in the application.

In this research, the idea of inserting particles EPS packaging foam as thermal insulation in to a 10 cm width of cavity space between two panels as shown in Figure 2.4 was introduced. This idea can be applied to either new walls to be constructed or old walls to be improved.

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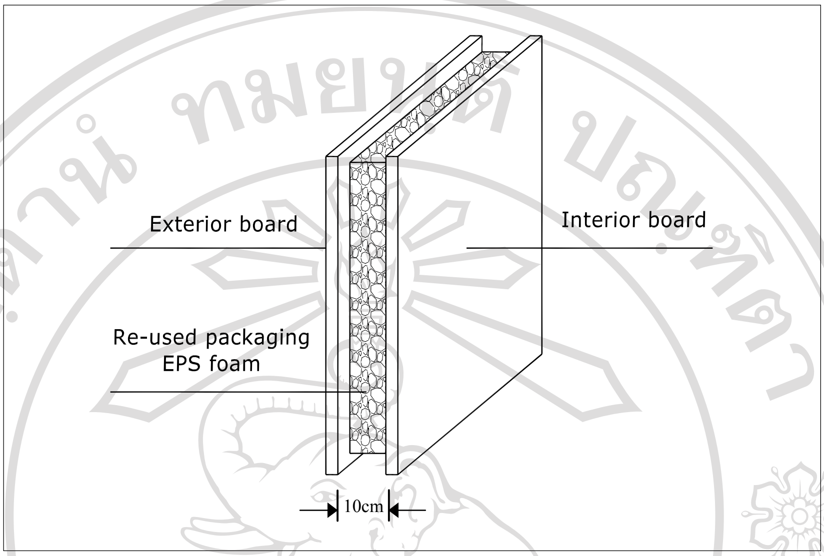

Figure 2.4 Wall insulation panel incorporating particles of packaging EPS foam

The most effective shape of foam to be inserted in the cavity should be a geometrical solid. However, EPS packaging foam pieces are in various forms, therefore, it is not practical to specify any certain size and shape because there will be a lot more remaining parts left. On the other hand, labor cost for both cutting and inserting into wall cavity will be high due to a predictable slow process. In order to use all over every piece of EPS package foam, the best way is to scratch into small particles. Thus the most effective size and shape of scratching EPS packaging foam will be studied and approximated thermal properties by comparing to the standard insulation materials according to the experiment.

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