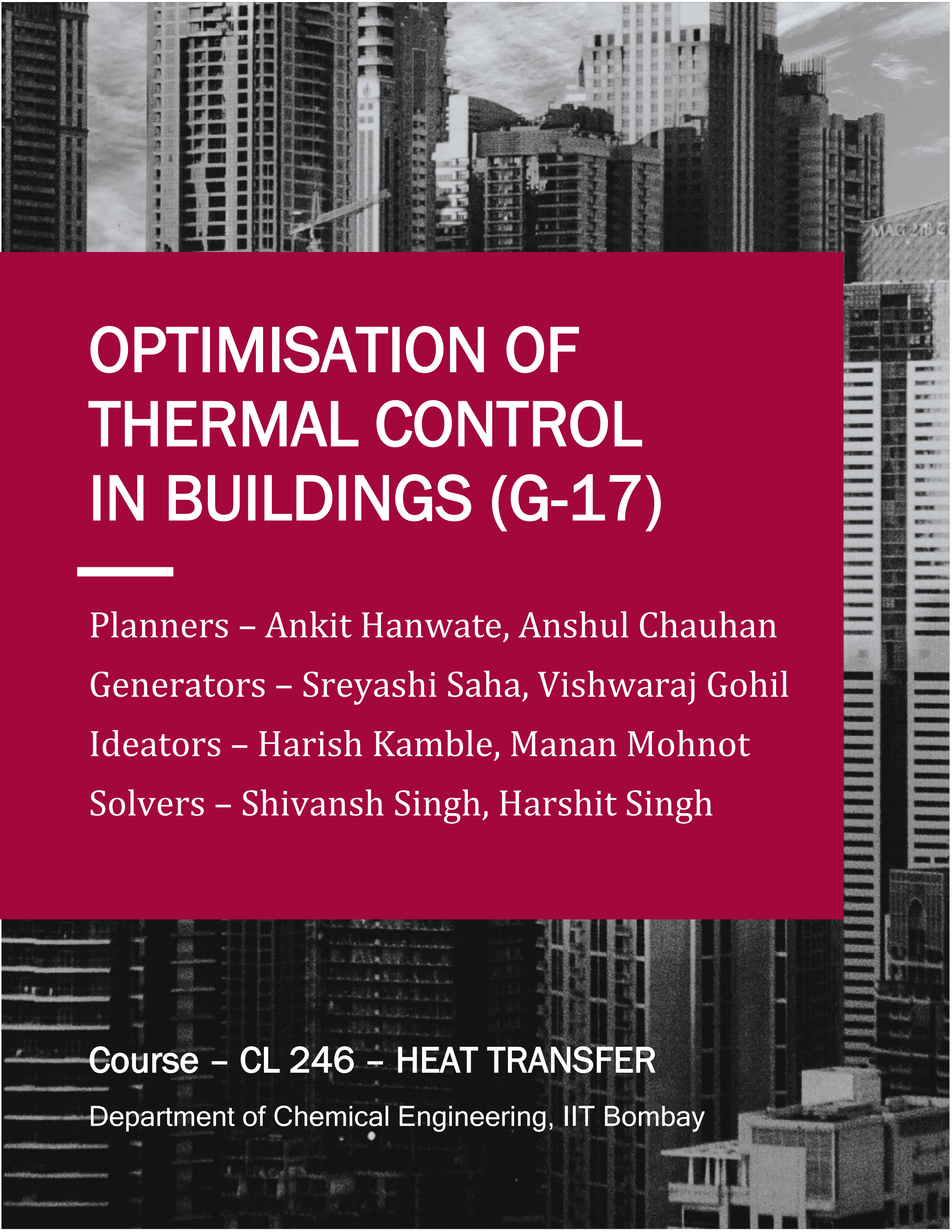

OPTIMISATION OF THERMAL CONTROL IN BUILDINGS (G-17)

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Course – CL 246 – HEAT TRANSFER

Department of Chemical Engineering, IIT Bombay

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ABSTRACT

This project has been created as a part of the course CL246 - Heat Transfer. This project aims to solve the problem of thermal control in buildings considering the economic and environmental costs associated with it. Thermal control is of prime importance in improving the quality of modern-day indoor living. Poor thermal designs can directly affect the thermal comfort of people in office buildings, theatres, commercial centres and residential buildings. A survey based on questionnaires was conducted to understand user pain points and subsequently frame our problem statement. A simple heat balance analysis has been then performed with certain underlying assumptions to calculate heat losses from buildings. A design solution has been proposed along with the use of Phase Change Materials (PCM) to address the optimisation problem, keeping in mind the economic aspect of it.

USER STORY

Over the past few decades, the **quality of indoor living has considerably degraded** due to both natural and man-made factors. Modern day constructions provide **comfortable living at the expense of energy**. Most materials used for construction contribute to the destruction of the urban thermal environments and significantly increase energy consumption. This also explains to a certain extent why **modern-day urban constructions require more HVAC systems** than those dating to a few decades ago. The construction industry, to reduce cost and increase the speed of construction, implement thermal designs that compromise the quality of indoor living and cause **detrimental impact on the health of the residents** in the long term, resulting in diseases like Sick Building Syndrome. We thus aim to **provide thermal comfort without excess space conditioning costs** which is one of the primary requirements of buildings.

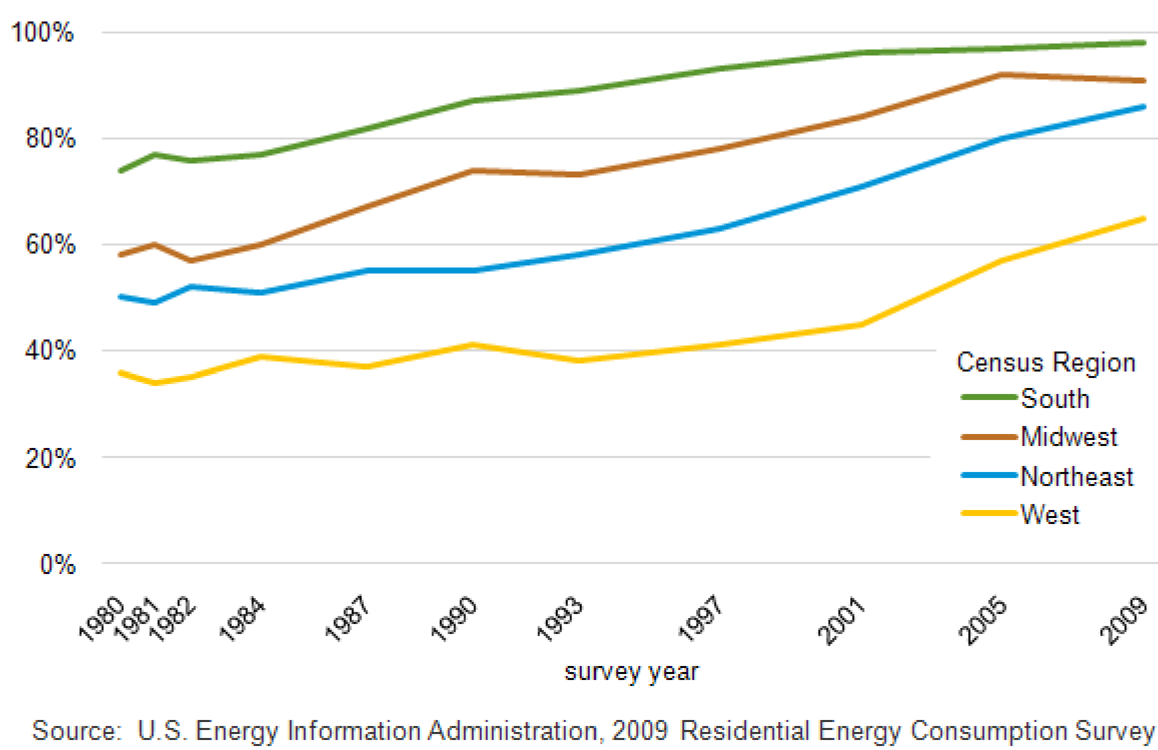


Fig (1): This figure shows the steady rise in the number of air-conditioned homes in the U.S. over the past few decades thereby showing the growing need for more HVAC systems in home

INTRODUCTION

WHAT IS THERMAL CONTROL?

In layman terms, it is **the moderation of temperatures in the interiors of a building to keep the occupants comfortable while reducing the energy consumption of a building for heating and cooling to a fraction of what it would be otherwise**. Thermal control seeks to maintain optimum indoor living temperatures by keeping houses cool during the summers and warm during the winters.

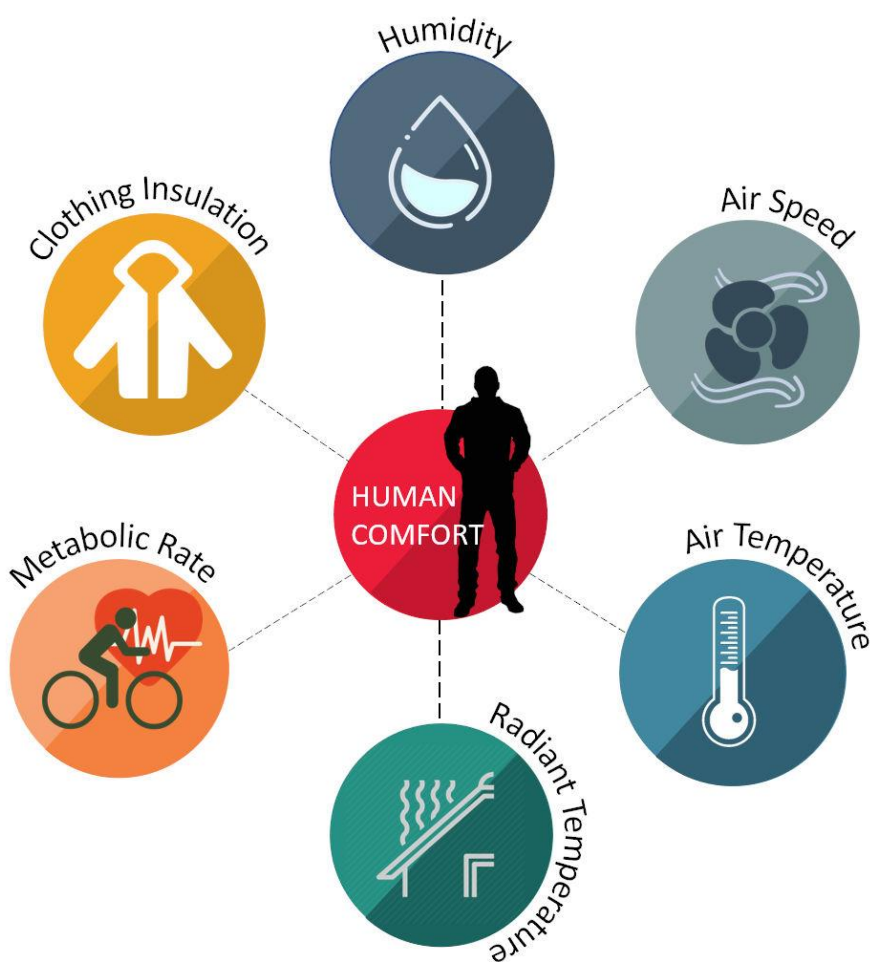


Fig (2): Factors Influencing Thermal Control in Homes

WHY IS THERMAL CONTROL NECESSARY?

1. Degrading thermal environments have severe impact on the health of the individuals and sometimes lead to **acute health conditions like SBS (Sick Building Syndrome)**.

2. Thermal control is of much importance at workplaces where it is desired that people are most productive. The environment and surroundings of a person can have **physiological and psychological effects, therefore defining the productivity of the individual**.

3. It affects day-to-day life when people are at their home at ease. A **good thermal environment in the house elevates the mood of the occupants** and makes the life more comfortable.

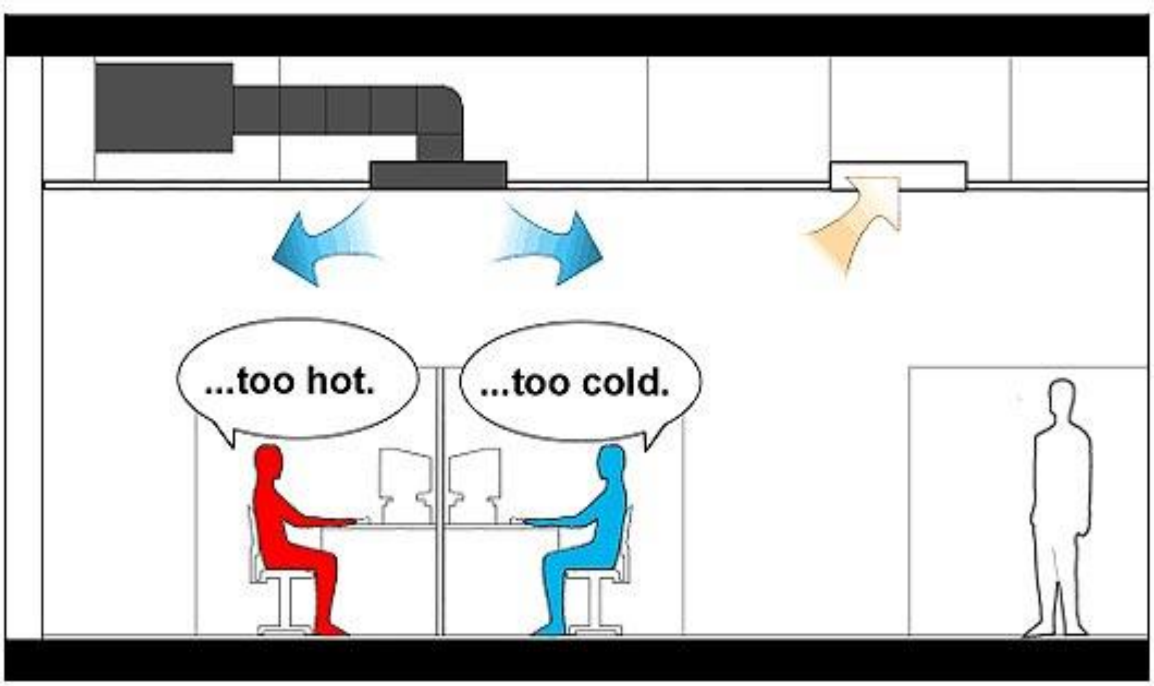
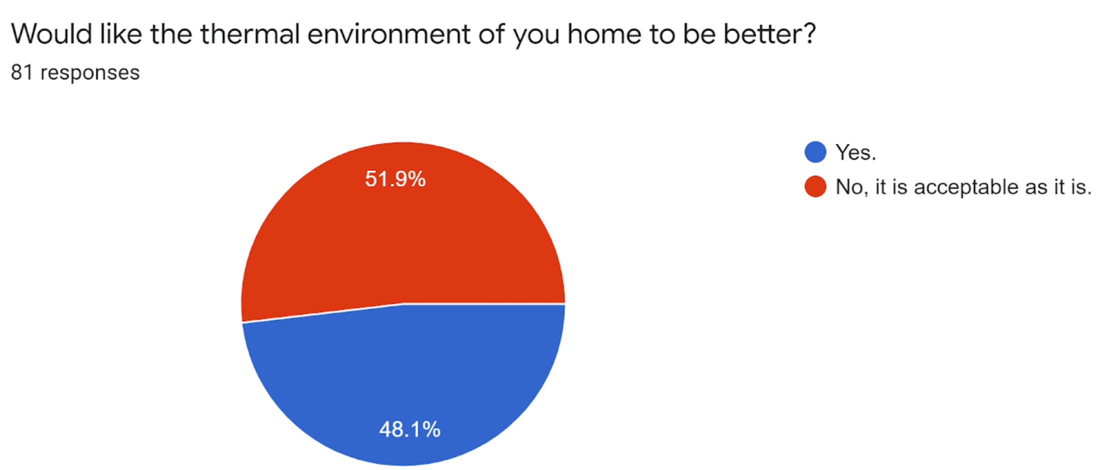


Fig (3): Poor thermal environments may lead to discomfort of residents

THEORETICAL BACKGROUND

While conducting a literature survey, several research papers and articles highlighted the issue of thermal control in buildings. Construction companies advertising that the homes have been designed to provide them optimal thermal comfort and yet **conditions like 'Sick Building Syndrome' are becoming increasingly common**. To test if this was true, a survey was conducted to understand the level of thermal comfort that people experience in their current residences. The responses confirmed the previous knowledge and assumptions. **52% people responded showing their dissatisfaction with the current thermal dynamics of the environment they were residing in**. It was a primary motivation for us to delve deeper into the problems persisting in modern day thermal designs of buildings and why people required more HVAC systems (therefore significantly more energy consumption) despite living in state-of-the-art residential places.



TECHNICAL PROBLEM (LIKE A TEXTBOOK)

A room in which HT takes place only through walls (no HT through roof/floor) has inside temperature of 30°C and the surrounding temperature of 5°C.

a. For the two different types of walls described show that the resistance of composite wall (having honeycomb structure) is more than that of normal wall. Thus, show that the heat flux through composite wall is less.

Required values: thermal conductivity of plaster 0.7 W/ (m.K); thermal conductivity of brick 1.13 W/ (m.K); thermal conductivity of the material used for honeycomb structure 0.4 W/ (m.K); velocity of air in the surrounding is 1m/s and inside the room taken as 0.1m/s
length of plaster ($l_{Plaster}$) = 0.012 m; length of brick (l_{Brick}) = 0.0762 m; length of composite ($l_{Composite}$) = 0.0522 m.
Dimension of the room being 3 X 3 X 3 [diagram of both the walls shown]

b. Show that the time taken for temperature drop of certain amount X (taken 3°C) at the centre of the room having normal walls is relatively more than time taken for the composite walls. Also find the temperature drop at the outer surface of the composite walls when the centre of the room has temperature drop of X.

Note: Use suitable assumptions for the b. part to solve the above using transient conduction in the (room + pair of opposite walls) with convection.

PROPOSED SOLUTION

Our **primary focus was on "How to increase the efficiency of the room (walls) to keep the room's temperature intact"**. In an attempt to implement this, a possible solution was to modify the design of the room keeping in mind the in-built ventilation and overall heat transfer i.e., minimum heat is lost to the surroundings.

METHOD 1: To introduce air gaps between the inner and outer walls which would allow us to neglect the conduction of heat between the walls due to the presence of air in between which conducts only in convectional and radial flow of heat to the outer walls.

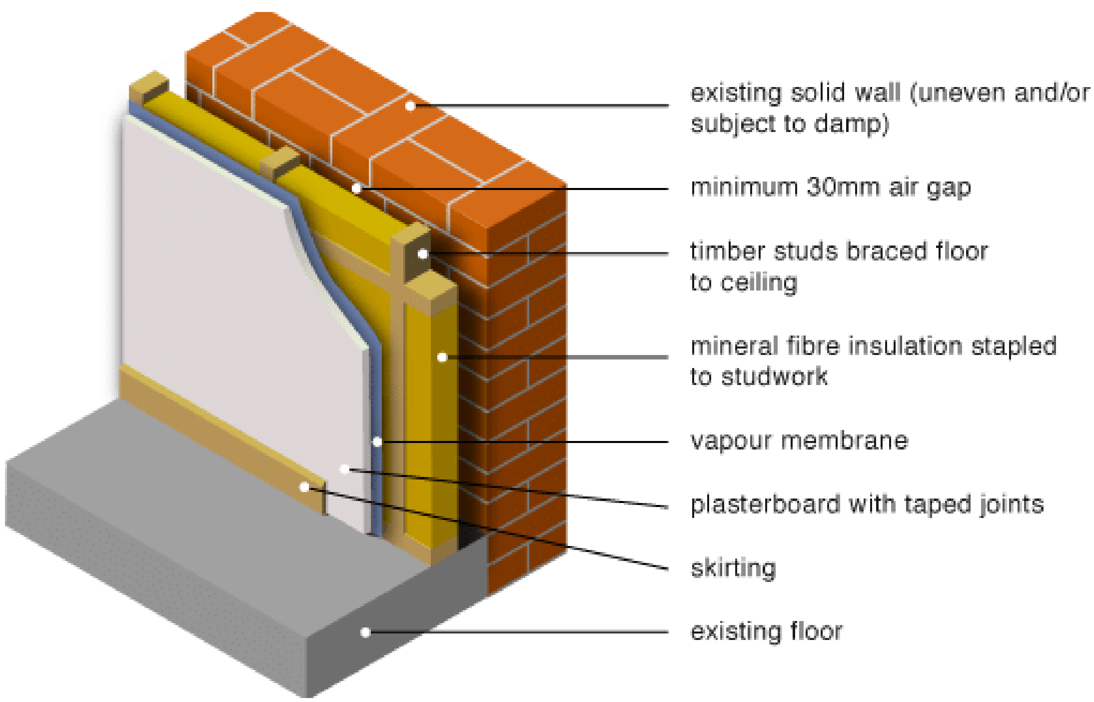


Fig (4): It shows the introduction of air gaps in walls of optimum thickness to reduce heat loss

METHOD 2: To introduce phase change materials in the inner walls which will take up and store the heat when any heating electrical appliance like heater is used to keep the room warm and store it. When the appliance is not in use, the heat is transferred back to the room thus making the room warm in absence of the use of appliances, thereby cutting the cost of electricity.

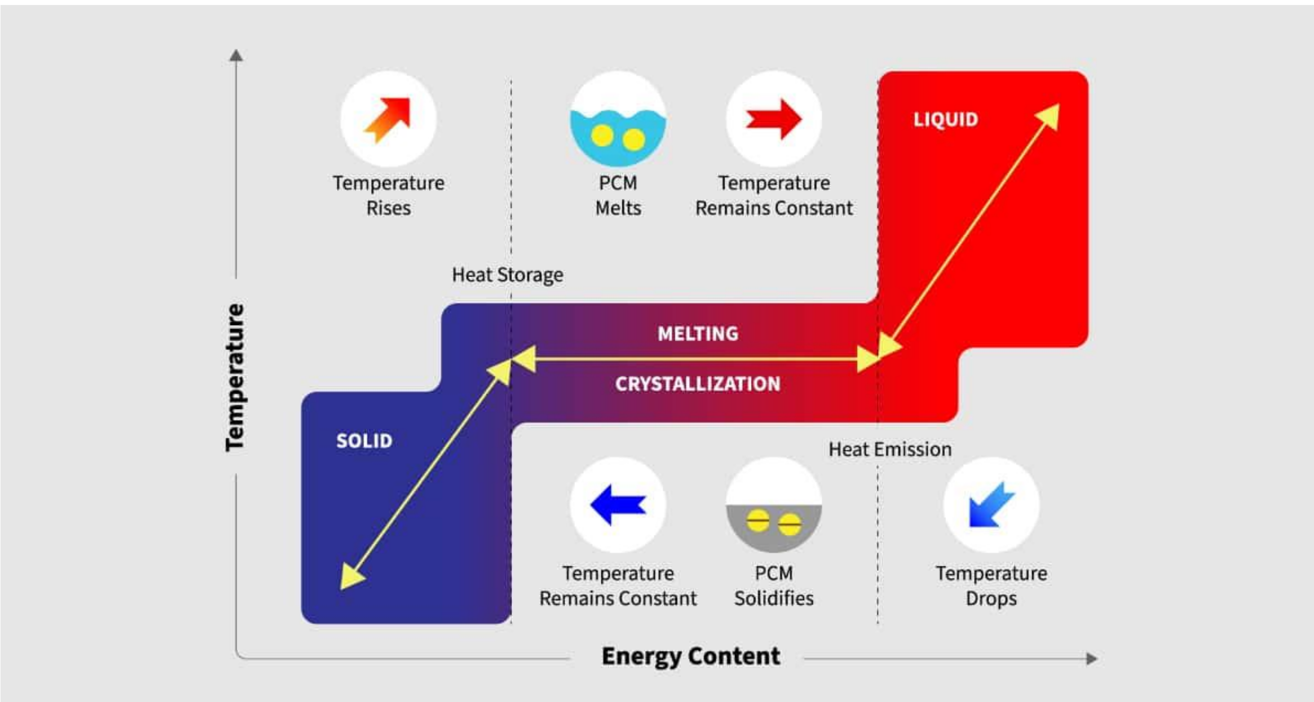


Fig (5): It shows a simple mechanism of working of PCMs when introduced in walls.

HYPOTHESIS DEVELOPMENT

***Hypothesis 1**: A composite wall (which has air gaps present) reduced heat flux through it as compared to the regular wall (without air gaps).*

***Hypothesis 2**: A composite wall will help in retaining heat in the transient state i.e., the time taken to reduce the temperature by the same amount is more for the composite wall as compared to the regular walls.*

HEAT TRANSFER MODES

1. **CONDUCTION (Heat Transfer through walls)** - For problem we have used concrete as we intend to limit heat loss. **Conduction through air has been neglected as the value of thermal conductivity of air is significantly small compared to the materials used in our problem**. Although **conduction occurs through all four walls of the room along with the ceilings and the floor**, however for purposes of ease of modelling, we have considered conduction only through the four composite walls of the room.

2. **CONVECTION (Heat Transfer inside room)** - In our problem, **convection is the mode of heat transfer in the air gaps of the honeycomb** cavity (for the steady state problem in first part) **and inside the room** between the two walls (for the transient state problem in second part).

3. **RADIATION (Heat Transfer through roof)** - To be warmed by a radiant heat source, the surface needs to be in the line of sight of the heat source. Radiative heat transfer usually takes place through the roof of the house as it is in line of sight of the Sun. However, in our problem we have **neglected the effects of radiation for simplicity of modelling and negligible contribution to heat loss as compared to other modes.**

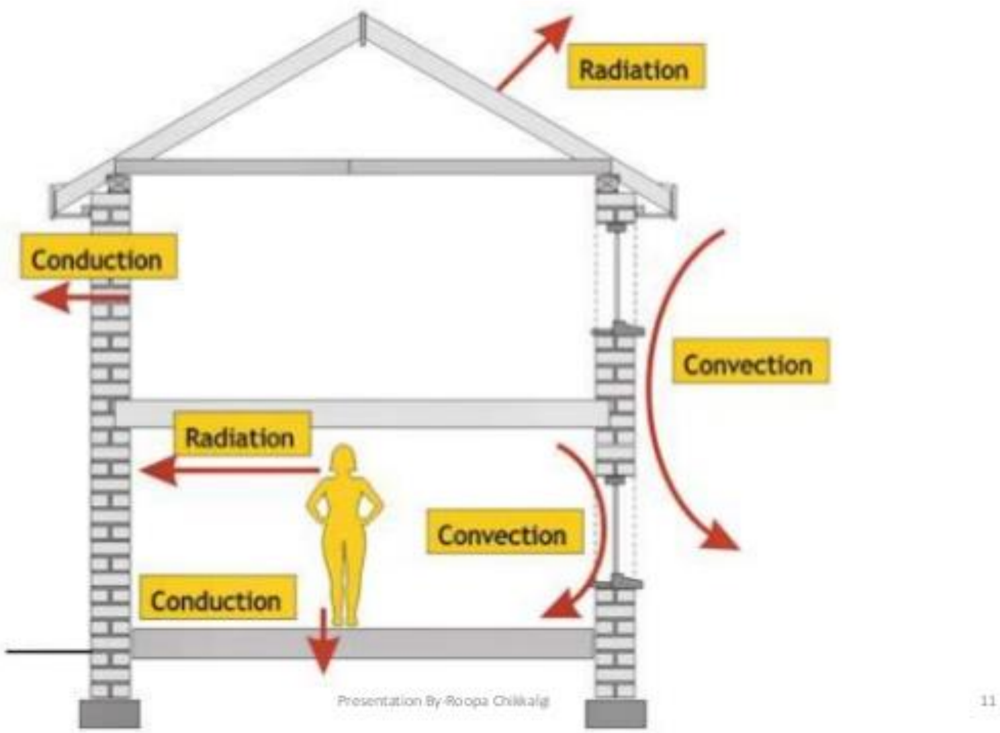


Fig (6): It shows the modes of heat transfer involved in buildings - Conduction through walls, convection inside room and radiation through the roof (major)

ESTIMATION OF HEAT TRANSFER MODES

```
%radiation for composite wall between surrounding and outer surface
T_s_outer = 282.2704; %outer surface temperature
Tinf = 278.1500; %inner surface temperature
line_of_sight = 0.017452; %angle cos(89)
emm = 0.85; %emmisivity of concrete
sigma = 5.670373e-8;
A = 5.5076;

Qradiation = sigma*emm*line_of_sight*A*(T_s_outer^(4)-Tinf^(4)) %radiation
```

```
Qradiation = 1.6800
```

```
qradiation = Qradiation/A %radiation flux
```

```
qradiation = 0.3050
```

In the above calculations. We have shown that the value of radiation comes out to be negligibly less, owing to the line-of-sight factor involved in the equation. Hence, we have neglected radiation in all our subsequent calculations.

CONDUCTION – The values of heat loss due to conduction have been neglected as it is significantly small compared to heat transfer through convection, owing to the small value of thermal conductivity of air.

CONVECTION – The values of heat transfer by convection have been calculated and shown in detail in the Steady – State Analysis and Transient – State Analysis parts, in the following pages.

CONTROL VOLUME DESIGN

CASE 1: STEADY STATE ANALYSIS

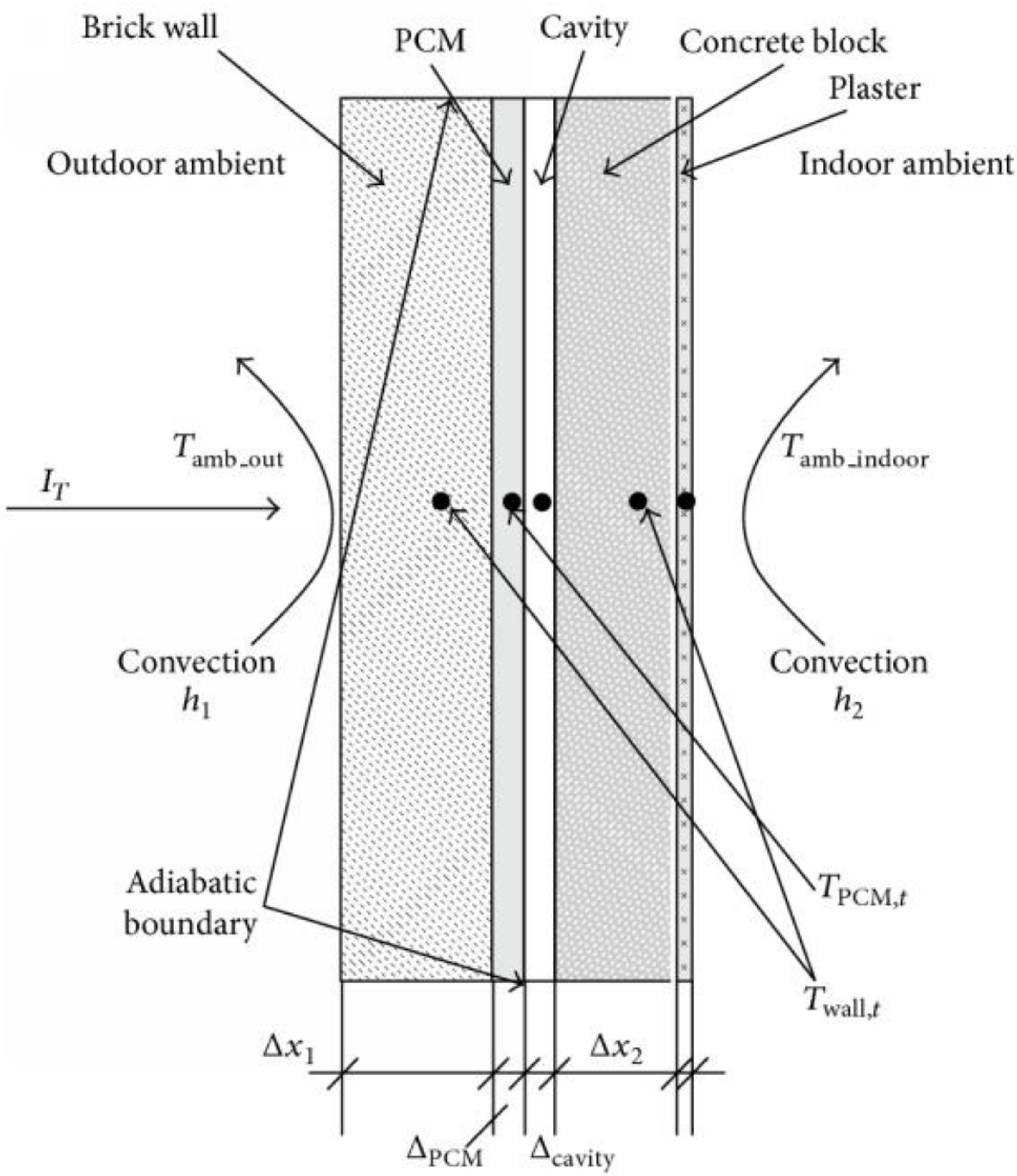


Fig (7): This schematic diagram illustrates the control volume for the steady state heat transfer problem

REASON FOR CHOICE OF CV

While a rigid wall with no air cavities would provide complete structural rigidity, it does not solve our issue of heat transfer. A wall with air cavities of desired thickness would provide effective insulation but would compromise with the structural rigidity. Therefore, the design is such that it strikes an optimal tradeoff between the two. The **choice of a honeycomb structure was the best** as it has shown to have **maximum structural rigidity** despite having air gaps, and thereby serving our purpose for the room walls' design.

3D – MODELLING OF CV IN SOLIDWORKS

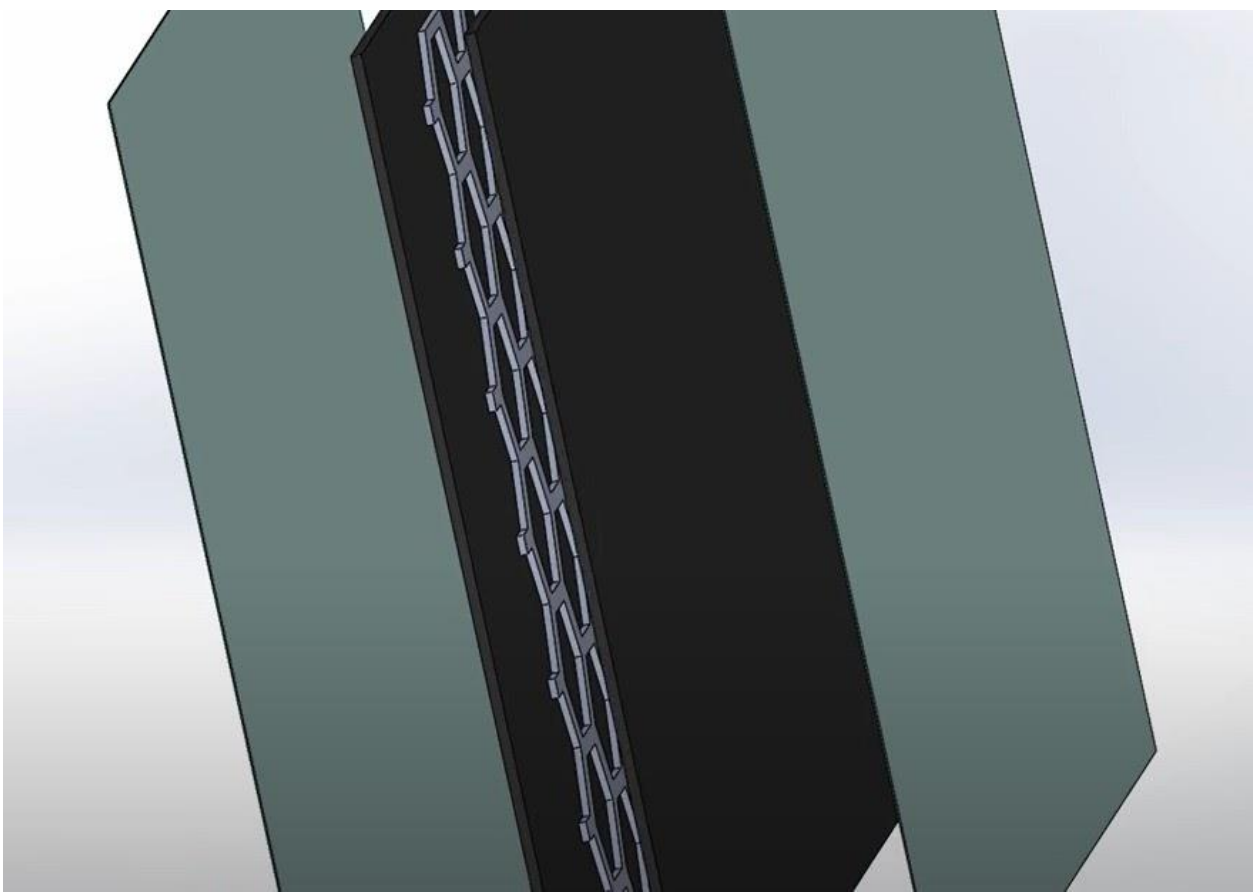


Fig (8): This figure shows the extruded view of all the parts of the composite wall

CONTROL VOLUME DESIGN

CASE 2: TRANSIENT STATE ANALYSIS

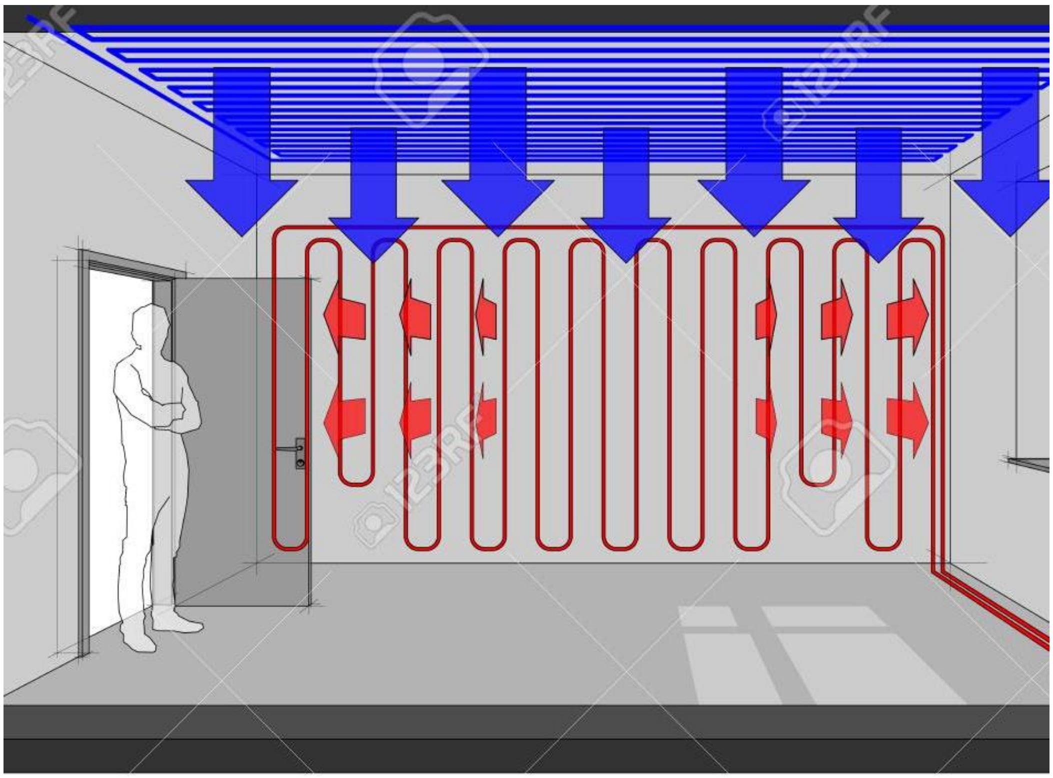


Fig (9): This figure qualitatively illustrates the CV diagram – the whole room enclosed by composite walls on two sides for modelling ease

The control volume for the transient state analysis is a **simplified model of a room enclosed by two walls**. This has been considered for ease of calculation but can be extrapolated to all four walls of the room. We have assumed it to be at the same temperature **T_i = 303.15 K at time t = 0** and then suddenly exposed to the air or surrounding which is at **Tinf = 278.15 K.** This assumption was taken to model the problem statement.

https://drive.google.com/file/d/1iHjvOXaORxymVrKzVxhbVGpHbL7Md_uh/view?usp=sharing -- Link to the CV Diagram

SIMPLIFYING ASSUMPTIONS (FOR BOTH CASES)

- Any heat transfer through the room floor has not been considered for ease of calculation
- The climatic conditions and surrounding temperature are assumed constant at any instant.
- The edge effects of walls have been neglected in all the calculations for simplification
- The room temperature is assumed constant in calculating the resistance of the wall
- The contact resistance, conduction losses through air gaps (k = 0.025) and radiation heat losses have been neglected as they are significantly less in comparison to convection through air

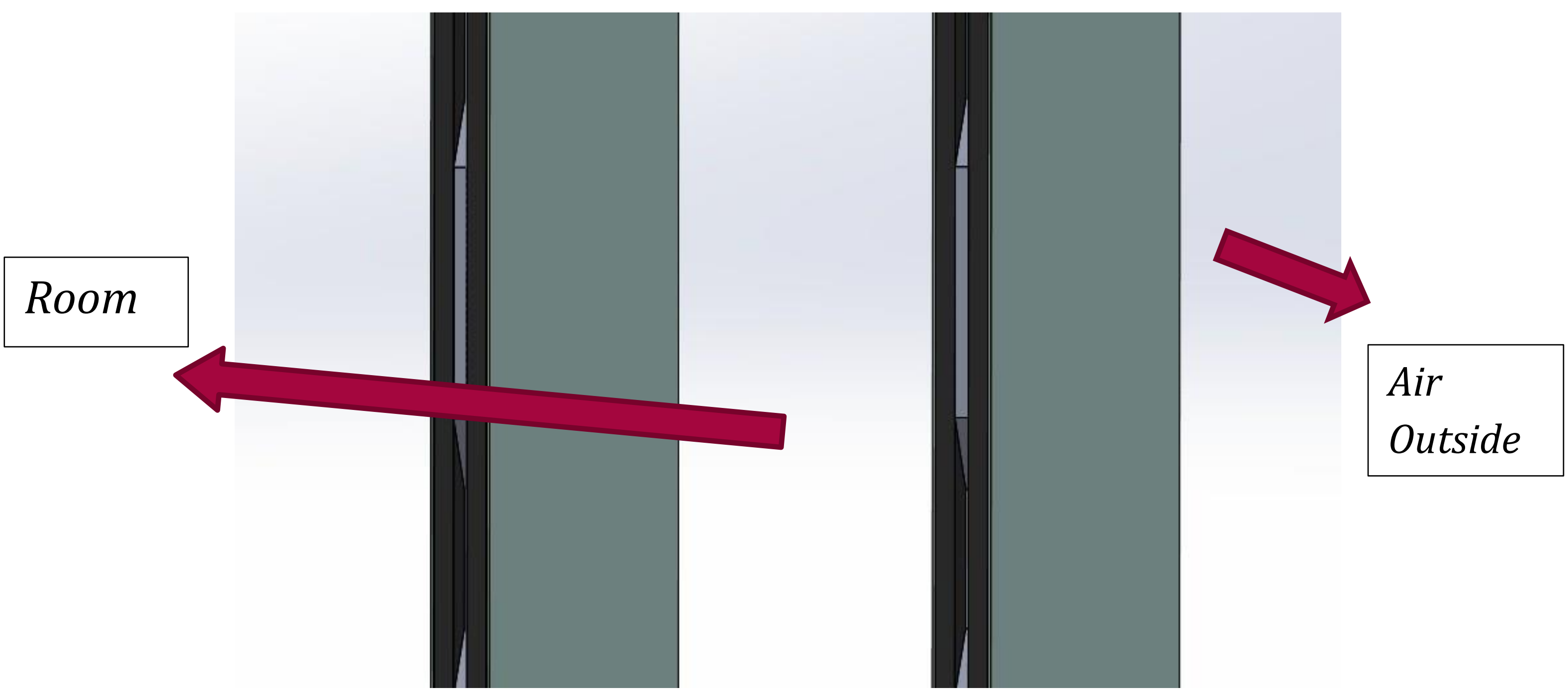


Fig (10): This figure shows the extruded view of all the two composite walls and the empty space denotes the room in between

QUALITATIVE TEMPERATURE PROFILE OF A COMPOSITE WALL WITH AIR GAPS

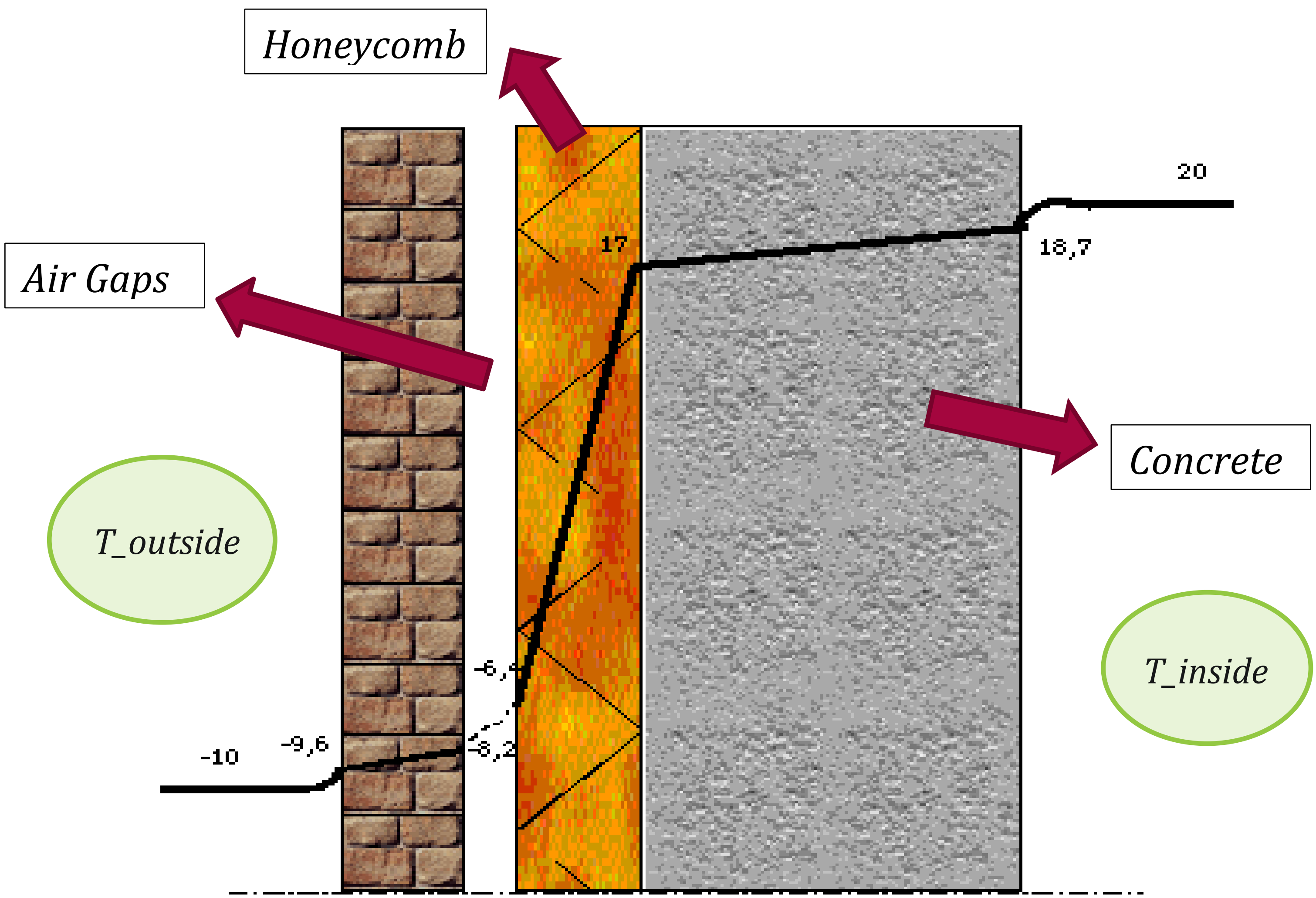


Fig (11); This figure illustrates a qualitative temperature profile across a composite wall with air gaps

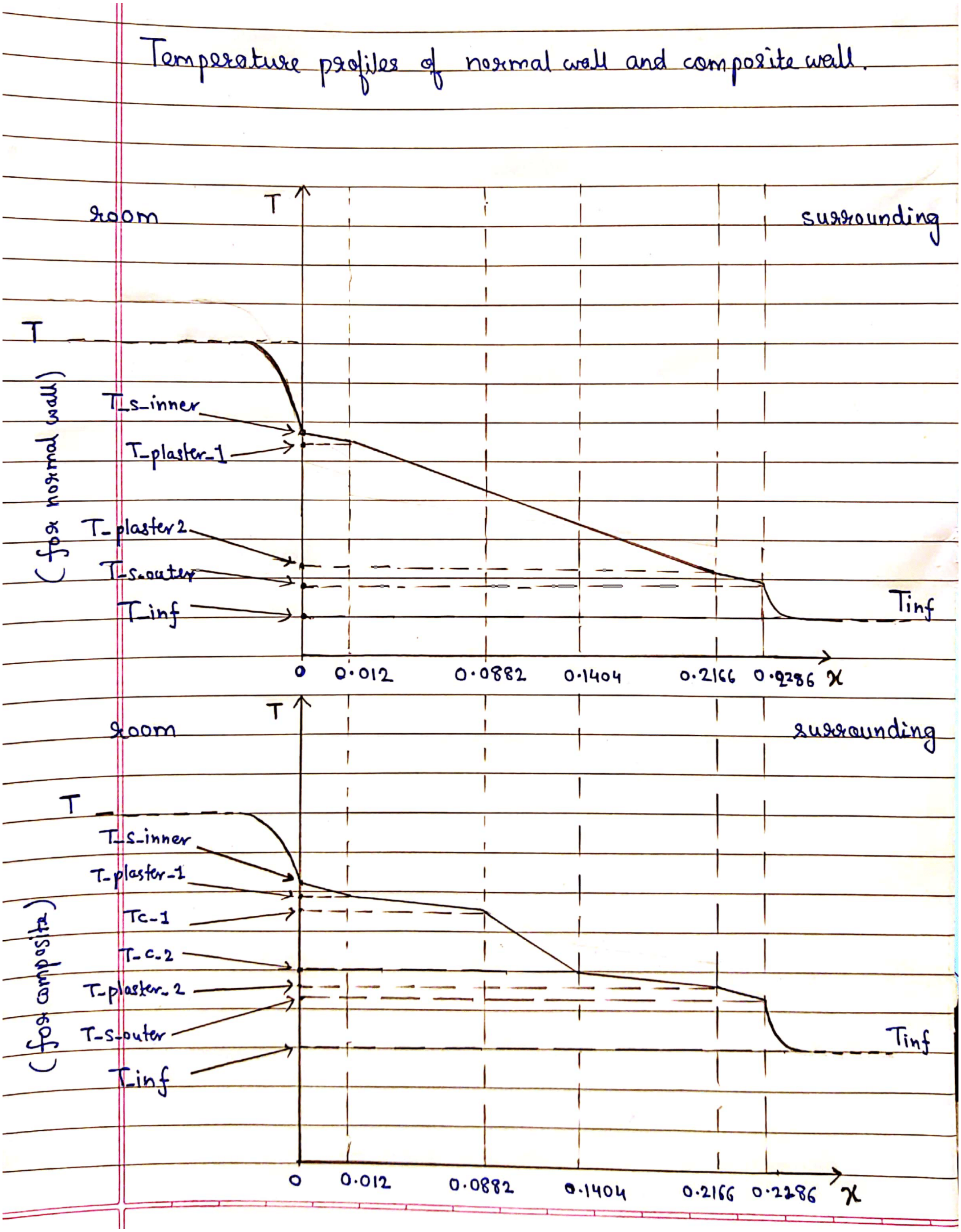


Fig (12): This figure shows the temperature profiles across normal wall and composite wall for steady – state analysis

MATHEMATICAL EQUATIONS

CASE 1: STEADY – STATE ANALYSIS

Part 1: Resistance Calculation

To find:

1. Total resistance of composite wall along with cavity

2. Total heat flux through the composite wall with cavity

$$A_{total} = 7*(A_{concrete} + A_{cavity})$$

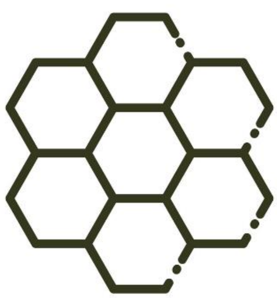


Fig (13): This is one repeating unit of the honeycomb wall

$$R_{composite} = 1/\ (7*k_{conc}*A_{concrete}/l_{Composite} + 7*h*A\_{cavity})$$

$$R_{new} = 2/(h*A) + 2*l_{Plaster}/(k_{Plaster}*A) + 2*l_{Brick}/(k_{Brick}*A) + R_{composite}$$

$$Q = \Delta T/R$$

$$q'' = Q/A$$

Calculation document (MATLAB file) -

https://drive.google.com/file/d/1AIAREtAHplRr4hjQmaOCncvtfNlP6q7C/view?usp=sharing

Nomenclature

- A_{total} = *Area of one repeating unit*
- $A_{concrete}$ = *Area of concrete wall*
- A_{cavity} = *Area of one hexagonal cavity*
- $R_{composite}$ = *resistance of composite wall*
- R = *total resistance of wall*
- k_{conc}, $k_{Plaster}$, k_{Brick} = *thermal conductivity of concrete, plaster and brick*
- h = *convective heat transfer coefficient of air*
- $l_{Composite}$ = *length of composite wall*
- q'' = *heat flux through the wall*
- ΔT = *temp. difference between inside (room) and outside*
- R_{new} = *resistance of cavity, composite wall and normal wall (in series)*

INFERENCE - Here, we infer that the **composite wall is better suited to reducing heat loss than a regular wall** thus solving the heat transfer problem and maintaining optimal room conditions. Our hypothesis is hence proved. Hence our first hypothesis turns out to be valid

MATHEMATICAL EQUATIONS

CASE 2: TRANSIENT – STATE ANALYSIS

To find:

1. Temperature drop in room for a 3°C drop in x* = 0 (centre of room)

2. Total convective heat flux from room in given time t

Equations Involved:

$$\Theta = \theta_o^* \cos(\mathcal{E}x^*)$$

$$\text{Where } \theta_o = C_1 * \exp(-\mathcal{E}^2 Fo) = (T_o - T_\infty) / (T_i - T_\infty)$$

Nu correlation, Prandtl numbers and Biot numbers used:

$$Pr = 0.71657$$

$$Re = (u * L)/\mu$$

$$Nu = 0.664 * (Re^{0.5}) * (Pr^{(1/3)})$$

$$h_c = (Nu * k_{air})/L$$

$$Bi = (h * L)/ k_{total}$$

$$Bi * Fo = (h * A_s * t)/ (rho * V * C)$$

Nomenclature

- *Pr = Prandtl Number*
- *Re = Reynolds' Number*
- *Nu = Nusselt Number*
- *Fo = Fourier Number*

- h_c = *Convective heat transfer coefficient*
- T_∞, T_o = *Temperature at far away from and at center of room resp.*
- C_1 *and* $\mathcal{E}$ *are coefficients used in the one-term approximation to the series solution for transient one – dimensional conduction*
- u = *velocity of air*
- k_{air} = *thermal conductivity of air*
- Bi = *Biot number*
- V = *total volume of room*
- A_s = *total surface area of room*

Justification for use of Nu correlation: The aforesaid Nu correlation has been used in our problem during numerical analysis as the flow of air in the room has been considered to be laminar.
Numerical Part for Calculation of time taken (MATLAB FILE) -
https://drive.google.com/file/d/1RAa5OgC7vEN7kU6ilsKL-UpRNtVNkp0U/view?usp=sharing

Numerical Part for Heat Flux Calculation (MATLAB FILE) -
https://drive.google.com/file/d/1tUwaZfskpK0kIYforC5qjpYjjwsS9kkJ/view?usp=sharing

INFERENCE - From the mathematical analysis we can comfortably conclude that by comparative study, **time taken for the same drop of temperature is more for the composite wall as compared to the regular wall**. For a drop of 18.3685 K of temperature of the surrounding wall only a 3 K drop is seen at the centre of the room (significantly less compared to outer walls), thus proving that room conditions remain relatively stable over the time. Our hypothesis is hence proved.

PHASE CHANGE MATERIALS IN WALLS

WHAT ARE PHASE CHANGE MATERIALS?

Phase change materials also referred to as latent heat storage materials (LHSMs), are materials that **can absorb or liberate energy** in terms of heat at certain temperatures. As the material absorbs or liberates heat, there is a **change in the physical state** of the material from either solid to liquid or vice versa.

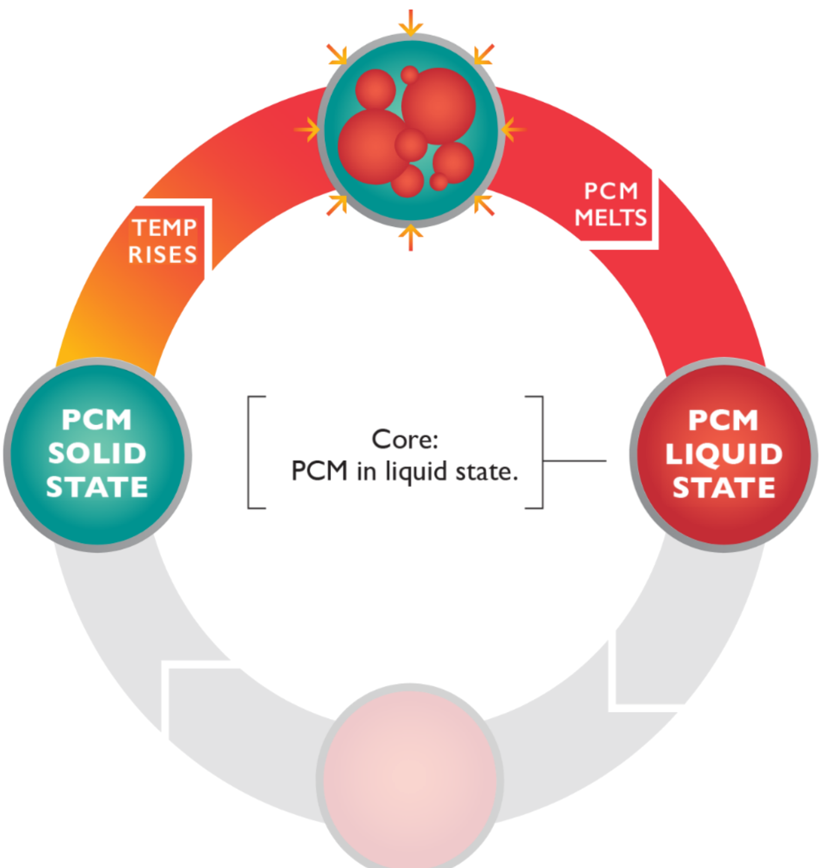


Fig (14): This figure shows how PCM allows absorption and release of heat by change of state

HOW DO PHASE CHANGE MATERIALS WORK?

When PCMs are exposed to a heat source, there is a physical change in the PCM from solid to liquid as a result of chemical bonds within the PCMs breaking. This breaking of bonds leads to absorption of heat. When the temperature of the source is below the phase change temperature of the PCM, the molten PCM begins to change in state. As the PCM solidifies, there is a release of heat energy into the environment. The heat stored and released during the phase change process is referred to as latent heat.

HOW TO INCORPORATE PCM INTO CONCRETE?

Direct: PCM granules or powder can be encapsulated and **directly mixed** with the concrete components. Encapsulation is important because it **prevents the PCM from the harsh alkali nature of concrete**. PCM encapsulated in small capsules are effective because they provide **cheaper way** to incorporate PCM into construction materials and allows effective heat transfer because of its small size.

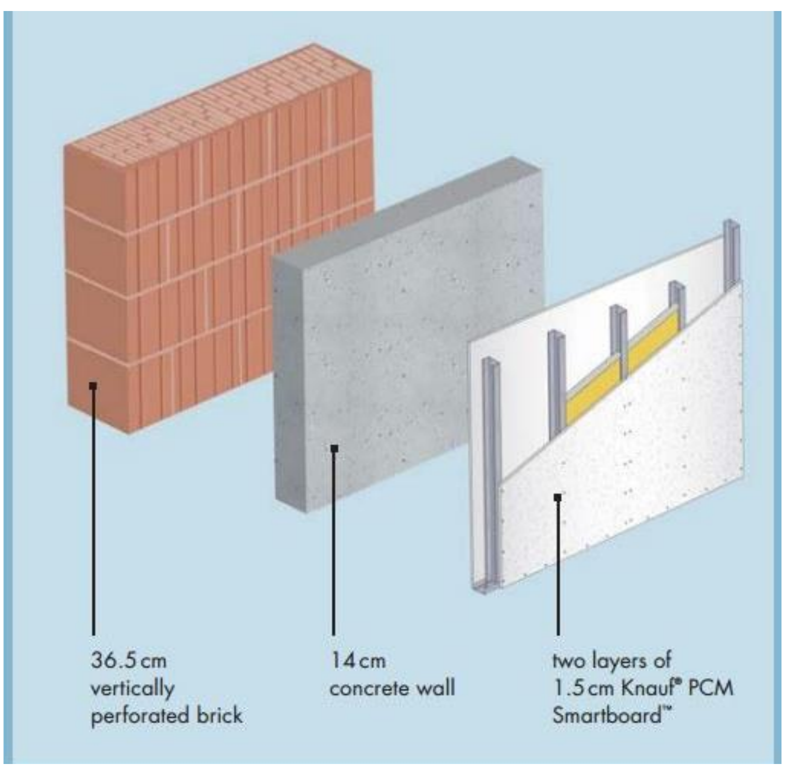


Fig (15): This figure shows how Phase Change Materials are incorporated in concrete walls

WHY INCORPORATION IN CONCRETE AND NOT A STANDALONE MATERIAL?

1. **Thermal conductivity**: Concrete has **high thermal conductivity** compared to all the other building components. Therefore, it will allow more absorption and release of heat energy compared to other components.

2. **Density**: Concrete's **high density** makes it a sensible heat storage.

3. **Thermal Mass**: Thermal mass is a characteristic of materials which permits the building material to absorb, store and release energy later. Concrete's **high thermal mass** provides it a high-energy saving advantage compared to other building materials. Incorporation of PCM into concrete would help in increasing its thermal mass and consequently shift the demand for energy during the off-peak period.

HOW DOES PCM SOLVE THE HEAT TRANSFER PROBLEM?

WHAT ARE ITS BENEFITS?

When the surrounding temperature is **higher** than the room temperature and the PCM is in solid state, some of the **heat entering is absorbed** by the PCM thus reducing the amount of heat entering inside the room. PCM absorbs heat until its completely converted into molten state. Then it starts conducting the heat to the room until the steady state is reached.

Now when the surroundings have **lower** temperature (mostly at night) and the PCM is in molten state (since absorbed heat at daytime), it **releases heat energy** by converting itself into solid. This leads to the flow of heat coming from PCM into the room. This approach was explored as if implemented, it can **significantly cut down electricity costs**. There is only a **one-time investment** in purchasing the Phase Change Materials during construction.

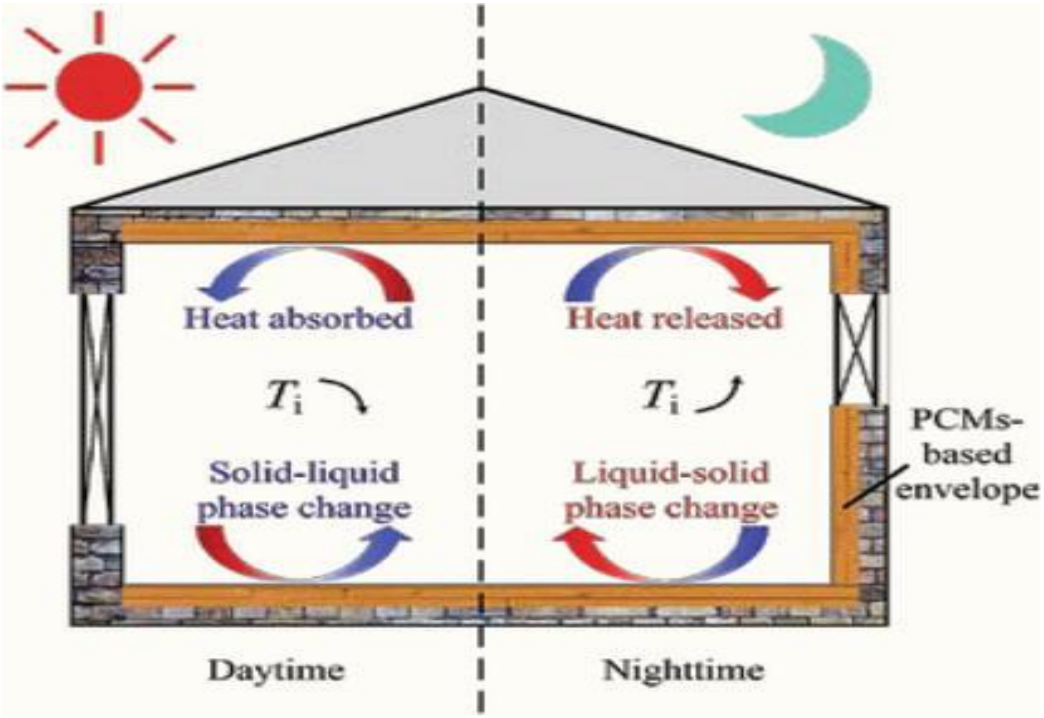


Fig (16): This figure shows how PCM absorbs and releases heat at different times of the day.

ACKNOWLEDGEMENTS

We would like to thank Professor P. Sunthar and Professor V. Gundabala for giving us this incredible opportunity to work on this project as a part of the course CL - 246 and for their constant support and guidance throughout the course. We would also like to extend our gratitude to the Teaching Assistants and the faculty for providing us with their time and esteemed guidance for our project.

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