HI-SMART

# HI-SMART: HIGHER EDUCATION PACKAGE FOR NEARLY ZERO ENERGY AND SMART BUILDING DESIGN

# MODULE #2

## CHAPTER 6: DYNAMIC INSULATION SYSTEMS

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## 2.6.1 DYNAMIC INSULATION AS AN APPROACH FOR NZEB

The two critical factors for an energy-efficient building sector are the energy supply from sustainable sources all over the year and the efficient utilisation of the produced energy with minimal losses. The building sector accounts for about 40% of energy consumption worldwide. Building insulation systems can be divided into two categories: conventional and dynamic insulation. Both aim to reduce thermal losses of the building envelope by increasing the thermal resistance of the building structure (roof and facades). Energy consumption in Europe is increasing at a 1.5 percent yearly pace due to economic growth, the expansion of the building sector, and the development of building services, particularly HVAC systems.

Meanwhile, the potential for energy savings through existing buildings operation management is substantial (Pérez-Lombard et al., 2008). The European union demonstrated its dedication to resolving the issue by introducing the “2020 by 2020” initiative, which plans to reduce energy emissions by 20% and increase the renewable energy share by 20% in 2020 compared to 1990 levels. In order to meet these objectives, several laws and regulations had to be introduced to lead the building sector toward Net-Zero Energy building (NZEB) (European Union, 2010). One of these approaches is using dynamic insulation in building envelopes. The proposed chapter investigates the different structures of thermal insulation for buildings. Furthermore, it classifies the background of dynamic (active) insulation, proposes a comparative investigation of the various mathematical models, experimental studies, and numerical simulations used by the literature.

## 2.6.2 HEAT TRANSFER IN BUILDINGS

This section introduces the heat transfer processes in buildings for the three modes; conduction, convection, and radiation.

## CONDUCTION HEAT TRANSFER

There are three primary forms of heat transfer processes. The first is conduction, which is defined as heat transmission through intervening matter that does not involve motion of the substance (matter is stationary). Figure 2.0.1 shows a solid block (Building wall in this case) with one surface at a higher temperature and the other at a lower temperature, this type of heat transfer can occur in the solid state when its molecules have a temperature difference. In conduction, energy is transferred within and through the body itself, unlike the other heat transfer modes.

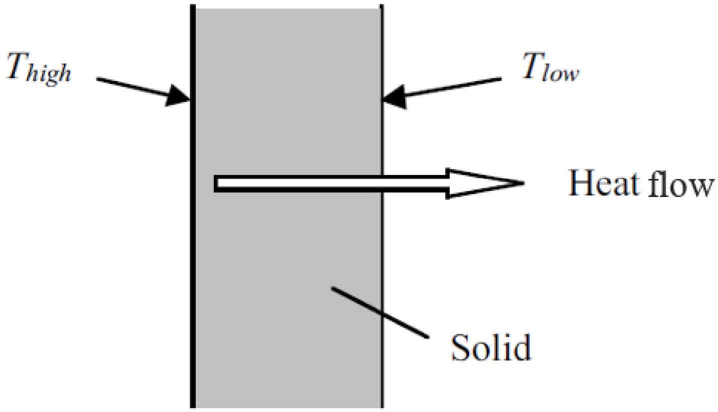


**Figure 2.0.1: Conduction heat transfer.**

## CONVECTION HEAT TRANSFER

Heat transfer due to a flowing fluid (liquid or gas) or convection is the second type of heat transfer modes. In convection, energy is transferred through a bulk transfer of a non-uniformly distributed fluid temperature. There are two types of convection heat transfer, free and forced.

- Free convection (or natural convection): Occurs due to the fluid temperature difference, leading to a difference in density, resulting in a buoyancy force.
- Forced convection: An artificially induced convection transfer occurs when a fluid is forced to flow over a surface by an external source such as a fan or pump.

## RADIATION HEAT TRANSFER

In radiation heat transfer, energy can be transmitted through space without the existence of a substance. It can occur in space (vacuum) or any transparent medium (solid, liquid, and gas). Radiation is fundamental for sweltering temperature bodies like the sun, where electromagnetic radiation transfers energy. Nevertheless, all existing bodies emit energy in photons that go in a random direction and have a random phase and frequency. Figure 2.0.2 shows a general illustration of the three modes of heat transfer.

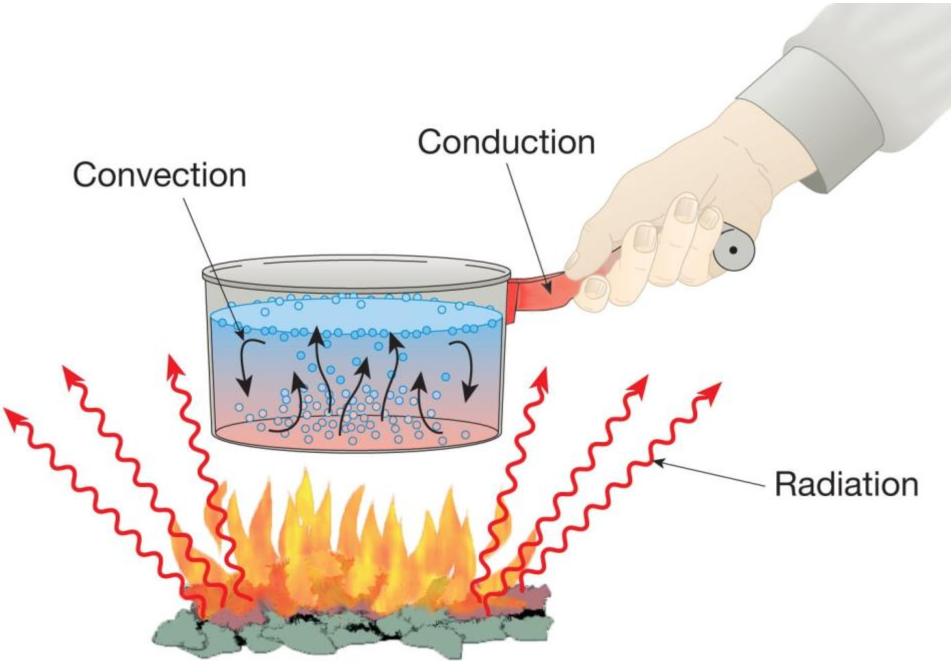


**Figure 2.0.2 Basic modes of heat transfer (Conduction, Convection, and Radiation) (SimWiki Documentation).**

## 2.6.3 BACKGROUND OF THERMAL INSULATION

Thermal insulation of building envelopes plays a significant role in energy saving by creating an additional layer with high thermal resistance between the interior and external environment. The main focus was finding the highest possible thermal resistance materials with the lowest costs. Using static insulation materials would decrease the heat losses from the building facades due to the temperature difference between inside and outside. In contrast, another solution is dynamic insulation with variable thermal resistance. In practice, materials with greater R-values (thermal resistance) are favourable due to a higher level of thermal insulation. Dynamic insulation can be achieved by having a running fluid added to the insulation layer, which can capture the heat loss throughout the building envelope. The fluid can be either water, air, or refrigerant.

## THERMAL INSULATION IN RESIDENTIAL BUILDINGS

Thermal insulation materials are used to decrease the flow of heat energy through building composite envelopes (walls and roof) due to their high thermal resistance $R_{th}$ values. Thermal insulating materials can be fibrous, particulate, film, sheet, or composite of these chemically or mechanically bonded materials. The insulating materials have the following functions:

1- Conserve energy by reducing heat loss rates or heat gain rates for pipes, ducts, equipment and building structures.
2- Control the surface temperature of building structures and equipment for both comfort and personal protection.
3- Prevent moisture condensation on building structures surfaces.
4- Reduce temperature fluctuations within the conditioned space for personal comfort.
5- Provide fire protection.
6- Reduce noise and vibration levels.
7- Reduce growth of mould.

## HEAT TRANSFER THROUGH COMPOSITE LAYERS WALL

Within the layers of composite walls (or roof), the heat transfer mode is conduction is the dominant as the hotter molecule energy is being transferred to the cooler molecule. Building walls are usually built with several layers, as shown in Figure 2.*0.3* shows the schematic diagram for the heat transfer in a three-layer wall. For steady-state conditions, the value of the heat flow rate through the wall layers is the same as that for each layer.

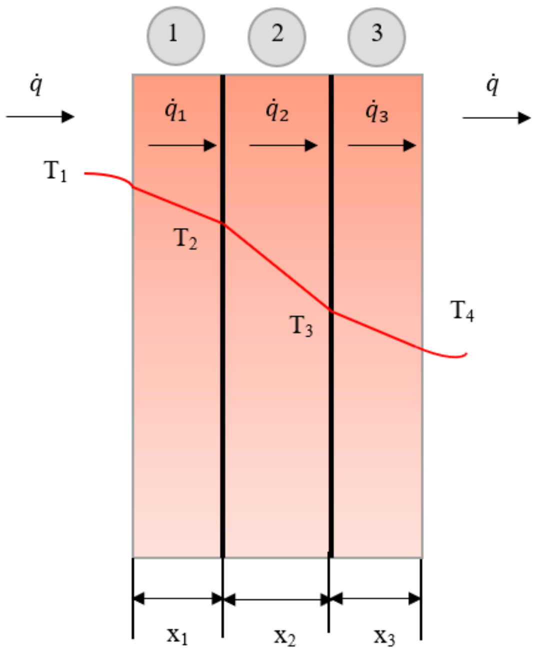


**Figure 2.*0.3* Schematic diagram for heat transfer in the composite wall.**

$$\dot{q} = \dot{q}_1 = \dot{q}_2 = \dot{q}_3 \qquad (0\text{-}1)$$

It was observed by Fourier that conduction heat flux ($\dot{q}/A$), in a given direction, is directly proportional to the temperature difference ΔT, in the direction of heat flow and inversely proportional to the distance Δx, in the same direction. Thus, Fourier's law is expressed as:

$$\frac{\dot{q}}{A} = -k\frac{dT}{dx} \qquad (0\text{-}2)$$

Where;

$\dot{q}$ = The rate of heat transfer by conduction [W]

A = Heat transfer surface area [$m^2$]

K = Thermal conductivity of the material [-]

dT = Temperature difference [K]

dx = Distance difference (section length) [m]

By applying equation (0-2) for section number (1) in Figure 2.0.3, the equation can be rewritten as the following:

$$\frac{\dot{q}}{A} = \frac{T_1 - T_2}{x1/k1} = \frac{T_1 - T_2}{R_{cond1}} \qquad 0\text{-}3)$$

Where: $R_{cond} = \frac{x}{k}$ , is the conduction thermal resistance (static thermal resistance) in [$m^2$=.K/W] which is analogous to the thermal resistance of electric circuit as the following Figure shows:

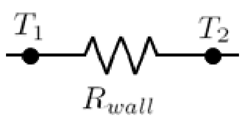


**Figure 2.0.4 Analogy of static thermal resistance and electrical resistance**

In addition to the conduction thermal resistance for the composite layers wall, the air is in contact with the outside and inside surfaces of the wall from stagnant thin layers of the air adjacent to these surfaces. The resistance of each side is given by (*1/h*), where *h* is the air film or convection heat transfer coefficient. The thermal resistance for each inside and outside air layer depends on the wall geometry, the airflow velocity, heat flow direction, and type of convection heat transfer (free or forced). Therefore, by applying equation (*0-2*) for the whole composite layers wall, the following equation results:

$$\frac{\dot{q}}{A} = \frac{T_i - T_o}{R_i + (R_1 + R_2 + R_3) + R_o} \qquad 0\text{-}4)$$

Where $R_i$ and $R_o$ are the inside and outside convection resistance of the air films, respectively.

The total thermal resistance for the heat transfer from the air on one side of a composite wall of *n* number of layers to the air on the other side is given as follows:

$$R_{th} = R_o + \sum_{j=1}^{n} (R_{cond})_j + R_i \qquad (0\text{-}5)$$

The overall heat transfer coefficient of the wall or the thermal transmittance U, in [$W/m^2 \cdot K$] is defined as follows:

$$U = \frac{1}{R_{th}} \qquad (0\text{-}6)$$

Finally, the heat transfer rate in the composite layers wall will be expressed as the following:

$$\dot{q} = UA(T_i - T_o) \qquad 0\text{-}7)$$

Lately, significant efforts are being directed to achieve the Nearly Zero Energy Building (NZEB). Over the years, the building services engineers presented several novel solutions to reduce buildings energy consumption by tunning the heat transfer through the building envelope. One of these approaches is to control the building envelope's overall heat transfer coefficient, decreasing the overall $U_{th}$ (or increasing the total thermal resistance $R_{th}$). The following sections investigate the different structures of thermal insulation for buildings. Furthermore, it classifies the background of dynamic (active) insulation, proposes a comparative investigation of the various mathematical models, experimental studies, and numerical simulations used by the literature.

## 2.6.4 BUILDING THERMAL INSULATION

Using static insulation materials would decrease the heat losses from the building facades due to the temperature difference between inside and outside. In contrast, another solution is dynamic insulation with variable thermal resistance.

## CONVENTIONAL (STATIC) THERMAL INSULATION

Several static insulation materials are available nowadays, ranging from traditional/conventional to high-performance thermal insulation, with the latter exhibiting much lower thermal conductivity values. When choosing an insulation material, the goal is to get the best feasible thermal insulation values by selecting higher thermal resistance. This involves using materials with reduced thermal conductivity to achieve the lowest thermal transmittance (U-value) feasible on the building's façade. Table 0-1 show a thermal conductivity comparison between some static materials to state of the art (high-performance) insulation ones (Jelle, 2011).

**Table 0-1 Comparison between conventional (static) and high-performance thermal insulation.**

| | Material | Thermal Conductivity |
|---|---|---|
| **Conventional** | Cellulose | 40-50 W/(m.K) |
| | Cork | |
| | Mineral Wool | 30-40 W/(m.K) |
| | Expanded Polystyrene (EPS) | |
| | Extruded Polystyrene (XPS) | |
| | Polyurethane (PUR) | 20-30 W/(m.K) |
| **State-of-the-art (High-performance)** | Aerogels | 13-14 W/(m.K) |
| | Vacuum Insulation Panels (VIP) | 3-4 W/(m.K) |
| | Vacuum Insulation Materials (VIM) | < 4 W/(m.K) |
| | Gas Insulation Materials (GIM) | |
| | Nano Insulation Materials (NIM) | |

Building's insulating capacity depends on many factors, including its thermal inertia, moisture-absorbing capacity, and airtightness and not only the type and thickness of insulating material (Bokalders & Block, 2010). In winter, as an example, having a static higher insulation level will assist in reducing heat losses from buildings, but it will also limit heat flow across the wall when this is potentially valuable. On the other hand, in summer cases, removing the heat collected in the building compartments is necessary due to internal loads and solar gains through windows during the day. Highly insulated buildings are more likely to experience significant overheating problems because internal temperature responds more quickly to solar and internal gains. The traditional way of thinking is that the higher constant R-value for the envelope always lowers energy consumption and running energy costs. However, some recent studies had criticised this theory by demonstrating that increasing thermal resistance beyond a certain point may increase energy's overall annual consumption. Therefore, it is necessary to develop new technology in the building insulation sector in order to overcome the disadvantages of using traditional static insulating materials and move forward to achieve the Nearly Zero Energy Building (NZEB) concept.

## DYNAMIC INSULATION

Dynamic insulation (DI) or (active insulation) means the ability to adjust the envelope's thermal resistance "R-value or U-vale" makes it possible to control the heat transfer rate in/out of the building. Furthermore, DI can be integrated into the building structure of walls and roofs as a heat exchanger, and then the ventilated outdoor air can be either pre-heated in winter and pre-cooled in summer. Accordingly, the transmission heat loss is no longer constant in the envelope.

| Dynamic insulation = Conventional insulation + Dynamic heat exchange within the building envelope |
|---|

Dynamic insulation's primary function is to maintain the inside with a suitable temperature range to minimise energy use and the associated carbon dioxide emission. Also, dynamic insulation can be implemented in most climate conditions as the indoor/outdoor temperature difference does not significantly impact it. Figure 2.0.5 shows the available utilisation strategies that dynamic insulation is able to work as. For example, in cold climates, the goal is to minimise the heat loss from the warm indoors to the cold outdoor through the building envelope by increasing the thermal resistance "R-value" (decreasing the thermal transmittance "U-value"). On the other hand, In the summertime, when the outdoor condition is very hot and cold inside, the goal will be to increase the thermal resistance to keep the desired indoor condition. Furthermore, some buildings use passive heating/cooling strategies in which dynamic insulation can also be used to increase the heat loss in the nighttime by decrease R-value "increase U-value". Based on that, the direction of the ventilated airflow and heat flux can be classified into two dynamic insulation operating modes:

- Proflux heat exchanger, the airflow and heat flux are moving in the same directions.
- Contraflux heat exchanger, airflow and heat flux are moving in opposite directions.

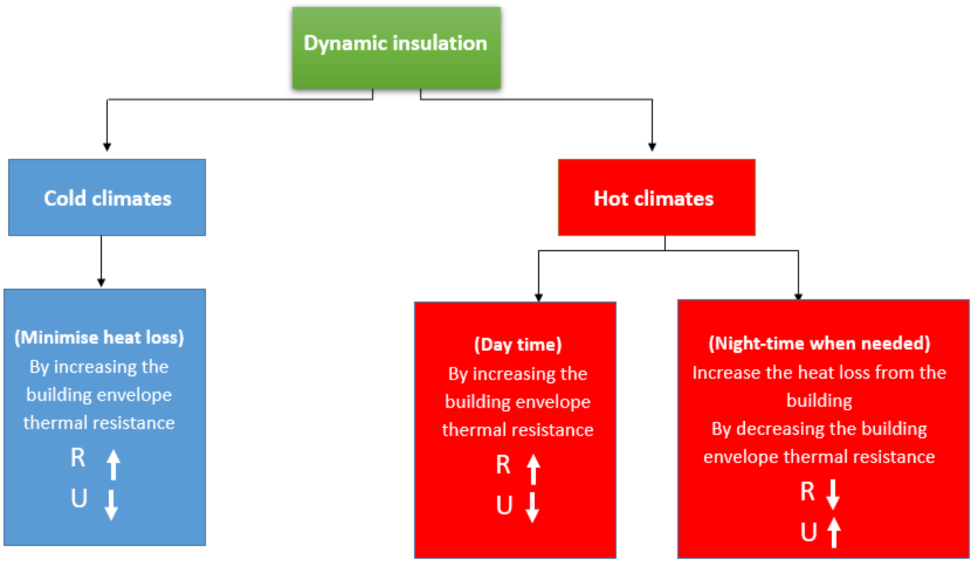


**Figure 2.*0.5* Possible dynamic insulation strategies based on climate and purpose of usage.**

The concept of DI was first developed in the 1960s in agricultural buildings in Norway utilising dynamically insulated ceilings, which discovered that conventional barn air supply, pulled by natural stack ventilation, exchanged heat with stored materials in the hayloft (Morrison et al., 1992). However, in the 1980s, investigators began to study the physics of dynamic insulation. Bartussek was the first to use the idea in a domestic configuration. With an appropriate construction detail, a zero U-value was obtained without draughts in two Norwegian residential structures that have been dynamically insulated (Baker & Phd, 2003). Even though the concept of dynamic insulation was proposed more than 30 years ago, it has not yet been utilised in building design due to its diverse challenges and uncertainties. Figure 2.0.6 summarises the strength, weaknesses, opportunities, and threat analysis (SWOT analysis) that the dynamic insulation technology has.

1- Despite the considerations and challenges associated with using this technology in buildings, it has the following advantages:
2- The system can act as a heat exchanger, i.e. the indoor ventilation can be either pre-heated in winter and pre-cooled in summer.
3- DI can work as a filter that can capture particulate matter with a diameter less than 0.5µm and larger than 5µm (Taylor et al., 1998), providing better indoor air quality.
4- The dynamic insulation limits the passage of water vapour to the interior environment when in contra-flux mode, lowering the danger of interstitial condensation and mould formation (van der Aa et al., 2011).
5- As the heat loss through the building structure would be much less using the DI, it would provide a better solution instead of using the conventional building envelope. A lightweight, cheap, and thinner walls and roofs will exist (van der Aa et al., 2011).

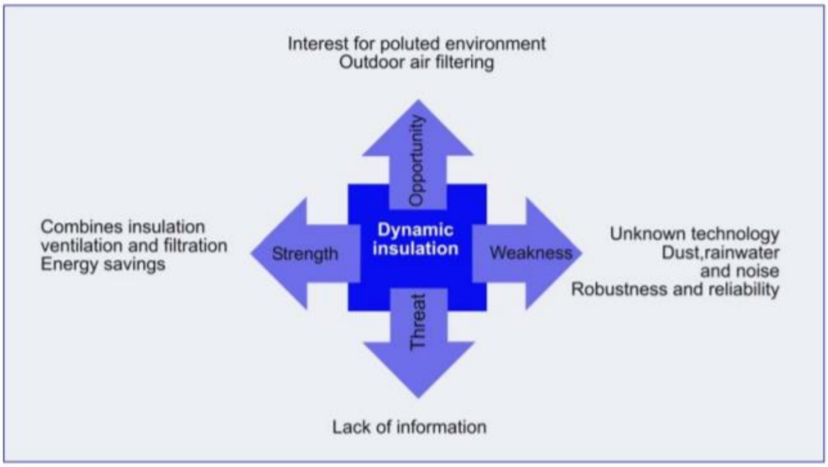


**Figure 2.*0.6* SWOT analysis for the dynamic insulation approach (van der Aa et al., 2011).**

## AVAILABLE APPLICATIONS

There are several existed structures for the dynamic insulation categorised based on the fluid type and circulation type, as Figure 2.0.7 shows. The following section will be based on the previous studies done by the available literature.

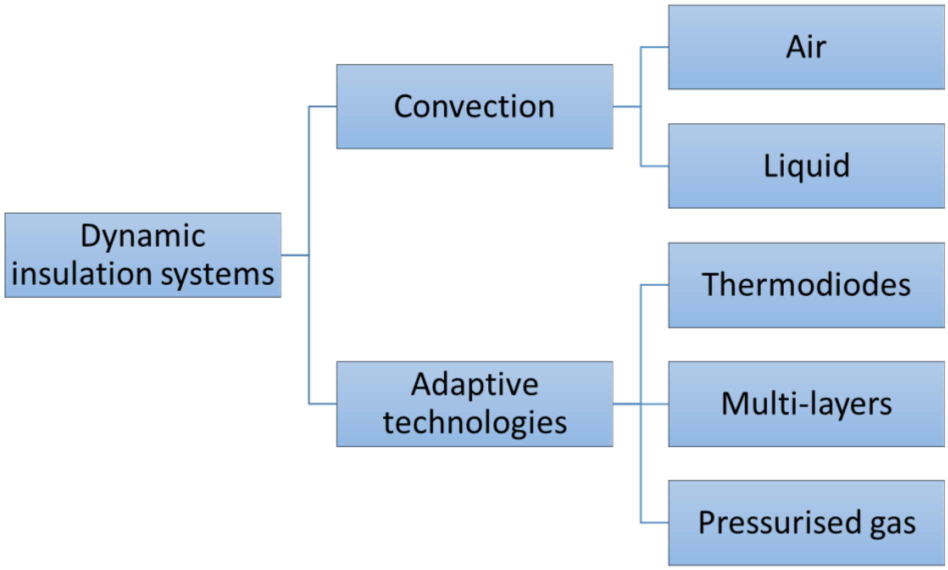


**Figure 2.*0.7* Available dynamic insulation systems based on fluid type/circulation.**

## (A) DYNAMIC INSULATION BY CONVECTION

Dynamic insulation basic principle is by having a running fluid added to the static insulation layer. The flowing fluid can be mainly (air), water, or refrigerant. Therefore, it aims to minimise the building envelope heat losses by allowing effective preheating of the ventilation air and capturing the heat loss through the envelope. For simplicity, in this chapter, DI is being handled based on the winter season so that the heat loss will be from inside to outside. For the winter season, dynamic insulation will:

- Reduce the heat loss through the wall/ceiling.
- At the same time, deliver pre-warmed air into the indoor space.

## 1) DYNAMIC INSULATION USING AIR

It is considered to be the most common application of dynamic thermal insulation. As the flowing air is heated or cooled according to the operating conditions, the walls serve as a heat exchanger, and this phenomenon enhances the energy performance of the whole building system. Variable R-values are achievable by allowing outside air to penetrate wall cavities and then through channels located within the walls into indoor spaces. (Brunsell, 1994) defined dynamic insulation as construction where the air is being forced through the insulation, typically from the colder outside air, into the heated building to achieve the theoretical zero U-value. There are two categories of dynamic insulation technologies now available:

- Cavities in the wall to circulate air. In these cavities, air movement is ordinarily parallel to the wall, which acts as a heat exchanger.
- Using breathing walls which is an air-permeable wall design that allows air to pass through. The interaction of the gas and solid phases can also serve as a heat exchanger in the contra-flux mode.

The first category is often called parietodynamic insulation (airflow passes parallel to the wall plane), as

Figure 2.0.8 (a) shows that the employed materials are ideally airtight, and the passageways can be sealed or exposed. While the second category is called permodynamic insulation (airflow passes perpendicular to the wall plane), as

Figure 2.0.8 (b) shows. In this type, the configuration consists of three layers: An external layer, which is exposed to the outdoor ambient air; A breathing layer, which is consists of a porous material that allows the airflow to supply the inside by the resulting pressure difference (low pressure-drop between the indoor and outdoor); and the third layer is the air gap between the first and second layers. Breathing walls have been studied as an approach for a distributed ventilation air supply system where the wall functions as a supply source, heat exchanger, and filter of airborne pollutants (Imbabi, 2006).

An important example of parietodynamic insulation is integrating solar energy and dynamic insulation savings using the transpired solar collector (TSC), which is considered as one of the most reliable and cost-efficient systems for solar space heating. Besides the primary duty of TSC for preheating the ventilated air, it can also be considered as an effective tool to provide additional active insulation on the building façade where it has been installed. Figure 2.0.9 shows the transpired solar collector’s working principle and how it would be considered an active insulation system (Fawaier et al., 2021).

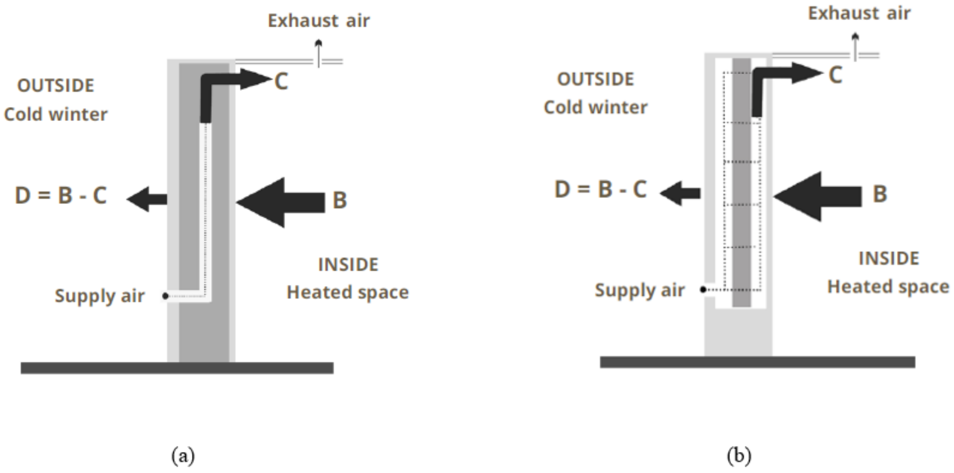


**Figure 2.0.8 (a) Parietodynamic wall construction. (b) Permeodynamic wall construction (Imbabi, 2012).**

Accordingly, TSC would have three significant benefits that can be obtained by using TSC in the buildings. The first one is a reliable solution to provide ventilation (heating/preheating) into the buildings, the second one can be considered as a thermal barrier which can block the heat losses from the heated interior to the cold ambient, and the third one is when TSC in operation mode, the air handling unit will be able to recapture the transmission heat losses inside the TSC air cavity (thermal barrier in the second benefit).

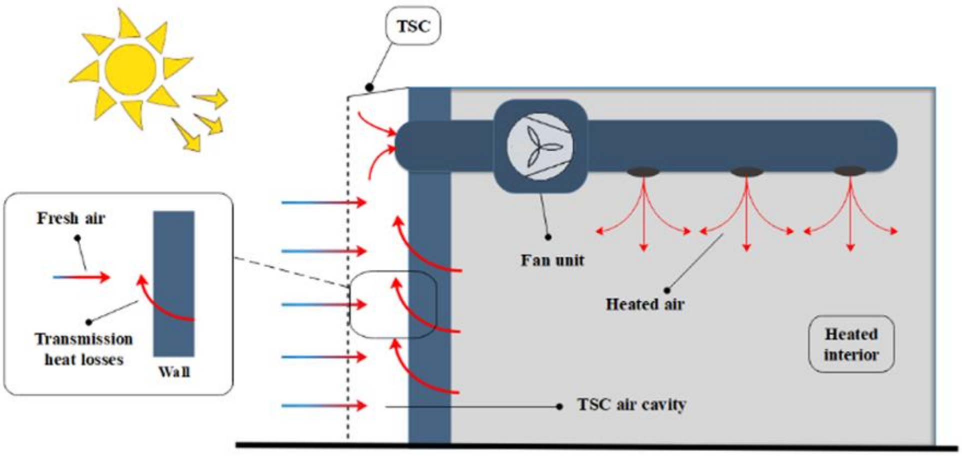


**Figure 2.0.9: Working principle of the transpired solar collector as a dynamic insulator (Fawaier et al., 2021).**

The Trombe wall is another application where the air is circulating due to the indirect heat transfer caused by the sun. Therefore, dynamic insulation will be existed (Kisilewicz et al., 2019). Trombe wall (or solar wall) was initially patented in 1881 by Morse, but it was not popularised until Trombe patented a similar system in 1972. Figure 2.0.10 shows the Trombe wall working principle as additional dynamic insulation. Many studies investigated the

Trombe wall as a dynamic insulator, showing how it reduces heat loss and improves indoor air quality levels (Shen et al., 2007) and (Claes et al., 2010).

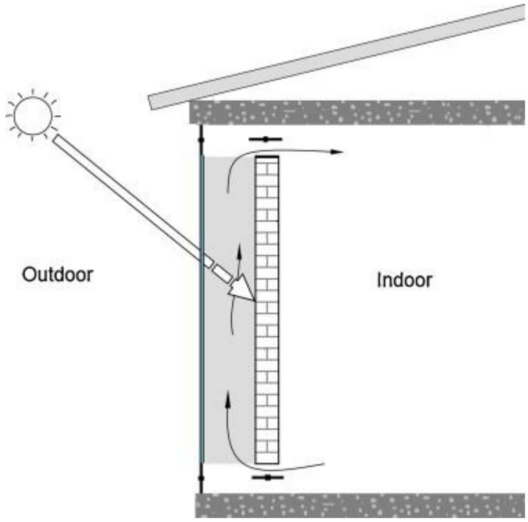


**Figure 2.0.10: The Trombe wall's dynamic insulation effect results from the air movement in the façade air cavity (Shen et al., 2007).**

Back to the literature, and as development on the parietodynamic insulation systems. (Imbabi, 2012) presented new Void Space Dynamic Insulation (VSDI) configuration, which provides an efficient building envelope and a higher indoor air quality in thin wall constructions. The basic concept is to limit air movement within a co-planar void space defined by one or more layers of insulating material and the wall structure. The study hypothesis had a flow simulation using Solidworks for a low-cost conventional static insulation coupled with efficient ventilation. Another study on the convection air DI was done by (Ascione et al., 2015), in which they applied the finite difference method using MATLAB code to investigate the transient conditions of the cold seasons' dynamic insulation. The energy efficiency of dynamic insulation is measured by the 'dynamic U value', which varies when the air flows through the air cavity. (Pflug et al., 2015) presented a new way of realising a switchable U-vale by controlling the air convection within a closed element. Simulation representation using TRNSYS was used to validate the experimental results of using this idea for the cooling season. The switching conducting-insulating U value can reduce the cooling demand by up to 29.6%. In this chapter,

Table 2.0-2 will summarise the available dynamic insulation literature used in the text.

## 2) DYNAMIC INSULATION USING LIQUID

The second fluid system of dynamic insulation is performed using liquids such as water or refrigerant. For this type, a system of pipes is placed inside the structure of an external building envelope in which heating and cooling medium circulate depending on the required application. investigated a novel building wall structure using a capillary pipe network with low-grade thermal water. They developed a mathematical model to evaluate applying the dynamic thermal system in three locations in the wall. Results showed less fluctuation in the internal walls surface temperature when the tube system is placed on the inner side; according to that, an improved indoor thermal comfort will be established.

(Kisilewicz et al., 2019) experimentally investigated a family house in Nyíregyháza, Hungary. The building walls were coupled with a system of pipes in which glycol (refrigerant) was circulated. The coupled coil has been connected to a ground heat exchanger located 1.75 m below the ground level. This thermal barrier has improved thermal comfort in summer and winter, and it has reduced the heat losses by 63% compared to the conventional static insulation materials, as Figure 2.0.11 shows. Another innovative system (Al-Nimr et al., 2009) proposed a dynamic insulation system for the building envelopes that is also based on fluids. The system consists of a movable partition between two gaps filled with different conductivity and thermal expansion fluids. Both fluids are connected to a control system and small tanks. It is possible to control the whole wall construction's thermal resistance by controlling the amount of both fluids on either side of the gap.

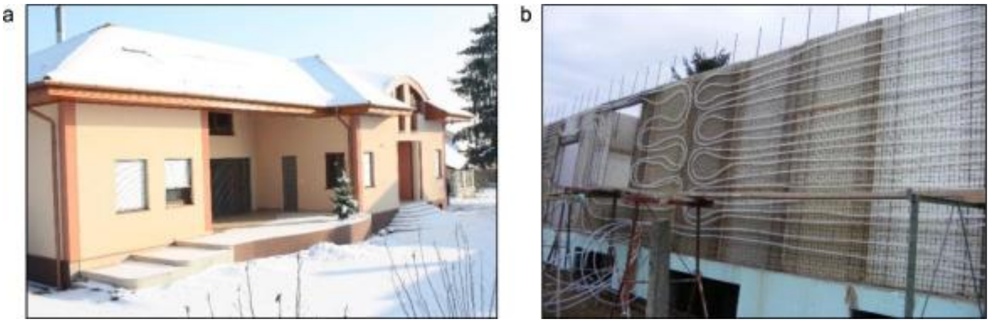


**Figure 2.0.11 (a) Overview of the building west façade (b) Heat exchanger arrangement in the ground floor wall (Kisilewicz et al., 2019).**

(Figiel & Leciej-Pirczewska, 2020) Studied the energy performance and the $CO_2$ emission resulted from using the active thermal insulation. A water-based Thermo active wall barrier was mounted in the wall construction, where the system pipes provide an active thermal barrier for heat transfer between the outer and the heated space. The research was implemented on the basis of the Polish meteorological base in a temperate climate for a single-family house.

There are also increasing efforts to integrate the building's dynamic insulation with the phase change materials (PCM). (Kishore et al., 2020) investigated this integration, showing the effect of using this technique for different climate conditions. The results showed a 15–72% reduction in annual heat gain and 7–38% saving from heat loss.

## (B) DYNAMIC INSULATION ADAPTIVE INSULATION TECHNOLOGIES

Despite the advantages of using dynamic convection insulation by air or liquid, the method has several challenges. These challenges are related to the system design's complexity and the mechanical components required for fluid circulation. The following section explores other options DI researchers did to integrate the technology in buildings facades.

### 1) USING THERMODIODES

The first method uses a bidirectional thermodiode that can transfer heat in one direction and provide insulation in the other direction. Varga et al. (Varga et al., 2002) studied different design variations of the bidirectional thermodiode under cooling season conditions. The results showed that the apparent conductivity, depending on the temperature difference, was three to five times higher in the direction of heat transfer. Chun et al. (Chun et al., 2009) Also proposed a series of experiments to investigate the performance of a bi-directional thermodiode and how it would be affected using different working fluids and operating conditions. Results showed that this system could transfer up to 40% of the radiation absorbed from ambient to indoors.

### 2) USING MULTILAYERS

Another mechanism is to use multilayered insulation, which allows switching between high and low R-values. Kimber et al. (Kimber et al., 2014) proposed new multifunctional insulation, where thin polymer membranes are installed within a wall to create air layers so that the effect of natural convection becomes negligible. The article focused on both the insulating and conductive configurations of the typical conditions. In order to achieve low R-values, the air is removed, and the layers are compressed, leaving only conduction heat transfer through the polymer membranes. Park et al. (Park et al., 2015) evaluated the effect of using dynamic insulation materials on the end-use of heating and cooling energy. Three US climates for single-zone residential building was analysed. The insulations material are rigid cell panels positioned within a building's exterior wall cavities. The bulk thermal diffusivity of the assembly is adjusted to the addition of variable conductivity inert gases (carbon dioxide, nitrogen, helium), thereby influencing the heat transfer rate through the building envelope, as Figure 2.0.12 illustrate. The insulation media can be adjusted through control strategies based on indoor-outdoor temperature differences daily, weekly, or seasonally.

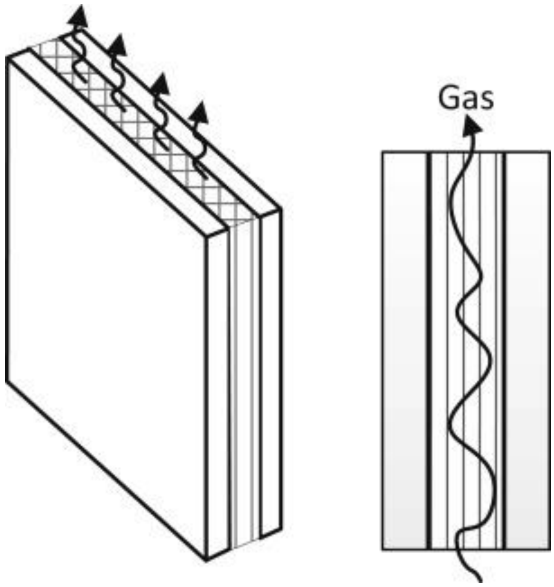


**Figure 2.0.12 Multilayers dynamic insulation operating principle using variable conductivity inert gases (Park et al., 2015).**

## 3) USING PRESSURISED GAS

Several approaches to design a variable resistance (dynamic U-value) using gas pressure were implemented. Benson et al. (Benson et al., 1994) introduced a concept for vacuum insulation of variable conductance. The system's thermal resistance difference was accomplished by electronically adjusting the temperature of a small metal hydride attached to the vacuum envelope. Design observations were compared with the findings from bench-scale sample laboratory experiments. Some potential automotive applications were also suggested for this variable conductance vacuum insulation system. By regulating the air pressure, Berge et al. (Berge et al., 2015) developed a method for modulating the air's thermal conductivity in the nanoporous fumed silica structure of a vacuum insulation panel and aerogel blanket. The findings showed a variation in the thermal conductivity of around three times for a fumed silica and less than two times for an aerogel blanket when the pressure ranged from 1 to 100 kPa.

For solar heating of building façades, computer simulations have been carried out by Horn et al. (Ronny et al., 2000) for switchable thermal insulation, as Figure 2.0.13 shows. The method uses metal hydride to adjust the Hydrogen gas pressure inside the panel and thus change the heat conductivity by approximately half.

Table 2.0-2 summarises an overview of the available dynamic insulation systems literature.

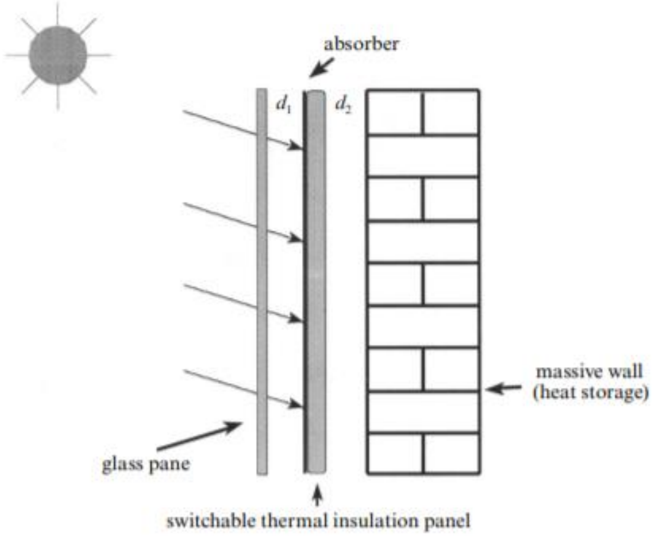


**Figure 2.0.13 Side view of a building facade equipped with switchable thermal insulation (Ronny et al., 2000).**

**Table 2.0-2 An overview of the available dynamic insulation systems literature**

| Mechanism | Description | Approach | Reference |
|---|---|---|---|
| **Convection (air)** | Preheated air is being forced through the insulation from the colder outside air into the heated building. | Experimental measurements compared with a mathematical model | (Brunsell, 1994) |
| | Heat transfer study for dynamic insulation residential wall. | Numerical analysis | (Morrison et al., 1992) |
| | Void Space Dynamic Insulation (VSDI). | Flow simulation using Solidworks | (Imbabi, 2012) |
| | Modular breathing panel | 1-D Analytical model | (Imbabi, 2006) |
| | Air-permeable building envelope components with ventilation. | Numerical analysis (Finite difference method FDM) using MATLAB | (Ascione et al., 2015) |
| | Translucent dynamic insulation system envelope with switchable insulation. | Experimental measurements & Simulation representation using TRNSYS | (Pflug et al., 2015) |

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| **Convection (liquid)** | Direct coupling between façade element and ground heat exchanger. | Experimental measurements | (Kisilewicz et al., 2019) |
| | Capillary tube network embedded in active tuning building wall. | Mathematical model and MATLAB analysis | (Niu & Yu, 2016) |
| | Movable partition between two gaps filled with different thermal properties fluids. | Analytical heat transfer model | (Al-Nimr et al., 2009) |
| | Water-based Thermo active wall barrier. | Experimental measurements | (Figiel & Leciej-Pirczewska, 2020) |
| **Adaptive Insulation Technologies** | | | |
| **Thermodiodes** | Bidirectional thermodiode panels. | Experimental measurements & Analytical heat transfer model | (Varga et al., 2002) |
| | Bi-directional thermodiode. | Experimental measurements | (Chun et al., 2009) |
| **Multilayers** | Collapsing number of air layers. | Mathematical model | (Kimber et al., 2014) |
| | Dynamic insulation panels with controllable thermal resistance. | Simulation representation | (Park et al., 2015) |
| **Gas pressure** | Variable conductance insulation. | Experimental measurements & Mathematical model | (Benson et al., 1994) |
| | Variable pressure on aerogel blanket. | Experimental measurements & Simulation representation | (Berge et al., 2015) |

| | Adsorption/Deabsorption of hydrogen | Simulation representation | (Horn et al., 2000) |
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