Thermal Performance of Common Building Insulation Materials – Operating Temperature and Moisture Effect

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***Abstract*—To achieve an accurate cooling/heating load calculation, and consequently precise sizing of the heating, ventilating, and air-conditioning (HVAC) equipment, requires an accurate prediction of the heat transfer through the envelope components of the building. This also depends on the accuracy of the thermal conductivity of the building insulation material. The proper use of thermal insulation in buildings (k-value) contribute significantly to reducing the HVAC size and consequently the annual energy cost. The objective of this paper is to present an overview of the basic principles of thermal insulation, and present the effect of the operating temperature and the moisture content on the thermal conductivity changes of polystyrene insulation material which is widely used for building insulation in Oman. Best-fit linear relationship of the k-value in term of the operating temperatures and different percentage of moisture content by weight has been established. Indeed, the k-value of the sample increases with the increase of the moisture content and the increase of the operating temperature.

***Keywords*—Building insulation material, moisture content, operating temperature, thermal conductivity.

I. INTRODUCTION

Insulation products have developed significantly with technological advances. Legislation has acted as the catalyst for development, from the basic requirements under the Building Regulation Part L, in compliance with government carbon reduction targets, driven through advanced programs such as the Code for Sustainable Homes and BREEAM [1].

Insulation products vary in terms of color, surface finish and texture, core composition and, importantly, performance. The specification of materials that insulate is a science-based decision, but a successful specification relies on the specifier understanding not only the mathematical performance, but the peripheral factors that can influence the final installation.

Specification of insulation products is often based upon the minimum requirement of the Building Regulations AD (Approved Document) Part L and their relationship with manufacturer's performance data. In order to specify insulation correctly, however, the specifier needs to understand the reasons why it works, and apply the correct technology to any given construction detail. In understanding more fully the processes that make insulation work, and indeed the factors that stop it from working, specifiers will be in a far stronger position to specify the correct material for the correct application.

The installed performance of an insulation product is reliant upon not only performance characteristics and the adherence of contractors to manufacturers and general best practice workmanship requirements, but also the suitability of the insulant specified to its installed location.

In the middle east region buildings account for a major share of electric energy consumption. In the urban region more than 70% of electric energy is consumed by buildings [2] and the majority of this energy is used by the air-conditioning and ventilation systems [3]. A big portion of this energy is directly related to the heat transfer by conduction through the building envelope, which can be reduced by using effective thermal insulation material.

Due to the absence of regulations and standards, few buildings in Oman are insulated; consequently, they consume more energy than is necessary for their operation [4].

Thermal insulation is a material, or a combination of fibrous materials, that can be in the form of film or sheet, block or monolithic, open cell or closed cell, and can be chemically or mechanically bound or supported to retard the rate of heat flow by conduction [5].

Thermal insulation materials like other natural or man-made materials exhibit temperature dependence properties that vary with the nature of the material and the influencing temperature range. For most materials, the thermal conductivity increases with the increase of the influencing temperature. Therefore, temperature-dependent thermal conductivity is an empirical relationship based on experimental measurements [6]. For a given aged material sample, the average conductivity mainly depends on the density (ρ), temperature (T) and water content (w) [7].

In addition to the operating temperature that has been studied by the author and reported in several researches [4], [7], [8] and [9]; the moisture content within the material is another major parameter affecting the thermal conductivity of insulation materials [10]. In extant studies, investigations of the performance of polyurethane insulation [11], fiberglass [12] and mineral wool [13] used for heating and cooling pipes subjected to underground water influences have been

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conducted. For example, the effective thermal conductivity of the wet fiberglass insulation was found to be many times higher than that of the dry insulation. Similarly, Budaiwi and Abdou investigated the impact of thermal conductivity change of moist fibrous insulation on the energy performance of buildings under hot-humid conditions. Their results revealed that the moisture behavior of the insulation layer is tangibly influenced by the moisture characteristics of other wall components [14]. The author presented also some results related to the effect of moisture content on the thermal conductivity of polystyrene insulation [8].

Consequently, both operating temperature and moisture content have a significant influence on the thermal performance of insulation materials. Based on the results presented in this paper, it is clear that accurate cooling load calculation depends on the accuracy of the thermal conductivity of the insulation materials comprising the building envelope.

The objective of this paper is: (1) to present an overview of the basic principles of thermal insulation, (2) and present the effect of the operating temperature and the moisture content on the thermal conductivity changes of polystyrene insulation material which is widely used for building insulation in Oman.

II. HOW INSULATION WORKS

Insulation products are designed to frustrate the transfer of heat across the material itself. There are three methods of heat transfer: radiation, conduction and convection [1].

- Radiation

Any object whose temperature is higher than the surfaces that surround it will lose energy as a net radiant exchange. Radiant heat can only travel in straight lines. Introduce a solid object between points A and B, and they will no longer direct exchange radiant heat. Radiation is the only heat transfer mechanism that crosses vacuum.

- Conduction

Conduction is reliant upon physical contact. If there is no contact, conduction cannot take place. Contact between two substances of different temperature results in a heat exchange from the higher temperature to the lower temperature substance. The greater the temperature differential, the faster the heat exchange.

- Convection

Convection is the transfer of energy via fluids (gases and liquids). It is this method that plays the greatest role in the liberation and the transfer of heat in buildings. The most common propagation of this effect is from solid to gas, i.e. object to air, and then back again, typically as the air meets with the external building fabric.

A. What is Thermal Conductivity

Thermal conductivity (k) refers to the amount/speed of heat transmitted through a material. Thermal conductivity is the time rate of steady state heat flow (W) through a unit area of 1 m thick homogeneous material in a direction perpendicular to isothermal planes, induced by a unit (1 K) temperature difference across the sample [15].

Materials of high thermal conductivity are widely used in heat sink applications and materials of low thermal conductivity are used as thermal insulation. Thermal conductivity of materials is temperature and moisture content function.

B. What is Thermal Resistance

Thermal resistance (*R-value*) is a heat property and a measurement of a temperature difference by which an object or material resists a heat flow. It is a function of material thermal conductivity, thickness and density. *R-value*, is expressed in m^2-K/W (h-ft^2-F/Btu).

C. What is Thermal Conductance

Thermal resistance (*R*) and thermal conductance (*C*) of the materials are reciprocals of one another and can be derived from thermal conductivity (k) and the thickness of the materials. It is similar to thermal conductivity except it refers to a particular thickness of material. *C-value*, is expressed in W/m^2-K (Btu/h-ft^2-F).

D. What is Thermal Transmittance

Known as *U-value*, is the rate of transfer of heat (W) through a unit surface of a structure divided by the difference in temperature across the structure (K). Well-insulated parts of a building have a low thermal transmittance whereas poorly insulated parts of a building have a high thermal transmittance. It is often called the *Overall Heat Transfer Coefficient, U-value*, and expressed in W/m^2-K (Btu/h-ft^2-F).

E. Insulation of buildings is a key measure for energy saving.

The heat delivered to the building by means of the heating system escapes through the external structures (walls, floors, windows, doors) into the outside environment with a lower temperature. To avoid temperature drops within the building the heat must be permanently supplemented (case of heating). Heat losses can be reduced by the insulation of the external structures, which can save you a part of the heating costs. Energy savings are evident mostly in buildings with worse thermal and technical properties. It also applies vice versa – the better the original thermal and technical properties of the building, the lower is the efficiency of an additional insulation with the same thickness.

How much can you save?

Up to 50 % energy savings can be achieved by thermal insulation of buildings constructed on the basis of requirements valid by 1983. If you decide for thermal insulation focus on building structures which allow the highest heat losses. This applies mainly to the thermal insulation of the external cladding, exchange of windows or insulation of non-heated rooms. At the same time right regulation of the heating system is important [16].

F. Advantages of Thermal Insulation

- Reduction of energy consumption for heating/cooling (by 30 % at least).
- Creation of a thermal comfort by increasing the surface temperature of the inside walls, leaking elimination.
- Reduction of thermal stress of the framework.
- Building lifetime prolongation.
- Improvement of the architectural look of the building.

- Reduction noise levels and therefore enhance the acoustical comfort of insulated buildings.
- Proper design of thermal insulation helps in preventing vapor condensation on building surfaces.
- Appropriate selection of the insulation and if properly installed, it can help in retarding heat and preventing flame propagation into building in case of fire.

G. Types of Thermal Insulation

Many types of building thermal insulation are available which fall under the following basic materials and composites [17]:

- *Inorganic Materials*
  - Fibrous materials such as glass, rock, and slag wool.
  - Cellular materials such as calcium silicate, bonded perlite, vermiculate, and ceramic products
- *Organic Materials*
  - Fibrous materials such as cellulose, cotton, wood, pulp, cane, or synthetic fibers.
  - Cellular materials such as cork, foamed rubber, polystyrene, polyethylene, polyurethane, polyisocyanuarate and other polymers.
- *Metallic or metalized reflective membranes*. These must face an air-filled, or evacuated space to be effective.

H. Reflective Insulation [18]

Reflective insulation products consist of one or two layers of industrialized polyethylene bubble film laminated between one or two layers of highly reflective metalized aluminum film to provide extreme resistance to heat transfer. The bubble layers are designed to provide increased strength and puncture resistance, to aide in the reduction of condensation when used in metal buildings, pole barns, and agricultural facilities, and to resist conductive heat transfer through the insulation.

Used in conjunction with an airspace, some *reflective insulations* will block 96% of radiant heat as opposed to mass insulations like fiberglass, cellulose and foam which merely absorb and slow down the transfer of conductive heat.

Reflective bubble insulation is ideal for crawl spaces**,** radiant floor heating**,** and basic floor heat retention applications as well as for insulating pole barns, post frame, and metal and steel buildings.

White reflective bubble insulation is designed for applications where non-cured concrete will come in contact with the insulation (heated floor slab installations) or metal building installations where an aesthetic indoor look is desired. Always place white side towards any non-cured cement mixtures. Foil side will corrode if it comes in contact with non-cured cement.

I. Reflective Insulation Applications

- Commercial and residential buildings
- Metal buildings and pole barns
- Insulation for food and drug shipping
- Automotive/transportation
- Airplane Hangers

J. When and where to use reflective insulation?

In order to retard heat flow by conduction, walls and roofs are built with internal air spaces. Conduction and convection through these air spaces combined represent only 20% to 35% of the heat which pass through them. In both winter and summer 65% to 80% of the heat that passes from a warm wall to a colder wall or through a ventilated attic does so by radiation.

The value of air spaces as thermal insulation must include the character of the enclosing surfaces. The surfaces greatly affect the amount of energy transferred by radiation, depending on the material's absorptivity and emissivity, and are the only way of modifying the total heat transferred across a given space. The importance of radiation cannot be overlooked in problems involving ordinary room temperatures [19].

The best application of a radiant barrier is in hot climates just under the roof to reduce radiant heat from the sun. It is also beneficial in walls receiving direct sun radiation, such as west walls. Reflective insulation is not economic in cold climates and surfaces that are heavily shaded and/or well insulated. The optimum air space thickness should be used (~ 20 mm) [20].

III. THERMAL MASS

Thermal mass is most commonly used for passive heating, though it can also be used to absorb and dissipate heat for passive cooling. Thermal mass can be achieved by an exposed concrete floor; or a wall made of heavy material such as concrete, concrete masonry, stone or earth; or a specifically designed thermal mass feature such as a Trombe wall.

Whatever thermal mass is used, it must be exposed to direct sunlight during the times of year when passive heating is required. It must not be covered with any insulating material (including mats and carpets) – otherwise it will not be able to absorb heat. But it must be insulated on the building’s exterior, and the building envelope must be properly insulated so that any heat gain from thermal mass does not dissipate.

For good performance, thermal mass must be considered in conjunction with other passive design features such as insulation, location, orientation and layout, window sizing, and shading.

For example, if thermal mass is being used for passive heating, it should receive maximum exposure to sunlight during cooler months, but minimal exposure to sunlight during summer. This can be achieved through a combination of orientation (to maximize exposure to north sun), shading (to minimize summer exposure), floor plan (for example, a shallower north-south floor plan will allow more sun exposure for a concrete floor slab), and window sizing and placement [21].

A. Wall Requirements to Provide Thermal Mass for Heating

While floors are more commonly used to provide thermal mass (because they usually receive more sun and are therefore more effective), in the right situations walls can also be used. Walls to provide thermal mass should be concrete, concrete masonry, stone or earth. They should:

- Be exposed to direct sunlight if possible
- Be of a mid to dark mat color
- Be 100–150 mm thick to provide sufficient mass for optimal heat storage

- Be insulated underneath the slab (to give an *R-value* of at least 1.9) so that heat moves up into the interior space rather than into the ground
- Have slab edge insulation to reduce heat loss from the slab perimeter to the outside air.

Dense or heavy materials such as brick veneer or single-skin concrete masonry located outside the insulation do not add thermal mass to a building as the insulation prevents any heat being released into the interior of the wall. A polystyrene block wall will not provide thermal benefits unless the polystyrene on the inside face of the wall is removed.

An internal wall will transmit stored heat through the wall to the room on the other side of the wall. The wall should be a dark color to maximize heat absorption.

B. *Using Thermal Mass for Passive Cooling*

Thermal mass can also be used as a heat sink for summer cooling. By absorbing heat from the surroundings when the temperature is higher than the thermal mass material, the ambient indoor temperature will be reduced. The heat must then be discharged to outdoors during the night-time – otherwise it will need to be released into the house later. For cooling, the thermal mass must be shielded from solar gain by:

- Shading
- Walls being located between internal rooms or on the south side of the house
- Being located where cooling breezes will remove heat.

C. *Floor Requirements to Provide Thermal Mass for Cooling*

The underside of a floor slab to be used as a thermal mass for cooling should not be insulated as the ground temperature (which tends to remain fairly constant throughout the year) is generally lower than the day-time summer air temperature. This allows the heat to be transmitted into the ground. However, the floor should be insulated at the perimeter to prevent heat entering the slab between the slab edge and the ground.

D.. *Wall Requirements to Provide Thermal Mass for Cooling*

Thermal mass walls to be used for cooling are generally concrete or stone, but an external water storage tank that is protected from solar gain can also be used to absorb heat. Heat from the interior space must be able to move into the water where it can be dissipated or removed by cooling breezes.

E. *Adding Thermal Mass to an Existing Home*

Thermal mass may be added to an existing house as part of alteration work by:

- Laying a concrete floor in a new extension
- Adding an internal thermal mass wall (e.g. hallway) that has exposure to direct sunlight (increase window areas where necessary)
- Removing existing insulating floor coverings such as carpet from existing concrete floors that are adjacent to large areas of north-facing glazing and replacing with tiles or polishing the exposed slab surface
- Adding a sunspace with high thermal mass and automated controls to manage the stored heat.

IV. MOISTURE CONTROL

Moisture control is fundamental to the proper functioning of any building. Controlling moisture is important to protect occupants from adverse health effects and to protect the building, its mechanical systems and its contents from physical or chemical damage. Yet, moisture problems are so common in buildings, many people consider them inevitable. [22].

Moisture causes problems for building owners, maintenance personnel and occupants. Many common moisture problems can be traced to poor decisions in design, construction or maintenance. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) notes that, more often than not, the more serious problems are caused by decisions made by members of any of a number of different professions. [23].

However, such problems can be avoided with techniques that are based on a solid understanding of how water behaves in buildings. Moisture control consists of:

- Preventing water intrusion and condensation in areas of a building that must remain dry.
- Limiting the areas of a building that are routinely wet because of their use (e.g., bathrooms, spas, kitchens and janitorial closets) and drying them out when they do get wet.

To be successful, moisture control does not require everything be kept completely dry. Moisture control is adequate as long as vulnerable materials are kept dry enough to avoid problems. That means the building must be designed, constructed and operated so that vulnerable materials do not get wet. It also means that when materials do get wet, the building needs to be managed in such a way that the damp materials dry out quickly.

V. VAPOR RETARDERS

A vapor barrier is any material used for damp proofing, typically a plastic or foil sheet, that resists diffusion of moisture through wall, ceiling and floor assemblies of buildings to prevent interstitial condensation and of packaging. Technically, many of these materials are only vapor retarders as they have varying degrees of permeability. Materials can be classified based on their permeability as follows [24].

- Vapor barriers which are very impermeable to water vapor (≤ 1 perm). These include polyethylene films, aluminum foils, oil-based paints, vinyl wall coverings, sheet metal, foil-faced insulation, glass, rubber membranes.
- Vapor retarders which are semi-vapor permeable to water vapor (1<10 perms) and include plywood, expanded polystyrene, paper and bitumen facing on fiberglass insulation, most latex-based paints.
- Breathable materials which are permeable to water vapor (≥10 perms) such as unpainted gypsum board, un-faced fiberglass insulation, cellulose insulation, cement, and other similar building materials.

A. What's the Difference Between a Vapor Barrier and a Vapor Retarder?

A vapor barrier stops more vapor transmission than a vapor retarder. A vapor barrier is usually defined as a layer with a permeance rating of 0.1 perm or less, while a vapor retarder is usually defined as a layer with permeance greater than 0.1 perm but less than or equal to 1 perm [25].

B. Where to use a vapor retarder?

In the regions with prevailing cold climate, the vapor retarder should be placed towards the inside warm surface of insulation to avoid migration of moisture through the building envelope from warmer and more humid inside air to colder drier outside air.

In regions with prevailing hot and humid conditions, the vapor retarder should generally be placed towards the outside surface of the insulation. In mixed climate, it is better not to use vapor retarder.

VI. THERMAL INSULATION SELECTION

Although the thermal resistance of insulation materials is the most important property when considering the energy conservation issues, many other parameters should be also considered when selecting thermal insulation. The factors that impact the choice of insulation materials can be summarized as follows [26]:

A. Thermal performance

- Thermal resistance
  - High R-value insulation material.
  - Material thickness vs. thermal resistance.
  - Material density vs. thermal resistance.
  - Operating temperature range vs. thermal resistance.
- Thermal bridging
  - Continuity of thermal insulation around walls/roof.
  - No/minimum framing.
- Thermal storage
  - Thermal storage benefits from massive walls (e.g., concrete, adobe).
  - Time lag capabilities.

B. Cost

- Extra cost of insulation.
- Extra cost of quality materials and workmanship.
- Impact on AC equipment size and initial cost.
- Impact on energy/operating cost.

C. Ease of construction

- Impact on workmanship requirements.
- Impact on ease/speed of construction.
- Impact on ease of operation, maintenance and replacement.

D. Building codes requirements

- Fire resistance capabilities.
- Health hazards.
- Structural stability.

E. Durability

- R-value change over time.
- Water and moisture effect.
- Thermal expansion and contraction.
- Strength.
- Chemical and other corroding agents.

F. Acoustical performance

- Sound absorption.
- Sound insulation.

G. Air tightness

- Vapor/infiltration barrier.
- Wall/roof construction quality.
- Sealed penetrations.
- No cracks.

H. Environmental impact

I. Availability

VII. WHAT IS THE OPTIMUM ECONOMIC THICKNESS OF THERMAL INSULATION?

The concept of economic thermal insulation thickness considers the initial cost of the insulation system plus the ongoing value of energy savings over the expected service lifetime of the insulation. The optimum economic thickness is the value that provides the minimum total life-cycle cost, as illustrated in Fig. 1 [27].

The thickness is a function of the following: the building type, function, shape, orientation, construction materials, climatic conditions, insulation material and cost, energy type and cost, and the type and efficiency of air-conditioning system [26], [28], [29], and [30].

As the insulation thickness in a wall increases, the heating and cooling transmission loads for a building decrease. The transmission loads are used as the input data for an economic model to determine the variation in the cost of the insulation plus the present value of energy consumption, considered lost energy, over the lifetime of the building with such insulation.

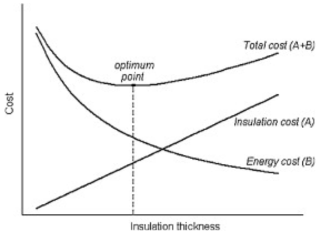

Fig. 1 Optimum insulation thickness

VIII. THERMAL INSULATION APPLICATIONS

A. What is the best location of insulation with respect to thermal mass?

The location of thermal insulation with respect to mass is not critical from thermal resistance point of view. Any building component will have the same overall thermal resistance for the same insulation type and thickness regardless of its placement within the assembly. However, there are other thermal and practical considerations for insulation placement as follows [26]:

- Insulation placement to the inside
    - Protected by mass against outside environment and damage. However, the structure will be closer to the outdoor temperature.
    - Expansion/contraction becomes more important.
    - More ‘thermal bridges’ due to the unavoidable crossings and penetrations. Therefore, all penetrations and joints must be tightly sealed.
    - Minimized potential heating benefits from the mass of the building structure.
- Insulation placement to the outside
    - Support for summer convective cooling and winter passive solar heating.
    - Allows mass to store excess solar and internal gains. However, less durability due to the exposure to outside environmental and damage effects.
- Insulation placement in the middle
    - Provides even distribution of the insulation in the component.
    - Can achieve a trade-off between the benefits of the above two arrangements.

B. What are the practical installation methods for insulating buildings?

Insulation installation depends on the type of structure, the type of insulating material used, and its location in the structure. For walls, the insulation can be placed to the inside, to the outside or in between (sandwich wall). The advantages and disadvantages of each location are as discussed above. For roofs, the insulation can be placed on top of the slab, beneath it or on top of a suspended ceiling. There are different methods of using/fixing the insulating material with the most common methods for concrete structures summarized in [31], [32], and [33].

IX. THE IMPACT OF CHANGES IN THERMAL CONDUCTIVITY OF POLYSTYRENE INSULATION MATERIAL UNDER DIFFERENT OPERATING TEMPERATURES AND MOISTURE CONTENT

A. Measurement of thermal conductivity of samples

Prior to developing the experimental procedure for measuring the thermal conductivity of the samples at different operating temperatures, an experimental apparatus based on the transient plate source was designed (Fig. 2). The apparatus was subsequently calibrated using the known thermal conductivity values at 10 °C of three polystyrene insulation samples characterized by high, ultra-high, and super-high density (HD, UHD, and SHD, respectively) provided by another company [2] and [4].

A known voltage and current were supplied to the heater, and its surface temperature (inner surface of the specimen) was measured. Similarly, the increase in the outer surface temperature was also measured until the steady state was achieved. This allowed calculating the temperature difference required for calculations [2] and [4].

Since thermal conductivity changes with the ambient (surrounding) temperature, all necessary precautions have to be taken to ensure that it will remain as constant as possible throughout testing. For this purpose, a special temperature control chamber was fabricated to maintain and adjust the temperature to the level required for testing. This control chamber was made of wood and was insulated with high-temperature heatproof material to prevent heat loss from the box [2] and [4].

A water reservoir shown in Fig. 3 was used in combination with a chiller and a heater-embedded water circulator pump. In addition, an aluminum radiator was installed on the back plate of the box. As water supply was allowed to circulate through the radiator, the chamber attained water temperature. A fan was mounted on the radiator to allow the temperature to be more efficiently extracted from the water and to be circulated evenly throughout the chamber. By changing the water temperature, the required ambient conditions were achieved, allowing the specimens to be tested for thermal conductivity at different stable conditions [2] and [4].

The chiller was only used for the testing at 10 °C, while the heat pump provided greater stability. The remaining temperature conditions (i.e., 24 °C, 37 °C, and 43 °C) were achieved by using the heater with the pump only. Although the heater temperature control is accurate, a separate thermometer was used for visual inspection of the reservoir's water temperature. To ensure accuracy, the samples were tested three times over an extended period and the average values, along with the reference levels, are shown in Table 1 [2] and [4].

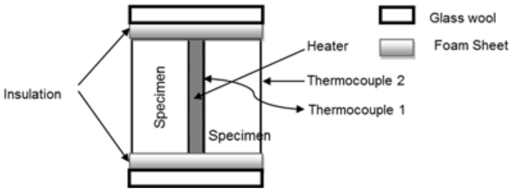

Fig. 2 Guarded hot plate

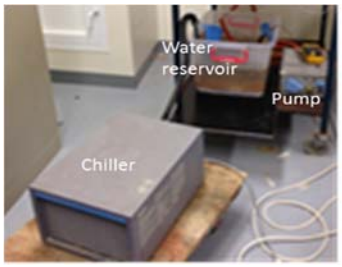

Fig. 3 Experimental setup, comprising of water reservoir, chiller, pump and heater

The average measured thermal conductivities of the three samples and the reference values are within the acceptable range of accuracy. The difference pertaining to the SHD sample was the lowest, at 1.5%. Therefore, the designed apparatus is considered sufficiently accurate to carry out the remaining measurements.

Table 1. Comparison between the thermal conductivity of the three samples and the reference values.

Samples	Average measured thermal conductivity ($Wm^{-1}K^{-1}$)	Thermal conductivity reference ($Wm^{-1}K^{-1}$)	k-values difference (%)
HD	0.03588	0.035	2.5
UHD	0.03329	0.032	4
SHD	0.03046	0.03	1.5

In order to get the sample moisturized an ultrasonic humidifier is utilized as shown in Fig. 4. An ultrasonic humidifier uses a piezoelectric transducer vibrating at high frequency. When water drops and hits the element, which vibrates at high frequency, it creates a mist of water droplets that gets evaporated into the air. The circuit of the humidifier is electronically modified to suit the desired rate of mist that gets evaporated [8].

As illustrated in Fig. 5, a small acrylic chamber is furnished, to trap the moisture, so our sample can be placed in it. The sample is elevated via a metal mesh to have minimal contact with the chamber surface to ensure the homogeneous distribution of moisture around the sample (Fig. 6). Once the humidifier is started, the opening of the chamber was covered with a piece of foam. A small opening was kept so that the excess moisture can be exited through the chamber. Within seconds the chamber is filled with moisture and the sample is weighed time to time to ensure the weight gain to the proportion of the moisture percentage that is required.

Fig. 4 Ultrasonic humidifier

Fig. 5 Chamber filled with moisture

A. Experimental results

The impact of operating temperature on the thermal conductivity values of polystyrene insulation material with four density levels—low (LD), high (HD), ultra-high (UHD), and super-high (SHD)—is illustrated in Fig. 7. As can be seen from the graph, the thermal conductivity of the four samples is linear and is affected by the operating temperature to varying degrees. However, in all cases, higher temperature results in higher thermal conductivity. Moreover, thermal conductivity decreases with the increase in the sample density [2] and [4].

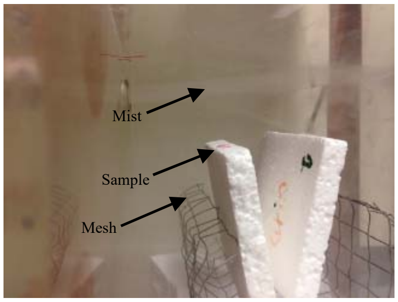

Fig. 6 Metal mesh carrying the samples

The effect of the moisture content of the k-value of polystyrene insulation with different densities at 10, 24, and 28°C was investigated using the developed apparatus described previously. However, it has been noticed that the change of the moisture content at different operating temperature has a very small effect on the k-value for the polystyrene insulation material with HD, UHD, and SHD densities. Indeed, they are more impermeable to water and moisture transfer due to their high densities.

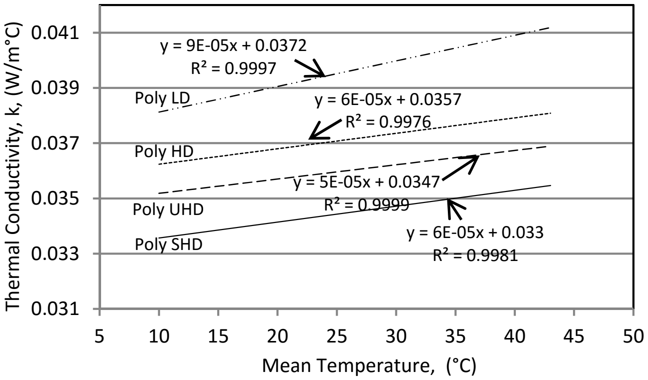

Fig. 7 Change of k-value with different densities vs. operating temperatures

Therefore, the investigation of the effect of the moisture content on k-value of the polystyrene insulation was limited to the LD density. The best-fit linear relationships between k-value and moisture content at a specified operating temperature are shown in Fig. 8. It was difficult to get any significant data at high operating temperature beyond 28°C due to the evaporation process in the sample during the measurement procedure.

In order to compare thermal conductivity variations for the different samples the measured k-values and the resulting operating temperature are established. This best-fit linear relationship is shown in Fig. 9. Indeed, the thermal conductivity of the LD sample increases with the increase of the moisture content and the increase of the operating temperature.

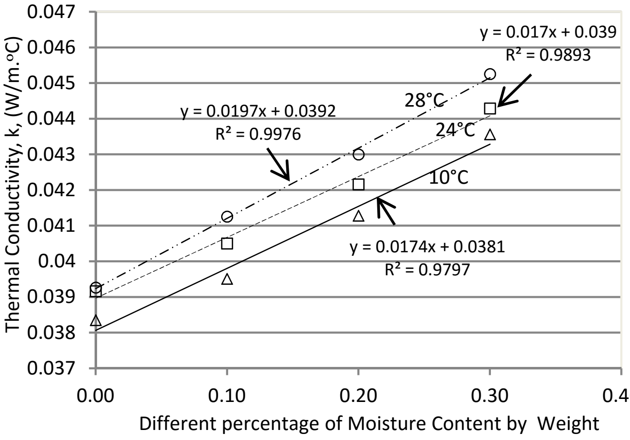

Fig. 8 Best-fit variation of k-values vs. moisture content level at 10, 24, and 28°C operating temperature

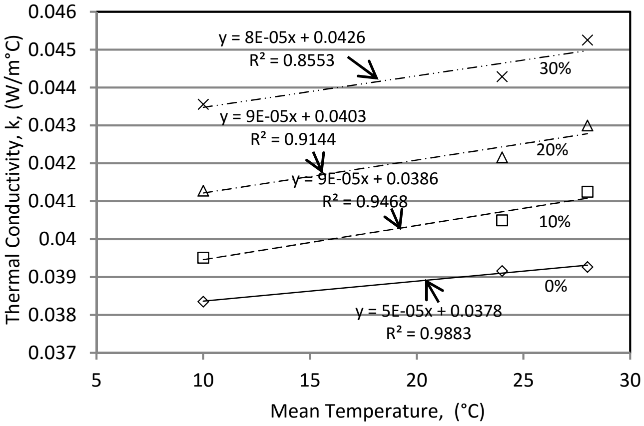

Fig. 9 Best-fit relationships of k-value measurement results of LD vs. operating temperatures and different percentages of moisture content by weight

X. Change of the k-Value of Polystyrene Insulation with Changes in Temperature at the Mid-thickness of the Insulation Material

Accurate sizing of the heating, ventilating, and air-conditioning equipment depends on the accuracy of the cooling load calculation, which requires an accurate account of the actual heat transfer through envelope components. The thermal resistance of the thermal insulation materials dependents on the operating temperature, as illustrated in the previous section.

The temperature to which the insulation materials are exposed depends on several parameters, including the thermal resistance of the material, the location of the insulation layer within the wall or roof assembly or system, and the effective or operating temperature. The last factor is a function of several parameters, including the outdoor air temperature, the surface solar absorbance of the system (wall or roof), the total solar radiation on the system surface, and the outdoor surface conductance [4].

At steady-state conditions, the temperature at any location within the wall can be given by

$$t_x = t_e - R_x/R_{tot}(t_o - t_i) \tag{1}$$

where t_e = effective or operating outdoor temperature; R_x = portion of thermal resistance measured from within; R_{tot} = total thermal resistance of the envelope assembly; t_o = outdoor air temperature; and t_i = indoor air temperature.

The effective outdoor temperature, also known as sol-air temperature, is evaluated by considering both the outdoor air temperature and the amount of solar radiation absorbed by the surface, and is given by

$$t_e = t_o + \alpha\, I_t/h_o - \varepsilon\, \Delta R/h_o \tag{2}$$

where α = surface solar absorbance; I_t = total solar radiation; h_o = outdoor surface conductance; and $\varepsilon\Delta R/h_o$ = correction factor (equal to zero for vertical surface).

The total solar radiation is given by the expression

$$I_t = H_b\left(\frac{\cos\theta}{\cos\theta_z}\right) + H_d\left(\frac{1+\cos\theta}{2}\right) + \rho_{gr} H\left(\frac{1-\cos\beta}{2}\right) \tag{3}$$

where H_b = direct horizontal radiation; H_d = diffuse horizontal radiation; H = global horizontal radiation; ρ_{gr} = ground albedo; θ = incident angle; and β = slope (90° for vertical wall and 0° for horizontal roof).

To investigate the impact of the operating temperature on the thermal conductivity of the insulation material within a construction assembly, a commonly used wall and roof construction is modeled. The wall is composed of a 200-mm thick concrete block layer, a 50-mm insulation layer, a 13-mm thick interior gypsum board, and a 19-mm concrete stucco from the exterior, with a total R-value of 2.79 m^2C/W. The roof system is mainly composed of a 200-mm thick concrete slab with a 15-mm plaster layer from the interior, whereby a waterproof membrane is placed above a 50-mm thick concrete sloping screed. A 75-mm polystyrene insulation layer is placed over the waterproof membrane covered with a weather-resistant barrier and a layer of 30-mm sandstone. The total R-value of the roof assembly is 2.4 $m^2.C/W$ [4].

Fig. 10 shows the hourly values of different solar radiation components for June at Seeb location in Muscat. The curves represent the total vertical radiation computed from the total horizontal value, as well as direct normal and diffuse horizontal radiation, from sunrise to sunset for June 15th, 2015. The total horizontal, direct normal, and diffuse horizontal radiation values are adopted from elsewhere [34]. Fig. 11 shows the hourly values of outside air temperature and wind speed obtained from the measurement in Seeb during June 15th, 2015.

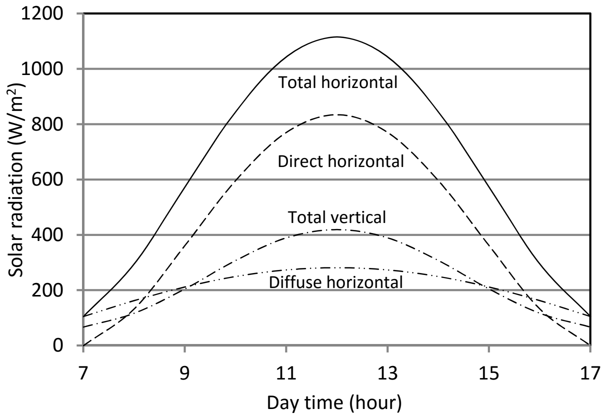

Fig. 10 Hourly values of different components of solar radiation for June 15th at the Seeb location in Muscat

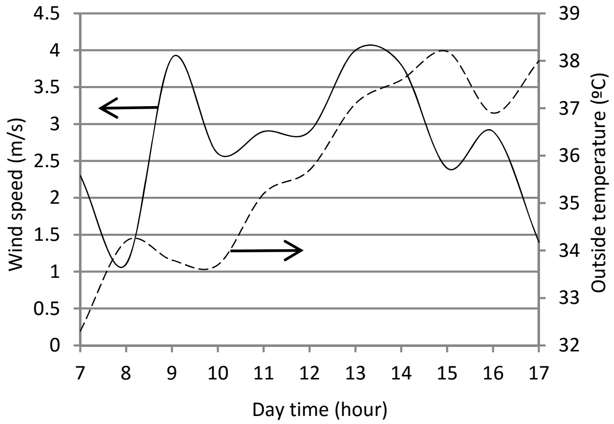

Fig. 11 Hourly values of outside temperatures and wind speed for June 15th at the Seeb location in Muscat

XI. RESULTS

Figs 12-15 show the change in insulation polystyrene thermal conductivity as a function of temperature at the mid-thickness of the material for different percentages of moisture content for horizontal and vertical surfaces during the daytime with dark and light color of the external surfaces. These curves have been plotted with the reference k-value of polystyrene insulation obtained at 24°C. It is evident from the graphs that the k-value of the samples increases with the increase of the moisture content within the layer of the samples and the operating temperatures. Moreover, the change of the k-value of the roof is more significant compared to the wall, due to the huge amount of the solar radiation received on the horizontal surface, which is also higher for dark color compared with a light one.

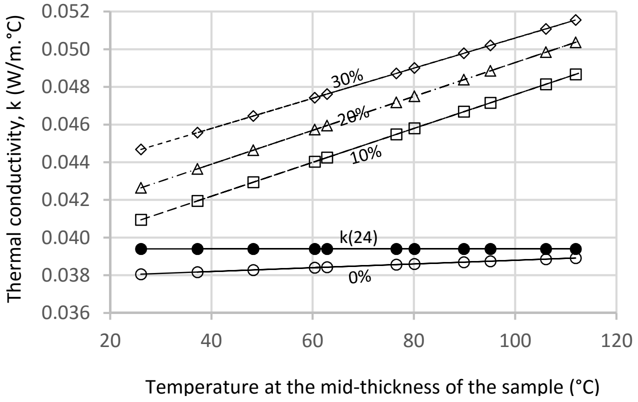

Fig. 12 Change in polystyrene k-value as a function of temperature at the mid-thickness of the material for different percentages of moisture content and k-reference comprising a horizontal surface (roof) during daytime with roof dark color (α=0.9)

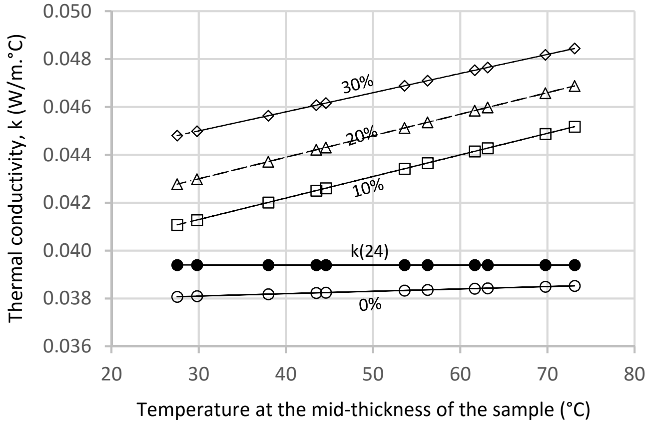

Fig. 13 Change in polystyrene k-value as a function of temperature at the mid-thickness of the material for different percentages of moisture content and k-reference comprising a horizontal surface (roof) during daytime with roof light color (α=0.5)

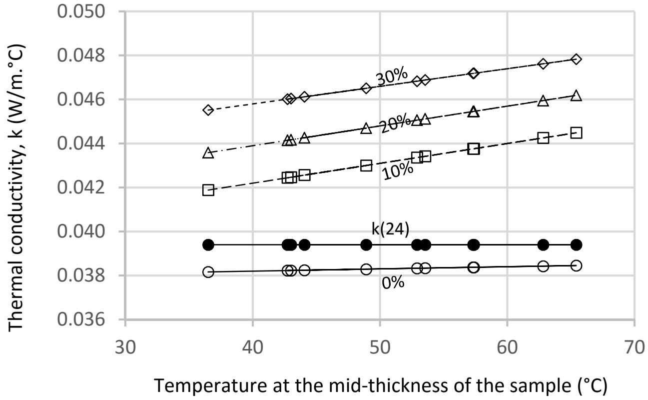

Fig. 14 Change in polystyrene k-value as a function of temperature at the mid-thickness of the material for different percentages of moisture content and k-reference comprising a vertical surface (wall) during daytime with roof dark color (α=0.9)

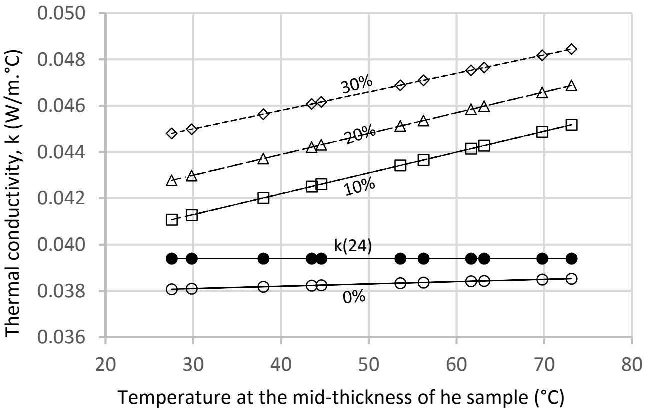

Fig. 15 Change in polystyrene k-value as a function of temperature at the mid-thickness of the material for different percentages of moisture content and k-reference comprising a vertical surface (wall) during daytime with roof light color (α=0.5)

XII. CONCLUSION

The first part of this paper presented an overview of the basic principles of the thermal insulation materials and their applications in a comprehensive and practical way for engineers and/or building owner.

The change in insulation polystyrene thermal conductivity as a function of temperature at the mid-thickness of the material for different percentages of moisture content for horizontal and vertical surfaces during the daytime with dark and light color of the external surfaces are presented in the second part in this paper.

It has been found that the HD, UHD, and SHD samples are impermeable to water and moisture transfer due to their high densities. Therefore, the study was limited to the LD sample.

Indeed, the thermal conductivity of the LD sample increases with the increase of the moisture content and the increase of the operating temperature.

Moreover, the change of the k-value for the roof is more significant compared to the wall, due to the huge amount of the solar radiation that falls on a horizontal surface, which is also higher for dark color compared with light one.

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REFERENCES

[1] http://www.designingbuildings.co.uk/.
[2] M. Khoukhi and M. Tahat, “Effect of operating temperatures on thermal conductivity of polystyrene insulation material: impact on envelope-induced cooling load,” Applied Mechanics and Materials, vol. 564, pp. 315-320, 2014.
[3] M.A. Abdelrahman and A. Ahmad, “Cost effective use of thermal insulation in hot climates,” Building and Envelope vol. 26, pp. 189-194, 1991.
[4] M. Khoukhi, N. Fezzioui, B. Draoui and L. Salah, “The impact of changes in thermal conductivity of polystyrene insulation material under different operating temperatures on the heat transfer through the building envelope, Applied Thermal Engineering (2016), http://dx.doi.org/10.1016/j.applthermaleng.2016.03.065.
[5] ASHRAE: Handbook of Fundamentals. Atlanta, GA, Chap. 23, 2001.
[6] B.A. Peavy, “A heat transfer notes on temperature dependent thermal conductivity,” Thermal Insulation Building Envelope, vol. 20, pp. 79-90, 1996.
[7] M. Khoukhi and M. Tahat, “Effect of temperature and density variation on thermal conductivity of polystyrene insulation materials in Oman”, Journal of Engineering Physics and Thermophysics, vol. 88, no. 4, pp. 994-998, July, 2015.
[8] M. Khoukhi, “Effect of Operating Temperature and Moisture Content on the Thermal Conductivity of Building Insulation Material”, 6th International Conference on Energy Research and Development, March 14-16, Kuwait, 2016.
[9] M. Khoukhi, Change of the Thermal Conductivity of Polystyrene Insulation in Terms of Temperature at the Mid-thickness of the Insulation Material: Impact on the Cooling Load”, 18th International Conference on Mechanical Engineering, May 16-17, Montreal, Canada, 2016.
[10] G.S. Kochlar and K. Monahar, “Effect of moisture on thermal conductivity of fibers biological insulation materials. Thermal performance of exterior envelopes of buildings VI,” ASHRAE/DOE Conference, 2-5 December, pp. 33-40. Florida,1995.
[11] M.C. Chyu, X. Zeng, and L. Ye. “The effect of moisture on the performance of polyurethane insulation used on a district heating and cooling pipe,” ASHRAE Tran., vol. 103 (part 1), pp. 309-317, 1997
[12] M.C. Chyu, X. Zeng, and L. Ye. “Performance of fibers glass pipe insulation subjected to underground water attack,” ASHRAE Tran., vol. 103 (part 1), pp. 303-308, 1997
[13] M.C. Chyu, X. Zeng, and L. Ye. “Effect of underground water attack on the performance of mineral wool pipe insulation,” ASHRAE Tran., vol. 104 (part 2), pp. 168-175, 1998
[14] I. Budaiwi and A. Abdou, “Effect of thermal conductivity change of moist fibrous insulation on energy performance of buildings under hot-humid conditions,” Energy and Building, vol. 60, pp. 388-399, 2013
[15] ASTM Standard C 168-97. Terminology relating to thermal insulating materials, 1997.
[16] http://www.vse.sk/.
[17] American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). Handbook of Fundamentals, Atlanta, GA, USA, 2001 [Chapter 23].
[18] www.radiantguard.com.
[19] www.radiantbarrier.com.
[20] Nisson JD, Dutt G. The super insulated home book. New York: Wiley; 1985.
[21] www.level.org.nz/.
[22] www.epa.gov.
[23] Claytor, R.A., and T.R. Schueler. Design of Storm Water Filtering Systems. The Center for Watershed Protection. (CWP) Silver Spring, MD. Prepared for the Chesapeake Research Consortium, Solomons, MD, and USEPA Region V, Chicago, IL. 1996.
[24] Lstiburek J. Moisture control for buildings. ASHRAE Journal 2002;44(2):36–41.
[25] www.greenbuildingadvisor.com/.
[26] Al-Homoud MS. Performance characteristics and practical applications of common building thermal insulation materials. Build Environ 2005; 40:353–66.
[27] Omer Kaynakli, A review of the economical and optimum thermal insulation thickness for building applications. Renewable and Sustainable Energy Reviews Volume 16, Issue 1, January 2012, Pages 415–425.
[28] Ansari FA, Mokhtar AS, Abbas KA, Adam NMA. Simple approach for building cooling load estimation. Am J Environ Sci 2005;1(3):209–12.
[29] Al-Khawaja MJ. Determination and selecting the optimum thickness of insulation for buildings in hot countries by accounting for solar radiation. Appl Therm Eng 2004; 24:2601–10.
[30] Yu J, Yang C, Tian L, Liao D. A study on optimum insulation thicknesses of external walls in hot summer and cold winter zone of China. Appl Energy 2009; 86:2520–9.

[31] American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). Handbook of Fundamentals, Atlanta, GA, USA, 2001 [Chapter 23].

[32] www.eere.energy.gov/buildings/components/envelope/insulation.cfm.

[33] Masonry Council of Canada. Guide to energy efficiency in masonry and concrete buildings, Ont., CA, 1982.

[34] H.A. Al-Hinai and M. Al-Alawi, “Typical solar radiation data for Oman,” Applied Energy vol. 52, pp. 153-163, 1995.