1. **Review of Research & development work in thermal properties:**

The properties of interest are the thermal conductivity ($\lambda$), the thermal diffusivity ($\alpha$) and specific heat (c). Since these three quantities are interrelated, ($\alpha = \frac{\lambda}{\rho c}$ where $\rho$ is density).

Knowledge of any two determines the third. Besides the three thermo physical coefficients needed to describe the thermal status of a substance, the heat storage coefficient (HSC) is an additional useful parameter to describe its thermal behavior.

(i)**Thermal conductivity:**

Thermal conductivity ($\lambda$) is the intrinsic property of a material which relates its ability to conduct heat. Heat transfer by conduction involves transfer of energy within a material without any motion of the material as a whole. Conduction takes place when a temperature gradient exists in a solid (or stationary fluid) medium. Conductive heat flow occurs in the direction of decreasing temperature because higher temperature equates to higher molecular energy or more molecular movement. Energy is transferred from the more energetic to the less energetic molecules when neighboring molecules collide.

Thermal conductivity is defined as the quantity of heat ($Q$) transmitted through a unit thickness ($L$) in a direction normal to a surface of unit area ($A$) due to a unit temperature gradient ($\Delta T$) under steady state conditions and when the heat transfer is dependent only on the temperature gradient. In equation form this becomes the following:

\[
\lambda = \frac{Q \times L}{A \times \Delta T}
\]

In literature, there are steady state and transient methods for the measurement of thermal conductivity of the materials. The two classes for measurement of thermal conductivity are divided according to the nature of the methodology used. These based on steady state techniques are:

(a) Guarded hot plate method  
(b) Heat meter method  
(c) Radial flow method  
(d) Comparative method  
(e) Schroeder method
While methods based on unsteady state are

(a) Line heat source method
(b) Plane heat source method
(c) High temperature transient method and others.

The steady state methods are simple in theory but practical applications involve rather elaborate
techniques including thermal guard system to eliminate lateral heat flow and electronic control
system to ensure stable conditions during test. Large quantities of test samples are required in
such measurements. Moreover, these methods do not permit in-situ measurement. In the
unsteady state measurement techniques temperature is a function of time. The time saving
feature of the technique provides rapid measurement and a distinct advantage is that they can be
used in-situ. These techniques are extensively used for the determination of thermal conductivity
of loose granular materials.

Kadjo et al. [1] developed Tantalum Short Hot Wire (TSHW) probe technique for determination
of thermal conductivity highly energetic character liquids like as nitric acids solutions and
similar nitric mixtures, required minimum volume samples.

The transient hot wire technique (THW) is widely used for measurement of thermal conductivity.
This technique is based on the measurement of the temperature rise of a linear heat source (Hot
wire) embedded in the test material. For an infinitely long metallic wire (radius \( r_0 \)) heated at
time \( t > 0 \) with a constant flux \( q \) per unit length and immersed in an infinite homogenous liquid
medium with uniform initial temperature \( T_0 \), the instantaneous temperature \( T_t \) of the wire is
given by Healy et al.(1976) [2]

\[
T_t - T_0 = \frac{q}{4\pi\gamma} \log \left( \frac{4F_0}{C} \right)
\]

Where \( \gamma \) is the Euler’s constant (\( \gamma = 0.5772 \)) with \( C = e^\gamma \) and \( F_0 \) is the Fourier number defined
by \( F_0 = \frac{at}{r^2} \)

better than 0.5%. Nieto de Castro et al. (1988) [4] also determined thermal conductivity of
liquids.

But in electrically conducting liquids, the THW method is not usable with bare metal wires
because leakage of electric current and polarization of the liquid at the surface of wire can occur,
leading to uncontrolled errors in the wire temperature and heating power measurements. For such
liquids, the wire must then be electrically insulated by coating with thin insulation layer.
For dry materials such as dry soil and rocks which are non homogeneous, steady state methods are suitable but for moist soil, the thermal conductivity under the condition of uniform water distribution can not be obtained because the water is redistributed according to the temperature gradient.

Singh et al. (1988)[5] determined effective thermal conductivity (ETC) of moist porous systems with different liquids and study of the effect of freezing on the ETC of soils saturated with different liquids. ETC of moist soil is calculated by

\[
\lambda_{ETC} = \frac{Q}{4\pi(T_2 - T_1)} \log \frac{t_2}{t_1}
\]

(ii) Thermal diffusivity:

In heat transfer analysis, **thermal diffusivity** (symbol: \( \alpha \) but the symbols \( \kappa \), \( D \), and \( k \) are all commonly used) is the thermal conductivity divided by the volumetric heat capacity. It has the SI unit of m²/s.

\[
\alpha = \frac{k}{\rho c_p}
\]
Where:

- $k$: thermal conductivity (SI units: W/(m·K))
- $\rho$: density (kg/m³)
- $c_p$: specific heat capacity (J/(kg·K))

The denominator of the thermal diffusivity expression above $\rho c_p$ can be identified as the volumetric heat capacity.

Kadjo et al.(2008){1} determined thermal diffusivity of nitric acid solutions and similar nitric mixtures have high energetic character liquids by tantalum short hot wire technique.

Motosuke et al.,(2003){6} determined thermal diffusivity with the forced Rayleigh scattering method. This is an optical technique of the thermal diffusivity measurement and is used to the real time monitoring of the thermal diffusivity. The fundamental working equation takes the form

$$\alpha = \frac{1}{\tau} \left( \frac{A}{2\pi} \right)^2$$

Substances with high thermal diffusivity rapidly adjust their temperature to that of their surroundings because they conduct heat quickly in comparison to their volumetric heat capacity or thermal bulk and they generally do not require much energy from their surroundings to reach thermal equilibrium.

In contrast to the thermal conductivity we find lesser attempts to determine thermal diffusivity. The experimental methods for the measurement of effective thermal diffusivity fall in to two categories are

(a) Periodic heat flow method
(b) Transient heat flow method.

Periodic methods require enough time where errors due to unwanted heat transfer will be present. In transient or variable state methods, shorter times are required and there by heat transfer errors are reduced. In fact, this was the reason for revival of interest in transient methods for determining thermal properties.

Gustafson [7] has developed a transient hot strip method (T.H.S.) for the simultaneous measurement of thermal conductivity and diffusivity using the expression given by Carslaw & Jaeger [8].

Transient heat flow methods have been used to measure the thermal diffusivity of metals, alloys, semiconductors, ceramics, dispersed and layered composites, soils, loose granular materials and
even liquid metals. Thus these are used for materials whose diffusivity range from $10^7$ to $10^{-3}$ m$^2$ sec$^{-1}$. Flash method also been used for the measurement of thermal diffusivity. General theory of calorimeter method was developed by Kondrot’ev {9} to determine thermal diffusivity of soil like materials. The method is based on the theory of cooling (heating) of soil when it is in the state of regular thermal regime. This method has been found suitable for the measurement of thermal diffusivity of loose granular materials. Parallel wire method was developed by Deboer and Hoogovens {10}, in this method a single measuring thermocouple parallel to heater wire was placed inside the sample. Thus the two parallel wires heater wire and thermocouple are put inside the material whose thermal diffusivity is to be determined.

(iii) Heat storage coefficient:

Thermal conductivity, thermal diffusivity and volumetric specific heat are three important parameters in deciding the thermal behaviour of a substance. Besides the three thermo physical coefficients needed to describe the thermal status of a substance, the heat storage coefficient (HSC) is an additional useful parameter to describe its thermal behaviour. Although its value is related to the three constants, in many cases it behaves as an independent characteristic of the sample.

If we consider a section of medium, then some of the heat entering is retained by it and the rest is transferred to subsequent layers. When the steady state is reached no heat is retained and is transferred to the subsequent layers. It can be seen that during the transient state the heat retained by a particular layer is a function of its HSC.

It is evident that the amount Q transported is determined by storage parameter $\beta$ of the system. In both the process of heat storing and heat conduction, restriction is on the quantity of heat involved. For insulation purposes one requires that the amount of heat passing through any material in time t, should be as less as possible and for storage purposes one also requires the same condition. Therefore, for storage purposes if $Q_1$ and are $Q_2$ respective heat amounts crossing the levels $z_1$ and $z_2$ in time t, through the material, on requires that ($Q_1 - Q_2$) should be maximum. For insulation purposes also one requires the same condition. While for conduction purposes the conditions turns to be opposite and one requires that ($Q_1 - Q_2$) should be minimum. In all such estimations the parameters $\beta$ plays decisive role.

In general, a loose granular material has a lower HSC than cellular one of the same material and porosity. Thus granular materials present better thermal insulation properties. For loose granular materials pores are usually much smaller and the drop in temperature under natural conditions never reaches values of 100°c, therefore thermal convection and thermal radiation is not being considered. There is very little migration of moisture in these materials. Therefore, mass transfer may also be treated negligible. Thus only conduction (under steady state) or diffusion (in transient state) plays an important role for heat losses in thermal storages. The temperature of the storage materials changes with time due to constant absorption.
The thermal parameter, HSC (β) of loose granular materials has rarely been measured directly. Generally it has been calculated from measured thermal conductivity and measured specific heat and density or thermal diffusivity. Sharma et al [11] have estimated its values for granular substances at varying interstitial air pressures by determining thermal conductivity and thermal diffusivity from independent experiments. Wechsler et al [12] have determined its value for granulated materials at varying particle sizes by determining thermal conductivity, density and specific heat from independent experiments.

Recently Verma et al, [13] have developed a plane heat source method for its direct determination of HSC.

In literature several authors have described the HSC under different names. Nerpin and Chudnovskii [14], while determining heat flux through a soil surface during half cycle of periodic heating and cooling has mentioned \( \sqrt{\lambda \rho c} = \frac{\lambda}{\sqrt{\alpha}} \) as a coefficient of heat storage or thermal susceptibility coefficient. The expression given by him for half a period is

\[ Q = A \, S \, \sqrt{\lambda \rho c} \, \frac{2T}{\pi} \]

Where \( Q \) is the amount of heat flux, \( A \) is the amplitude of temperature oscillation at the surface of area \( S \) and \( T \) is the time period of the heat wave. They also found that only two of the thermo physical characteristics \( \lambda \) and \( C \) appear as basic quantities in all the calculations of the temperature field. The two other being derivatives in the form \( \alpha = \frac{\lambda}{C} \) and \( \beta = \sqrt{\lambda C} \), are necessary in temperature field calculations only when the temperature at the surface is given and when one considers the flux in to the soil over a certain period.

For the thermal energy status of soil (and similar systems) it is useful to know all the four thermo-physical characteristics \( (\lambda, C, \alpha, \beta) \). This set gives a comprehensive representation of the thermal properties of the system.

Luikov [15] has named it coefficient of thermal activity. The expression given by him, while considering the case of heat transfer in walls with periodic variations in the temperature of the medium, for the instantaneous heat flow on the surface is

\[ g(\tau) = A \, t_{\text{max}} \sqrt{\lambda c \gamma \omega} \cos (\omega \tau + \pi/4) \]

\[ = A \, q_{\text{max}} \cos (\omega \tau + \pi/4) \]

Where \( A \) is the area of the external surface of the wall, \( t_{\text{max}} \) is amplitude of the temperature oscillation, \( \omega \) is the cyclic frequency \( (\omega = 2\pi/T, T \text{ being the period}) \) and \( \gamma \) is the density of the medium.
The amplitude of the temperature oscillation on the wall surface (x=0) is equal to \( t_{\text{max}} \) and the amplitude of fluctuation of the heat flow per unit surface is equal to \( t_{\text{max}} \sqrt{\lambda \rho c \omega} \). The ratio of these amplitudes \( \frac{q_{\text{max}}}{t_{\text{max}}} \) is called the coefficient of heat assimilation of the wall surface and it is denoted by the letter \( s \):

\[
S = \frac{q_{\text{max}}}{t_{\text{max}}} = \sqrt{\lambda c \gamma \omega}
\]

The coefficient \( S \) depends on the coefficient of thermal activity \( \sqrt{\lambda c \gamma} \) and the frequency \( \omega \) of the temperature oscillation, usually, 24 hours is assumed as the period of oscillation (\( \omega = \frac{2\pi}{24} = \frac{\pi}{12} \)), then the coefficient of heat assimilation becomes

\[
S = 0.51 \sqrt{\lambda c \gamma}
\]

Besides the coefficient of heat assimilation, a dimensionless quantity \( D \) is introduced, called the index of thermal inertia or the nominal thickness of the wall. For a homogeneous wall this quantity is equal to the product of the thermal resistance and the coefficient.

\[
D = \frac{1}{\lambda} S = \sqrt{\frac{c \gamma \omega}{\lambda}}
\]

The quantity \( D \) is proportional to the thickness of the wall.

Baranov [16] has called it the coefficient of heat assimilation. He mentioned that a knowledge of the heat assimilation coefficient \( \beta \) is necessary, for example, in calculating the heat accumulation \( Q \) for a definite period \( T \). In this case

\[
Q = A \lambda C
\]

Where, \( A \) is the amplitude of the temperature wave of period \( T \).

Sharma et al.[11] while dealing with theory of heat transfer through a semi infinite medium has described it as “coefficient of heat storage”. The expression given by them is

\[
Q = S \frac{\lambda}{\sqrt{\alpha}} t \sqrt{P} e^{-\psi t} \]

Where, \( P \) is a constant which is related to characteristic prosperities of the material.

In Carslaw and Jaeger [11] one also come across such a term in the expression for heat transfer through a semi infinite solid but no specific name has been given there.

The expression obtained by them for rise in temperature in an infinite composite solid is
\[ T = \frac{2q \sqrt{\alpha_1 \alpha_2 t}}{\lambda_1 \sqrt{\alpha_2} + \lambda_2 \sqrt{\alpha_1}} \text{erfc} \left( \frac{r}{\sqrt{4 \lambda_1 t}} \right) \]

Where \( \lambda_1 \) and \( \lambda_2 \) are the thermal conductivities of the two media, \( \alpha_1 \) and \( \alpha_2 \) are the respective thermal diffusivities, \( q \) is the power generated per unit area by the source and \( r \) is the distance of point from the interface plane.

Some researchers named it as the thermal inertia of the material. Luc and balageas [17] has called \( \frac{\lambda}{\sqrt{\alpha}} \) as “effusivity” of the medium. While dealing with the problem of non stationary thermal behaviour of reinforced composites there authors obtained a solution for a homogeneous material subjected to convective heating as

\[ \frac{T}{T_r} = 1 - E \left( \frac{h \sqrt{t}}{b} \right) \]

Where, \( T \) is the temperature of front face, \( T_r \) is recovery temperature and \( b = \sqrt{\lambda C} \) is the thermal effusively, \( \lambda \) is thermal conductivity and \( C \) is volumetric specific heat. Hence

\[ E(u) = \exp(u^2) \text{erfc}(u) \]

In Ingersoll and others [18] were invariably find this constant while dealing with the theory of heat exchangers etc., but no specific name has been given there too. We quote here:

If certain amount of heat is flowing through a composite wall, then the temperature of the interface plane is given by.

\[ T_s = \frac{\lambda_1 T_1 / \sqrt{\alpha_1} + \lambda_2 T_2 / \sqrt{\alpha_2}}{\lambda_1 / \sqrt{\alpha_1} + \lambda_2 / \sqrt{\alpha_2}} \]

Where, \( T_1 \) and \( T_2 \) are the temperature of the two media. The condition that the temperature of interface plane may be \( \frac{T_1 + T_2}{2} \) is \( \lambda_1 \rho_1 c_1 = \lambda_2 \rho_2 c_2 \) this condition is nothing but the equality of HSC of the media.

In plane heat exchanger the rate of flow of heat per unit area through the exchanger is given by,

\[ \omega = \frac{\lambda \Delta T}{\sqrt{\alpha} \sqrt{\pi t}} \]

Where, \( \Delta T \) is the temperature difference between the two surfaces.

(1) In cylindrical heat exchanger for a short pipe length \( L \) and radius \( R \) the temperature \( \Delta T \) between two surfaces can be written,
\[ \Delta T = \frac{q}{4\pi \lambda^2} [4.6\lambda \log(L / R) + \frac{\lambda}{\sqrt{\alpha}} \frac{L}{\sqrt{\pi t}}] \]

(2) In spherical heat exchanger for a spherical exchanger the amount of heat flowing is

\[ q = 4\pi \lambda R \Delta T + 4\pi R^2 \cdot \frac{\lambda}{\sqrt{\alpha}} \frac{\Delta T}{\sqrt{\pi t}} \]

(3) Rate of heat flow by each face of a slab to the surrounding medium is given by,

\[ q = \frac{\lambda T_0 \eta}{\sqrt{\pi}} [1 - \exp(-t^2 \eta^2)] \]

Where, \( \eta = \frac{1}{\sqrt{4\alpha t}} \), \( T_0 \) is the initial temperature and \( L \) is the thickness of the slab.

All these expressions suggest that \( \lambda/\sqrt{\alpha} \) plays an important role in deciding the heat flow and the temperature profile of a sample. Recently studied [19], the HSC of different loose granular materials with variation of temperature, pressure and moisture. Further, now, in this dissertation we will study thermal properties of multiphase systems.

3. International and National Status:-

Heat transfer in multi-phase systems has received renewed importance in recent times by physicists and engineers interested in development of cheaper insulating material for solar energy storage devices, buildings, refrigerators and air conditioners. Such a study is also needed in explosive material industry, the ceramic industry, nuclear reactors and oil exploration. Granular substance of practical importance, range from simple two phase system to complex systems of irregular particles with more than two constituent phases. Three phase systems with porous cementing materials are yet more complex. The theoretical modeling of such systems with complex parameter is a challenging task. In recent time, a variety of approaches [20-22] have been developed for the estimation of effective thermal conductivity of heterogeneous multi-phase systems using resistor or flux concept. In addition, development of bound technique [23] has also helped a lot in the estimation of the optimum value of effective thermal conductivity of randomly oriented two phase systems. In literature few expressions, developed originally for two phase media have been extended up to three-phase systems. In this sequence Verma et al [24], have developed their two-phase equation for the estimation of effective thermal conductivity of three phase medium. Also there are some theoretical models [25, 27] assuming particulars shape and geometrical structure of the constituent phases.
4. Brief description of the applicant’s scientific work and vision:

In Rajasthan state, we have abundant waste of Marble powder, Kota stone powder, Dune sand and other cheaply available materials. These shall be used between double walls of the investigated systems and heat transfer will be studied on them. Thus we shall be having very useful data on all types of multi-phase systems. A comparative study of them shall recommend the system which can save more heat dissipation from a building/solar heat store. This study is also going to provide useful information in fabrication of buildings of natural comfort.

Energy saved is energy produced. Therefore, any scientific effort (to save energy) is welcome. Moreover, if such an endeavour is within our means then feasibility to carry out successfully becomes a survey. In this context I wish to study experimentally as well as theoretically the thermal properties of different multi-phase systems.

A detailed systematic study of the thermal parameters of such multi-phase systems, have not been studied. This requires an investigation on large number of materials. Heat conduction in powders, soils emulsions colloidal, stones, suspensions and moisture on similar multi-phase systems has been studied in detail.