OPTIMIZATION & PARAMETRIC ANALYSIS OF SENSIBLE HEAT BASED THERMAL ENERGY STORAGE MATERIALS BY USING FACTORIAL TECHNIQUE

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Abstract: In the present scenario, lots of research is going on regarding the utilisation of waste heat for other applications. Lots of technologists are finding or searching for various types of materials for the storage of waste heat. In this paper, existing materials for sensible thermal heat storage are studied. Different existing materials for sensible heat-based thermal energy storage materials are clay, feolite, alumina, steel balls, concrete, etc. A wide range of materials is available. After the brief study, lots of thermal energy storage materials exist. All existing materials must have different properties, such as specific heat, thermal conductivity, thermal diffusion, thermal expansion, etc. Heat storage by these materials depends on various factors such as diameter, length, heat transfer coefficient, and temperature differences. The focus of this paper is to find out the optimal result based on different parameters of heat storage material. In a packed bed thermal energy storage system, the arrangement of the materials in the bed and the shape of the materials play an important role during the charging or discharging of packed bed thermal energy storage. In this research paper, the analysis is done in two phases for three different materials (rock, brick, and feolite) having the same size. In the first phase, the sensible heat storage materials are analysed on the basis of Abaqus software, and in the second phase, full factorial DOE is applied for optimisation.

Keywords: Thermal heat storage materials, Abaqus Simulation, Full Factorial Technique, Thermal Energy storage (TES), Temperature analysis.

Highlights:

1. Thermal energy storage materials are studied using the Design of Experiment Technique **"Full Factorial Technique.**"
2. Abacus simulation is used for an analysis of temperature variation along the length.
3. Impact is analysed based on the ‘m’ constant value of the heat transfer coefficient, thermal conductivity, and area of materials.
4. Signal-to-noise ratio analysis and regression modelling for optimisation of the heat storage materials for selective design parameters

Graphical Abstract:

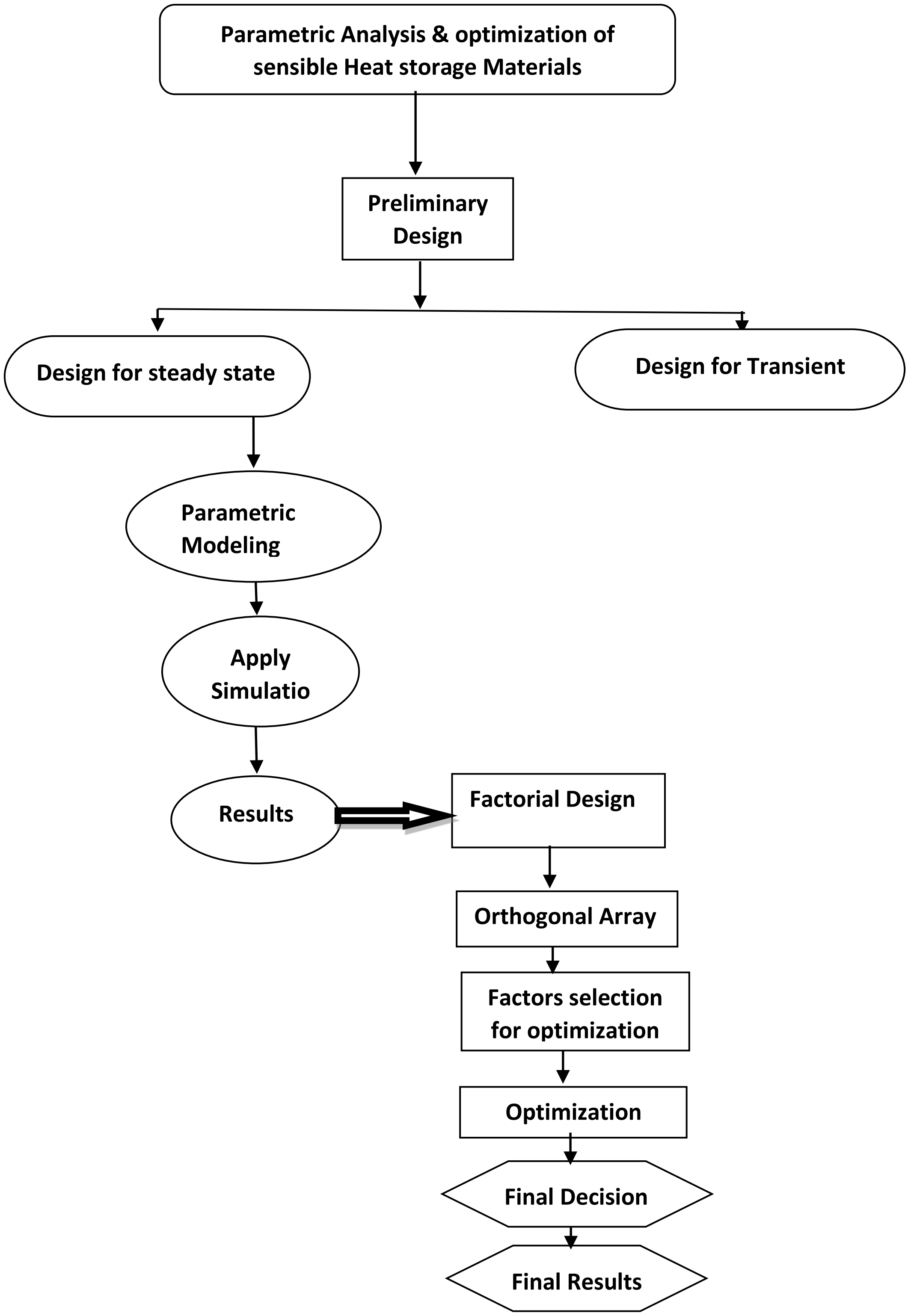

Fig. 1 Block diagram of Research adoption

Nomenclature:

ANOVA	**Analysis of Variance**
GRADT	**Gradient**
NT	**Nodal Temperature**
HFL	**Heat flux vector**
RFL	**Reaction fluxes**
FD	**Factorial Design**
HTC	**Heat transfer coefficient**
TC	**Thermal Conductivity**
D	**Diameter**
DOF	**Degree of freedom**
TES	**Thermal Energy Storage**
DOE	**Design of Experiment**
SS	**Sum of square**
MS	**Mean square**
S/N Ratio	**Signal to Noise Ratio**
S/NS	**Significance/Non-Significance**
P	**Perimeter**
A	**Area**
W	**Watt**
k	**Thermal conductivity**
ESS	**Energy storage system**
P	**Perimeter**
h	**Heat transfer coefficient**
T_b	**Base Temperature**
T_∞	**Surrounding Temperature/ Ambient temperature.**
A	**Area of storage material (Cylindrical shape)**
m	**Constant (Square root of (h.P/k.A)**
SE coef.	**Standard Error coefficient**
VIF	**Variance Inflation factor**
NC/MC/HC	**Not correlated/Moderately correlated/Highly correlated**
SHSM	**Sensible Heat storage Material**

A. Introduction: In a packed-bed thermal energy storage (TES) system, there is a big role for heat storage materials. As it will be shown in the analysis, the solid cylinder gives at least 14.5% more surface area than the sphere of equivalent volume, and when the particle aspect ratio (l_p/d_p) decreases, the heat transfer rate decreases [1]. Energy densities for a concrete-based thermal storage system have been estimated at 22 kWh/m^3[2]. Thermal energy storage based on heat has two types: sensible heat storage and latent heat storage. The materials for sensible heat storage are reliable to store heat up to their specific heat capacity because the sensible heat of any storage material is calculated by Q=mcΔT, where m is the mass of storage material that we are taking in use (kg), c represents the specific heat of storage material, and ΔT is the temperature of storage material that increased during the charging process [4]. Water and oil are the fluid media for sensible heat storage in materials [5]. During the charging process of sensible heat storage materials, they stabilise in a single phase during the interaction with temperature [6]. Sensible heat storage materials are used for low-temperature applications like space heating and industrial waste [4]. Based on natural convection, sensible heat storage is much more reliable. Lots of researchers, however, have studied the enhancement effect of sensible heat storage on the heat dissipation characteristics of electronic devices [10]. The improvement in the sorption systems is associated with the wide range of materials that may be used to enhance their performance [17].

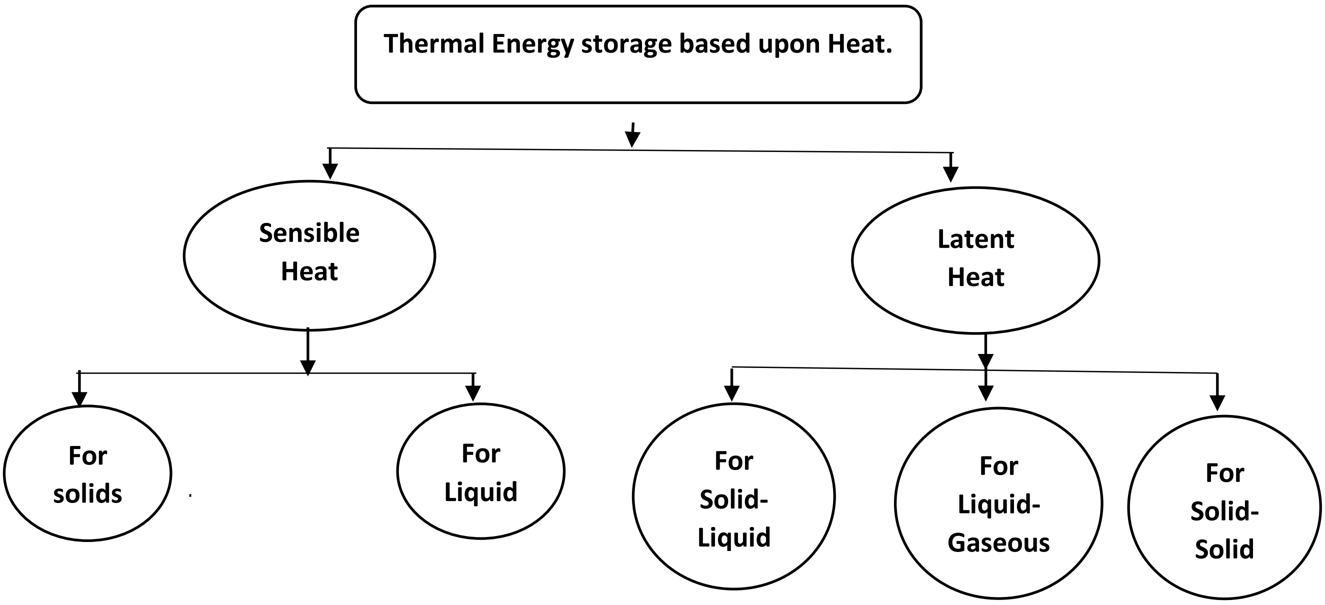

Fig.2 Block diagram of Thermal Energy storage system [3].

Sensible heat storage is the most simple and inexpensive way of storing energy. Although there are a few advantages to phase change energy storage over sensible heat storage, the technological and economic aspects make sensible heat storage superior [19]. The maximum difference in the temperature variation across the column cross-section [20] Sensible heat storage has a simple principle, has a low cost, and is the most widely used application [21].

B. **Numerical Modeling**

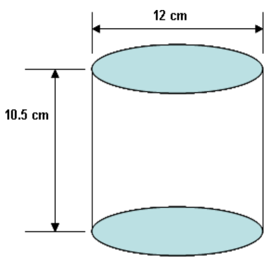	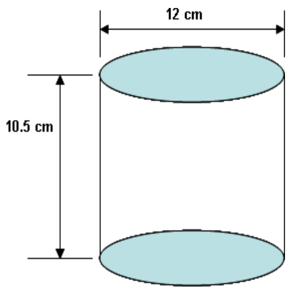	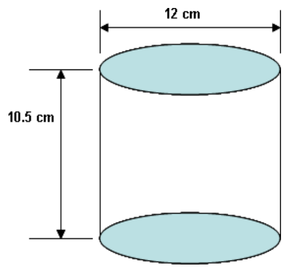
(a) Rock Material	**(b) Brick Material**	**(c) Feolite Material**
D=12 cm, L=10.5 cm	**D=12 cm, L=10.5 cm**	**D=12cm, L=10.5 cm**

Fig.3 Cylindrical shape of heat storage Elements [1].

Figure 1, in which the research methodology and techniques for the parametric optimisation of sensible heat storage materials are proposed, In the first phase of this research paper, three different sensible heat storage materials are selected, which are rock, brick, and feolite, after studying previous research papers. The temperature, gradient, heat flux, and reaction flux studies are carried out using Abaqus CAE software [22]. The size of all different materials is 10.5 cm in diameter and 12 cm in length [1]. These dimensions were selected based on previous studies.

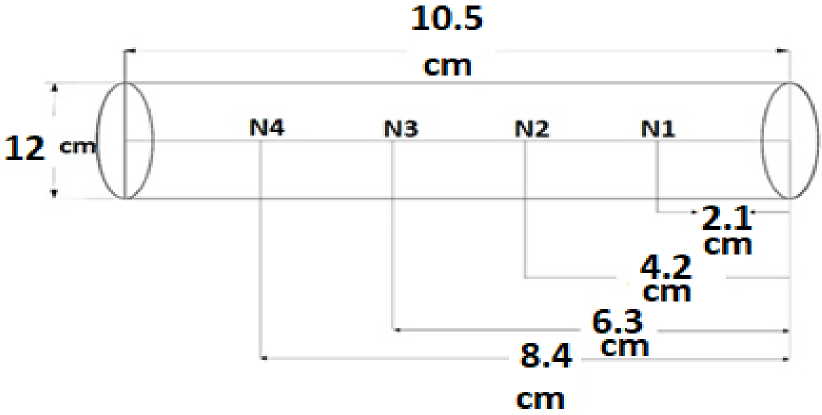

Fig.4 Nodes highlighted in cylindrical shape along length variation [1].

In Fig. 4, various nodes are highlighted for the analysis of temperature, heat flux, gradient, and reaction fluxes in the case of different sensible heat storage materials that have different thermal conductivities.

Table 1: Related Data for the analysis through Abacus software

Material	Rock	Brick	Feolite	References
Base Temperature (^{0}C)	500	500	500	**[1,7,10]**
Heat transfer coefficient (W/meter.K)	30	30	30	**[7,10]**
Thermal conductivity (W/meter^2.K)	0.55	1.18	2.1	**[1,3,7,10]**
Diameter (meter)	12	12	12	**[3,10]**
Length (meter)	10.5	10.5	10.5	**[3,10]**

Three different heat-sensitive heat storage materials (rock, brick, and feolite) having the same dimension are to be selected for the analysis of temperature variation along the length through abacus software. Through Abacus simulation, we have analysed NT11 (nodal temperature), GRADT (gradient), HFL (heat flux vector), and RFL11 (reaction fluxes) with respect to individual materials assigned parameters. With reference to the block strip, the formula of overall heat accumulation through the cylinder due to conduction and convection

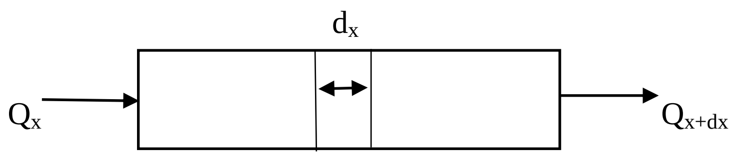

Fig. 5 Elementary strip from cylindrical shape

In case of conduction through cylinder

Heat flux in

$$Q_x = -k.A\left(\frac{dT}{dx}\right)_x \dots\dots\dots\dots\dots\dots\dots\dots.(A)$$

Heat flux out

$$Q_{x+dx} = -k.A\left(\frac{dT}{dx}\right)_{x+dx} \dots\dots\dots\dots\dots\dots\dots(B)$$

In case of convection through cylinder

$$Q_c = h.P.(T - T_\infty)\dots\dots\dots\dots\dots\dots.(C)$$

Total Heat accumulation through cylinder =Total Heat transfer through conduction – Total Heat transfer through convection

$$Q_T = k.A\left(\frac{dT}{dx}\right)_x + k.A\left(\frac{dT}{dx}\right)_{x+dx} - h.P.(T - T_\infty)$$

$$\frac{d}{dx}\left(\frac{dT}{dx}\right).k.A - h.P.(T - T_\infty)$$

$$k.A\left(\frac{dT^2}{dx^2}\right) - h.P.(T - T_\infty)$$

$$\left(\frac{dT^2}{dx^2}\right) - \frac{h.P}{k.A}(T - T_\infty)$$

$$The\ ratio\ of\ \frac{h.P}{k.A} = m^2$$

$$m = \sqrt{\frac{h.P}{k.A}}$$

$$\left(\frac{T - T_\infty}{T_b - T_\infty}\right) = \left(\frac{\cos\cosh m(L - x)}{\cosh(mL)}\right)$$

$$T_n = \left(\frac{\cos\cosh m(L - x)}{\cosh(mL)}\right).(T - T_\infty) + T_\infty \dots\dots\dots\dots\dots\dots\dots..(D)$$

P (perimeter)= π.D and A(area)=($\pi.D^2$)/4

N (nodes) = 1,2,3,4……..n

Table 2: m constant value (theoretical)

S.No.	h	p	k	A	h.p	k.A	Sqrt hp/kA	m value
1.	15	0.3297	0.55	0.00865	4.9455	0.004758	32.24153	37.2
2.	20	0.3297	0.55	0.00865	6.594	0.004758	37.22932	37.2
3.	25	0.3297	0.55	0.00865	8.2425	0.004758	41.62364	32.22
4.	25	0.3297	0.55	0.00865	8.2425	0.004758	41.62364	32.22
5.	25	0.3297	0.55	0.00865	8.2425	0.004758	41.62364	41.59
6.	25	0.3297	0.55	0.00865	8.2425	0.004758	41.62364	32.22
7.	20	0.3297	0.55	0.00865	6.594	0.004758	37.22932	41.59
8.	25	0.3297	0.55	0.00865	8.2425	0.004758	41.62364	37.2
9.	15	0.3297	0.55	0.00865	4.9455	0.004758	32.24153	32.22
10.	25	0.3297	0.55	0.00865	8.2425	0.004758	41.62364	41.59
11.	15	0.3297	0.55	0.00865	4.9455	0.004758	32.24153	41.59
12.	20	0.3297	0.55	0.00865	6.594	0.004758	37.22932	32.22
13.	20	0.3297	0.55	0.00865	6.594	0.004758	37.22932	41.59
14.	15	0.3297	0.55	0.00865	4.9455	0.004758	32.24153	41.59
15.	15	0.3297	0.55	0.00865	4.9455	0.004758	32.24153	37.2
16.	20	0.3297	0.55	0.00865	6.594	0.004758	37.22932	41.59
17.	20	0.3297	0.55	0.00865	6.594	0.004758	37.22932	37.2
18.	25	0.3297	0.55	0.00865	8.2425	0.004758	41.62364	32.22
19.	20	0.3297	0.55	0.00865	6.594	0.004758	37.22932	41.59
20.	15	0.3297	0.55	0.00865	4.9455	0.004758	32.24153	32.22
21.	20	0.3297	0.55	0.00865	6.594	0.004758	37.22932	41.59
22.	2	0.329	0.5	0.0086	6.594	0.00475	37.2293	37.2

	0	7	5	5		8	2	
23.	15	0.3297	0.55	0.00865	4.9455	0.004758	32.24153	32.22
24.	15	0.3297	0.55	0.00865	4.9455	0.004758	32.24153	37.2
25.	25	0.3297	0.55	0.00865	8.2425	0.004758	41.62364	37.2
26.	15	0.3297	0.55	0.00865	4.9455	0.004758	32.24153	37.2
27.	25	0.3297	0.55	0.00865	8.2425	0.004758	41.62364	32.22

Table 3: Theoretical values of temperature for different SHSM

Sr. No.	Variation in length	Rock	Brick	Feolite
1.	0	500	500	500
2.	0.021	362.154	379.616	395.132
3.	0.042	246.789	275.14	302.571
4.	0.063	162.059	195.005	229.046
5.	0.084	107.0142	138.556	174.846
6.	0.105	49.494	75.234	111.103

The values of different SHSM (rock, brick, and feolite) temperatures have to be calculated by using the equation (D) on the basis of the following parameters, which were carried out from Table 1.

C. Comparison of three different Sensible heat storage materials (SHSM):

In this study, three different heat storage materials, rock, brick, and feolite, are analysed using Abacus software to find out the result for the variation in temperature with respect to different parameters such as heat transfer coefficient, thermal conductivity of different materials, heat transfer coefficient, and base temperature of heat storage materials. In a simulation study, the effects of nodal temperature, heat flux, reaction fluxes, and gradient are going to be clear through the images. Dynamic simulation then makes it possible to calculate the temperature profiles of the fluid and solid as a function of time and the efficiency of the thermal reservoir, which is determined by the energy removed from the solid at the breakthrough time during discharge [8]. The application space of energy storage grows very quickly across the entire grid, from generation, transmission, distribution, and load. Tools are also required to analyse ESSs' interoperability across different spaces (e.g., ESSs that are in distribution systems but provide transmission services) [9]. Earlier studies on the properties of solid materials that have been considered for sensible heat storage systems Also, an assessment of different experimental techniques for determining the thermal properties of samples of solid materials is covered in terms of operational principles and their main characteristics [18]. For the analysis through Abaqus software, three different sensible heat storage materials have to be considered, which have different thermal conductivities and the same dimension. It is analysed through software with respect to the following input parameters:

Table 4: Input common parameters for the analysis through the software [1,3,7,10]

Sr. No.	Name of Input parameters	Values	Units
1.	Heat transfer coefficient	30	$W/m^2.k$
2.	Base temperature ($T_{b)}$	500	^0C
3.	Ambient temperature	30	^0C
4.	Diameter	0.12	meter
5.	Length	0.105	meter

All the listed parameters have to be selected for parametric analysis as well as optimisation, and these various parameters are selected from various research papers, the details are mentioned in Table 1.

Simulation Modelling of Sensible Heat Storage Materials

Heat transfer analysis for temperature variation through Abaqus software for rock material

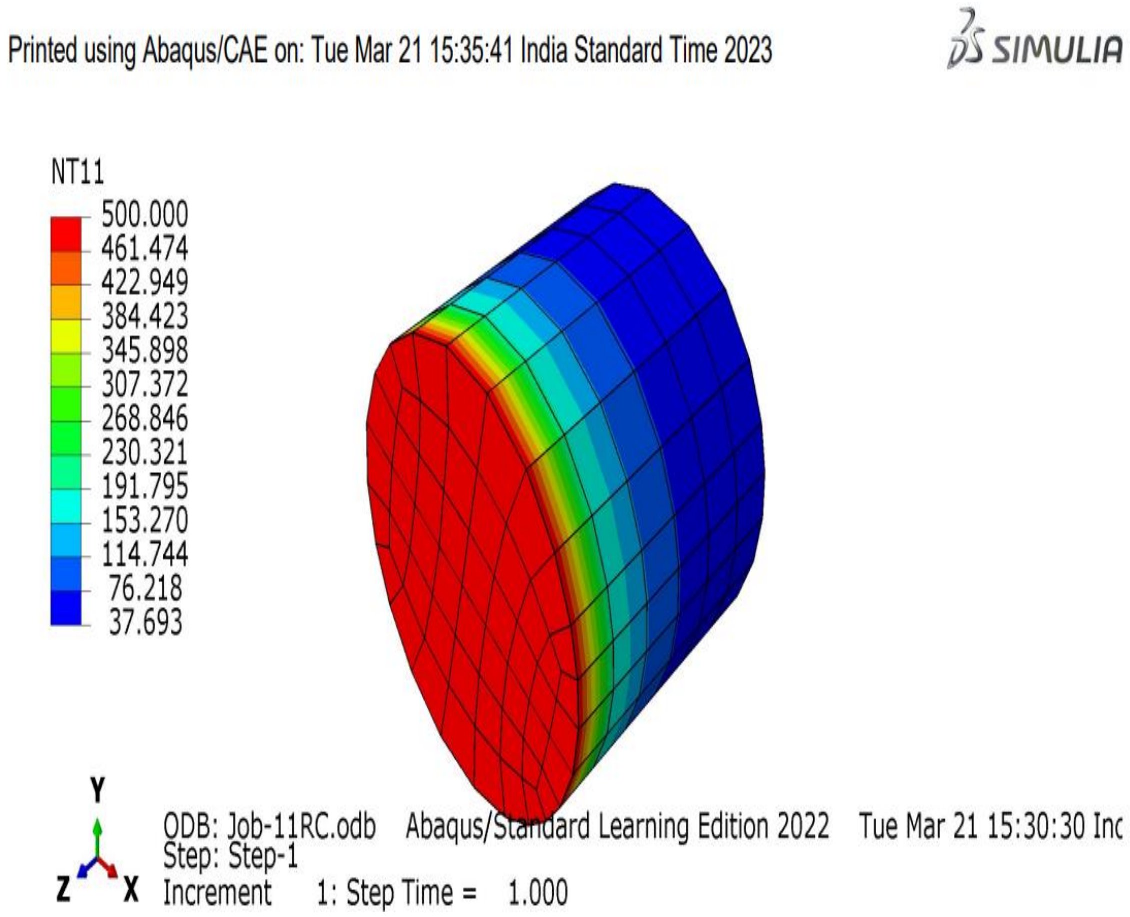

Fig. 6 Simulation of Rock Material

Heat transfer analysis for temperature variation through Abaqus software for brick material

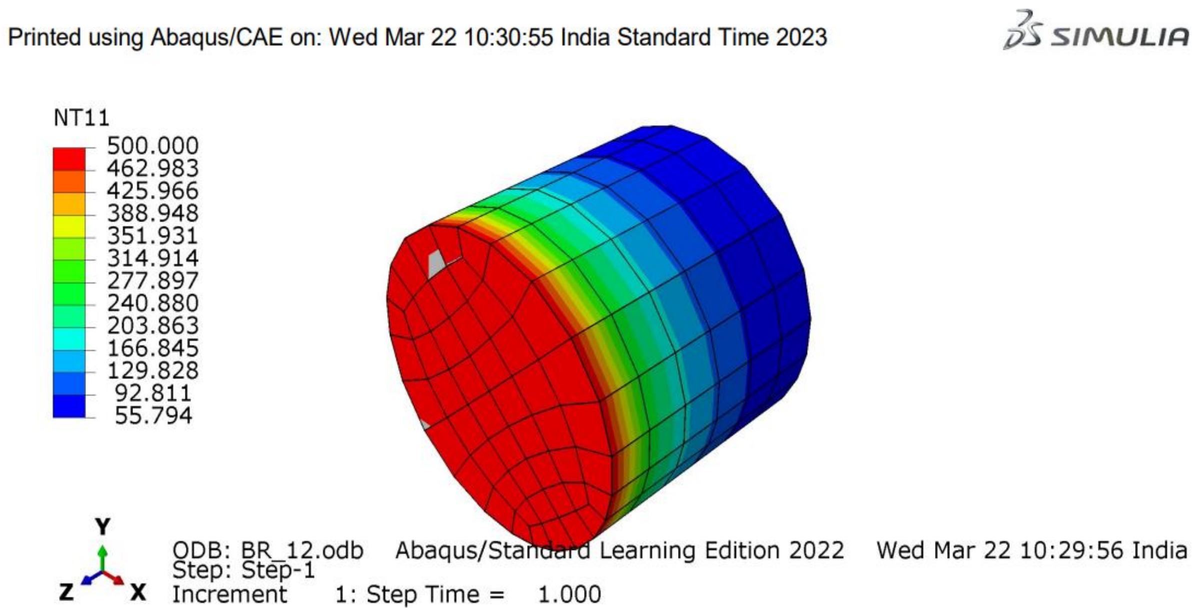

Fig. 7 Simulation of Brick Material

Heat transfer analysis for temperature variation through Abaqus software for feolite material

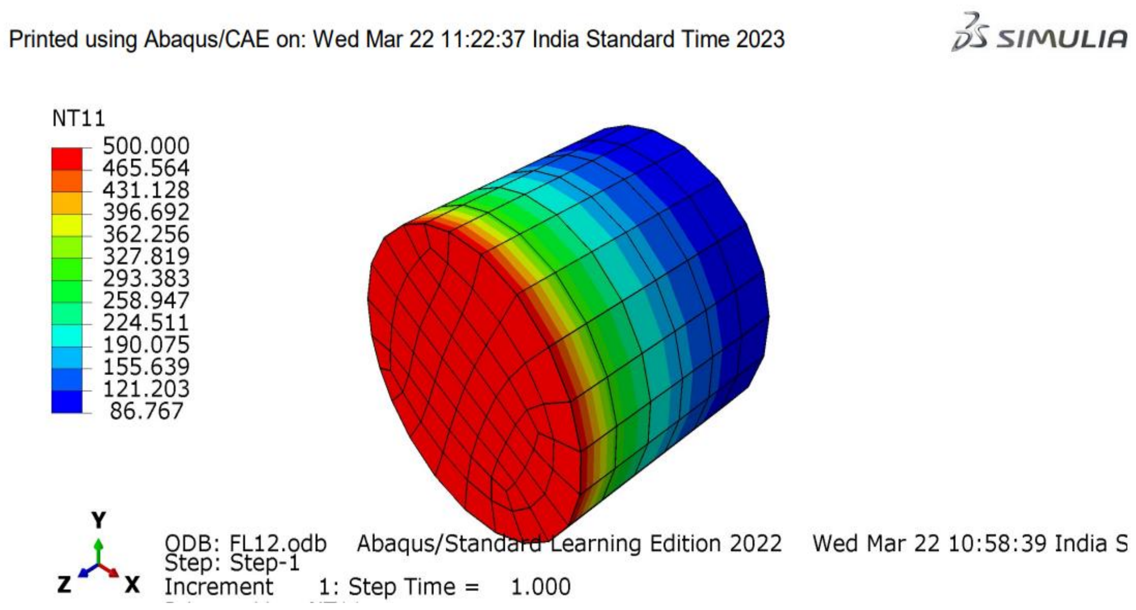

Fig. 8 Simulation of Feolite Material

D. Optimisation by using a full factorial DOE (Design of Experiment)

The factororial design technique was suggested by Fisher in 1926. It is used as an optimisation technique. In this experiment, the design consists of two or more factors, each with different possible values or levels. Factorial design is basically divided into two types: full factorial design and fractional factorial design. In this research paper, I have used or applied a full factorial design. Full factorial design, in which every setting of each factor appears with the setting of every other factor, is full factorial design. Number of runs: $N=y^x$.

Factorial design is employed to achieve the best overall optimisation of a process [11, 12]. The design determines the effect of each factor on the response as well as how the effect of each factor varies with the change in level of the other factors [13]. Interaction effects of different factors could be attained using the design of experiments alone [11, 12]. This technique was used to reduce the number of experiments, time, and overall process cost and to obtain a better response. The advantages of factorial designs over one-factor-at-a-time experiments are that they are more efficient and allow interactions to be detected [14]. The studies using experimental designs showed the relevance of this methodology [15, 16].

Table 5: Formula used for S/N Ratio and VIF (Minitab Help)

S/N Ratio	Formula
Smaller is Better	$\left[\frac{S}{N} = -10 \log \log \left[\frac{1}{n} \sum Y^2\right]\right]$
VIF	$VIF = \frac{1}{1 - R^2}$

Where n is the number of observations made through simulation, Y is the simulated value of response, and I is the number of repetitions of simulation; for this study, it is equal to one for all cases. The contributions of each input parameter are measured by "Analysis of Variance" (ANOVA) for optimum results. ANOVA helps to find errors in results gathered from simulation or experimental data.

Table 6: Input Data for Full Factorial Analysis

No.	Factors	Unit	Level-I	Level-II	Level-III
1.	Heat transfer coefficient	W/m^2K	15	20	25
2.	Thermal conductivity	W/mk	0.55	1.18	2.1
3.	Dimeter	m	0.105	0.115	0.125

Control factors and their levels selected for the present study are listed in Table 1. As seen in the table, total of three factors are selected, having three levels each. The factors and levels are selected as per previous studies published by various researchers [1, 3, 7, 10]. After studying all these research papers, the final factors and levels are selected, so proper analysis for the optimisation study can be performed for SHSM.

In the ANOVA table, the sum of squares, mean of squares, variance, contributions, and F-factor are the key indicators that help to find errors and perform better optimisations. All formulas required for ANOVA table generation are listed in Table 6 [26].

Table 7: Formula used for ANOVA

Description	Formula	-
Sum of Square (SS-mean)	$SS = n(x_1 - \underline{m})^2 + n(x_2 - \underline{m})^2 + n(x_3 - \underline{m})^2$	Where n total trials of experiment/simulation, x represent mean S/N ratio values, m is mean of all S/N ratio
Sum of Square (SS-total)	$SS_{total=\sum_{n=1}^{n=27}(x_i-\omega)^2}$	Where $\underline{\omega}$ is total mean of all experiment trials
Sum of Square (SS-Error)	$SS_{error} = SS_{total} - SS_{mean}$	-
Degree of Freedom	$DOF = Level - 1$	Where DOF is degree of Freedom
Variance/MS (Mean Square)	$Variance = \frac{SS_{error}}{DOF}$	-
F-Ratio	$F - Ratio = \frac{MS_{factor}}{MS_{error}}$	-
T-value	$T - Ratio = \frac{Coeff.}{SE\ Coeff.}$	Where SE is Standard Error.
% of Contribution	$\frac{SS_{mean}}{SS_{Total}} X100$	-
VIF (Variance Inflation factor)		

Design Table (randomized)
Number of runs (N)
$N=y^x$…………………………………….**(E)**
Where, y= number of levels, x= number of factors
In our research paper there is y=3 and x= 3
Total number of runs N= 3^3= 27

Table 8: Total Number of Runs (3^3)

Run	Blk	HTC	TC	D
1	1	15	0.55	0.115
2	1	15	1.18	0.115
3	1	20	2.1	0.105
4	1	20	1.18	0.115
5	1	20	0.55	0.105
6	1	25	0.55	0.125
7	1	20	0.55	0.115
8	1	20	0.55	0.125
9	1	15	2.1	0.115
10	1	15	2.1	0.105
11	1	15	1.18	0.105

12	1	25	1.18	0.115
13	1	20	2.1	0.115
14	1	15	0.55	0.105
15	1	20	2.1	0.125
16	1	15	2.1	0.125
17	1	25	1.18	0.105
18	1	25	2.1	0.105
19	1	25	2.1	0.125
20	1	15	0.55	0.125
21	1	25	2.1	0.115
22	1	25	1.18	0.125
23	1	20	1.18	0.125
24	1	25	0.55	0.115
25	1	15	1.18	0.125
26	1	20	1.18	0.105
27	1	25	0.55	0.105

Table 9: ‘m’ constant value of cylindrical shape with respect of variables

Run	Blk	HTC	TC	D	m
1	1	15	0.55	0.115	21.77862
2	1	15	1.18	0.115	14.86862
3	1	20	2.1	0.105	13.4687
4	1	20	1.18	0.115	17.16881
5	1	20	0.55	0.105	26.31807
6	1	25	0.55	0.125	26.96799
7	1	20	0.55	0.115	25.14778
8	1	20	0.55	0.125	24.12091
9	1	15	2.1	0.115	11.14556
10	1	15	2.1	0.105	11.66424
11	1	15	1.18	0.105	15.56055
12	1	25	1.18	0.115	19.19531
13	1	20	2.1	0.115	12.86979
14	1	15	0.55	0.105	22.79212
15	1	20	2.1	0.125	12.34427
16	1	15	2.1	0.125	10.69045
17	1	25	1.18	0.105	20.08859
18	1	25	2.1	0.105	15.05847
19	1	25	2.1	0.125	13.80131
20	1	15	0.55	0.125	20.88932
21	1	25	2.1	0.115	14.38886
22	1	25	1.18	0.125	18.41149
23	1	20	1.18	0.125	16.46774
24	1	25	0.55	0.115	28.11608
25	1	15	1.18	0.125	14.26148
26	1	20	1.18	0.105	17.96778
27	1	25	0.55	0.105	29.42449

The value of m (constant), which depends upon the value of heat transfer coefficient, thermal conductivity of material, and diameter of sensible heat storage material shape, is calculated for the different runs by using a formula. With respect to different runs (N = 27), there are a total of 27 values of m (constant).

Table 10: Coefficients

Term	**Coef**	**SE Coef**	**T-Value**	**P-Value**	**VIF**
Constant	18.332	0.125	146.58	0.000	
heat transfer coefficient					
15	-2.371	0.177	-13.41	0.000	1.33
20	0.098	0.177	0.55	0.586	1.33
Thermal conductivity					
0.55	6.729	0.177	38.04	0.000	1.33
1.18	-1.222	0.177	-6.91	0.000	1.33
Diameter					
0.105	0.817	0.177	4.62	0.000	1.33
0.115	-0.035	0.177	-0.20	0.846	1.33

A regression coefficient describes the size and direction of the relationship between a predictor and the response variable. Coefficients are the numbers by which the values of the terms are multiplied in a regression equation. The standard error of the coefficient estimates the variability between coefficient estimates that you would obtain if you took samples from the same population again and again. The calculation assumes that the sample size and the coefficients to estimate would remain the same if you sampled again and again. The T-value measures the ratio between the coefficient and its standard error. The p-value is a probability that measures the evidence against the null hypothesis. Lower probabilities provide stronger evidence against the null hypothesis. The variance inflation factor (VIF) indicates how much the variance of a coefficient is inflated due to the correlations among the predictors in the model [13].

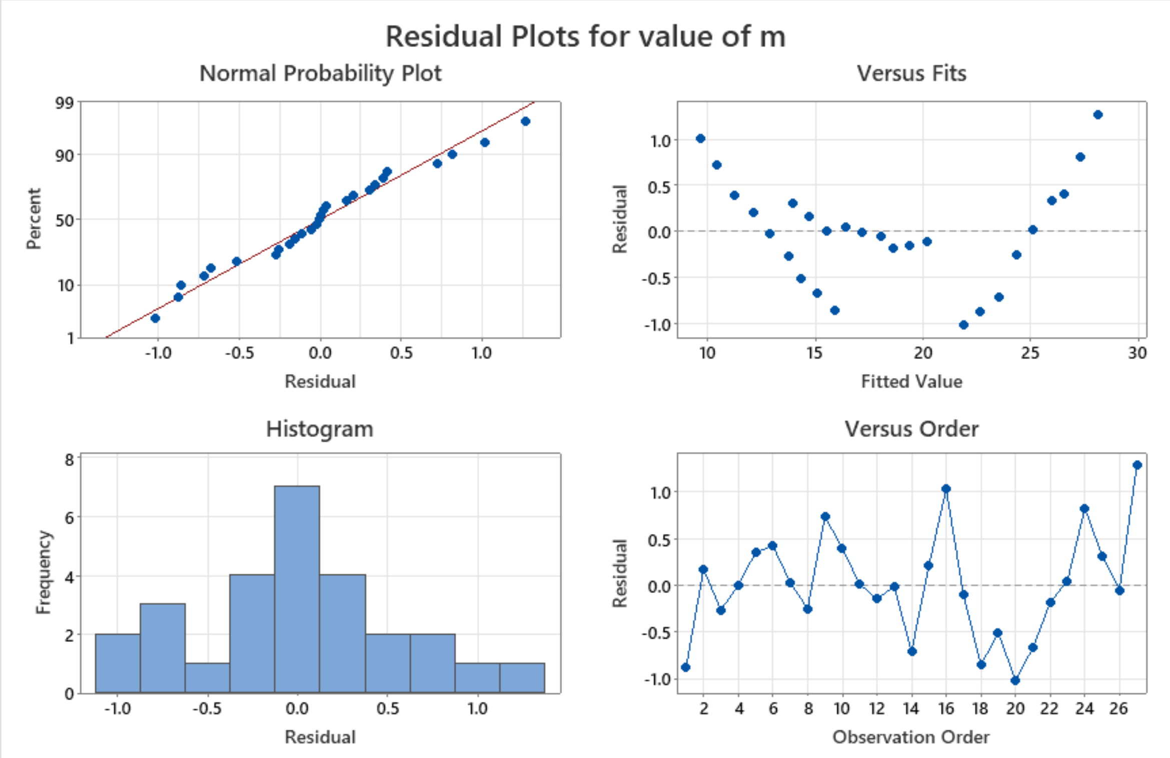

Fig. 9 Residuals plots for constant m

E. Result and discussion

In this research paper, the results of different sensible heat storage methods are evaluated in two parts, which were also highlighted in a graphical abstract. In the first part, the parametric analysis is conducted on different sensible heat storage materials and finds out the variation of temperature along the length of the same-size specimen at the different nodes through the simulation process as well as theoretically.

Table 11: Temperature Variation Table along the length for rock (SHSM)

Sr. No.	length variation	Temperature of Rock (Analytical value)	Temperature of Rock (Theoretical value)
1.	0	500	500
2.	0.021	362.154	222.085
3.	0.042	246.789	108.756
4.	0.063	162.059	62.909
5.	0.084	107.0142	45.258
6.	0.105	49.494	40.682

Table 12: Temperature Variation Table along the length for brick (SHSM)

	length variation	Temperature of Brick (Analytical value)	Temperature of Brick (Theoretical value)
1.	0	500	500
2.	0.021	379.616	286.390
3.	0.042	275.140	171.610
4.	0.063	195.005	111.430
5.	0.084	138.556	82.635
6.	0.105	75.234	74.129

Table 13: Temperature variation Table along the length for feolite (SHSM)

Sr. No.	length variation	Temperature of Feolite (Analytical value)	Temperature of Feolite (Theoretical value)
1.	0	500	500
2.	0.021	395.132	331.7489
3.	0.042	302.571	227.971
4.	0.063	229.046	166.4927
5.	0.084	174.846	134.1781
6.	0.105	111.103	124.1227

From the analysis of different types of sensible heat storage materials in phase one, the theoretical and analytical data are compared, and the temperature variations are 8.812^{0}C, 1.105^{0}C and 13.0197^{0}C respectively, for rock, brick, and feolite. The variation of temperature along the length of individual sensible heat storage materials is represented in graphs. Through this analysis, we are finding the variation in temperature of different materials along their length. Also analysing the combined effect of all selected materials in this research paper. Individually, the temperature variation on another end for rock, brick, and feolite is 49.494 ^{0}C, 75.234 ^{0}C and 11.103 ^{0}C respectively, for analytical analysis. Individual temperature variations for brick, rock, and feolite are 40.682 ^{0}C, 74.129 ^{0}C and 124.123 ^{0}C respectively, for theoretical analysis. By comparison of both the result the variation of temperature at the other end is 8.812 ^{0}C,1.105 ^{0}C and 13.02 ^{0}C respectively for rock, brick and feolite sensible heat storage materials.

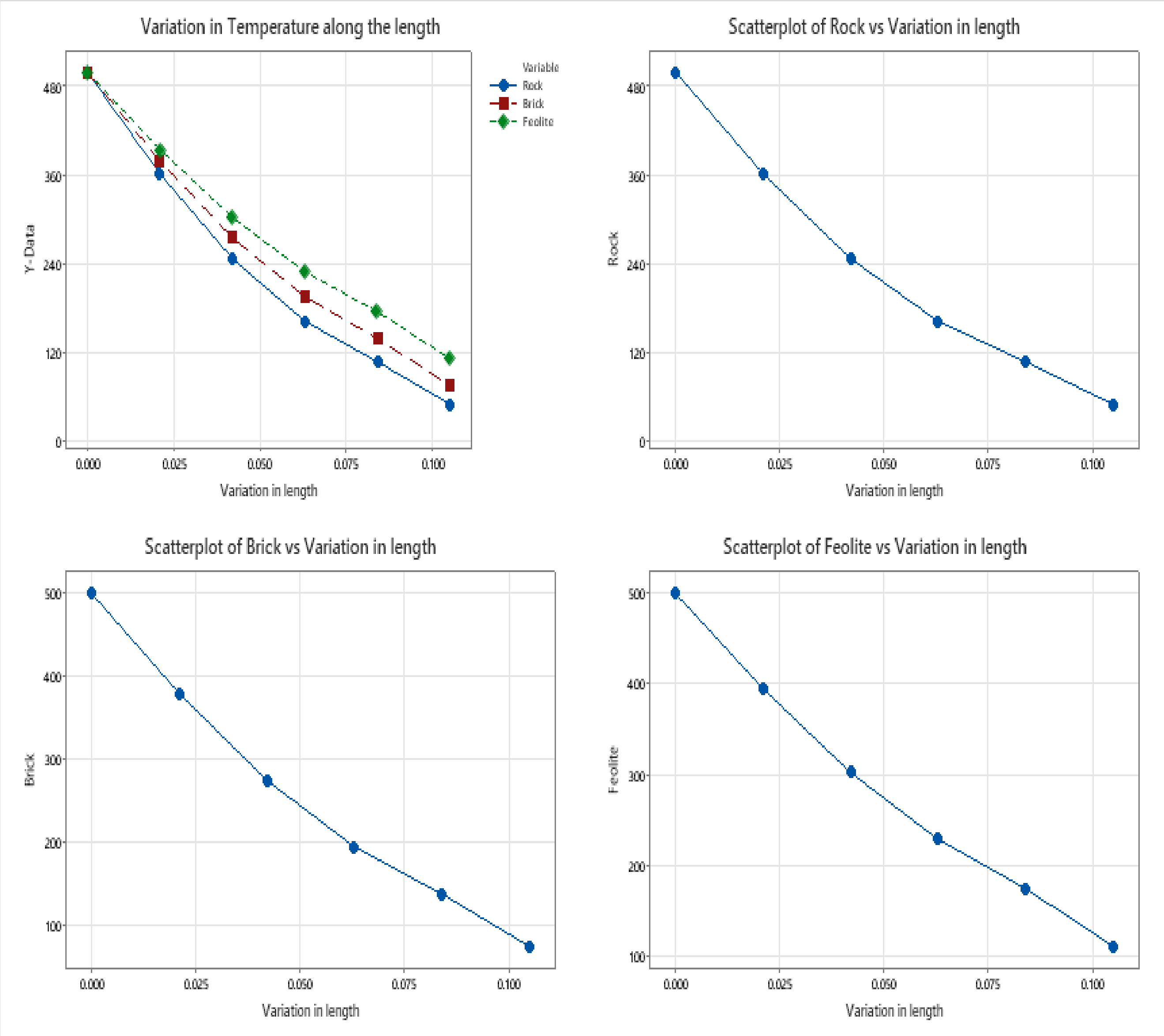

Fig. 10 Variation of Temperature along the length

Three factors have been considered for the study of ‘m’ constant value, which are the following: (a) heat transfer coefficient (HT), (b) thermal conductivity of SHSM (TC), and (c) diameter of SHSM. All three control parameters and their levels are shown in Table 6. Total trial Runs for this research study have been generated with the help of eq. (E), and a total of 27 runs have come out as the best, which is listed in table 8. This arrangement of factors and levels is the same for all three response parameters selected for study. After generation of the orthogonal array, for the ‘m’ constant value, simulation will be conducted with the help of a relation. For the complete simulation, the values are taken from Table 6. S/N ratio calculations for the ‘m’ constant value are done by using the equation presented in Table 5. Smaller is the best option selected for the 'm' constant value. Signal to Noise ratio of the value of ‘m’ is shown in Table 15. Three factors have been selected for the study of the 'm’ constant value.

In a second phase, optimisation results are collected using the full factorial optimisation technique. From the coefficient table for the fit regression model, the value of VIF is analysed, through which it is going to be clear that the values of heat transfer coefficient, thermal conductivity, and diameter of sensible heat storage materials are moderately correlated. In the case of all considerable parameters, the value of VIF is greater than one and less than 5. So, we can say that the value of m constant is moderately correlated with the values of heat transfer coefficient, thermal conductivity, and diameter. Through the analysis of variance, it is going to be clear that the parameters that we selected for full factorial optimisation are significant (S).

Table 14: Mean signal-to-noise ratio for the "m" constant value

Run	Blk	HTC	TC	D	m	S/N
1	1	15	055	0.115	21.77862	31.41086
2	1	15	1.18	0.115	14.86862	31.41086
3	1	20	2.1	0.105	13.4687	30.16251
4	1	20	1.18	0.115	17.16881	30.16251
5	1	20	0.55	0.105	26.31807	32.37978
6	1	25	0.55	0.125	26.96799	30.16251
7	1	20	0.55	0.115	25.14778	32.37978
8	1	20	0.55	0.125	24.12091	31.41086
9	1	15	2.1	0.115	11.14556	30.16251
10	1	15	2.1	0.105	11.66424	32.37978
11	1	15	1.18	0.105	15.56055	32.37978
12	1	25	1.18	0.115	19.19531	30.16251
13	1	20	2.1	0.115	12.86979	32.37978
14	1	15	0.55	0.105	22.79212	32.37978
15	1	20	2.1	0.125	12.34427	31.41086
16	1	15	2.1	0.125	10.69045	32.37978
17	1	25	1.18	0.105	20.08859	31.41086
18	1	25	2.1	0.105	15.05847	30.16251
19	1	25	2.1	0.125	13.80131	32.37978
20	1	15	0.55	0.125	20.88932	30.16251
21	1	25	2.1	0.115	14.38886	32.37978
22	1	25	1.18	0.125	18.41149	31.41086
23	1	20	1.18	0.125	16.46774	30.16251
24	1	25	0.55	0.115	28.11608	31.41086
25	1	15	1.18	0.125	14.26148	31.41086
26	1	20	1.18	0.105	17.96778	31.41086
27	1	25	0.55	0.105	29.42449	30.16251

Optimization

The goal is highlighted in Table 15. In Table 14, the maximum and minimum values of the 'm' constant are 29.42449 and 10.69, respectively.

Table 15: Objective goals required for CD function optimisation

Objective goals required for CD function optimisation			
Parameter	Desirable	Upper	Lower
'm' constant value	Minimize	5	25

Table 16: Discussion of Analysis of Variance (ANOVA)

Source	DOF	SS	Contribution	MS	F value	P value	S/NS
Regression	06	802.633	98.99%	133.772	316.73	0.000	S
HTC	2	97.206	12.11%	48.603	115.08	0.000	S
TC	2	693.910	86.45%	346.955	821.49	0.000	S
D	2	11.517	1.43%	5.759	13.63	0.000	S
Error	20	8.447	1.04%	0.422			
Total	26	811.080	100%				

This analysis of variance (ANOVA) may be used to determine the significance (S) or nonsignificance (NS) of different parameters. From Table 15, the parameters are significant, and the contribution of individual parameters is also shown. The maximum contribution is 86.45% of thermal conductivity, second is heat transfer coefficient, which is 12.11%; and the third is SHSM diameter, which is 1.43% in ‘m’ constant value.

Table 17: Coefficients Table for the Fit Regression Model

Term	Coef	SE Coef	T-Value	P-Value	VIF	NC/MC/HC
Constant	18.332	0.125	146.58	0.000		-
heat transfer coefficient						
15	-2.371	0.177	-13.41	0.000	1.33	MC
20	0.098	0.177	0.55	0.586	1.33	MC
Thermal conductivity						-
0.55	6.729	0.177	38.04	0.000	1.33	MC
1.18	-1.222	0.177	-6.91	0.000	1.33	MC
Diameter						
0.105	0.817	0.177	4.62	0.000	1.33	MC
0.115	-0.035	0.177	-0.20	0.846	1.33	MC

From the table, we find that the values of HTC, TC, and D are correlated, moderately correlated, and highly correlated. If the VIF value is equal to 1, the parameter is not correlated; if the value of VIF is greater than 1 and less than 5, it is moderately correlated. The value of VIF is more than 5; the value is highly correlated. From the table, all the selected parameters for the value of ‘m’ constant are moderately correlated.

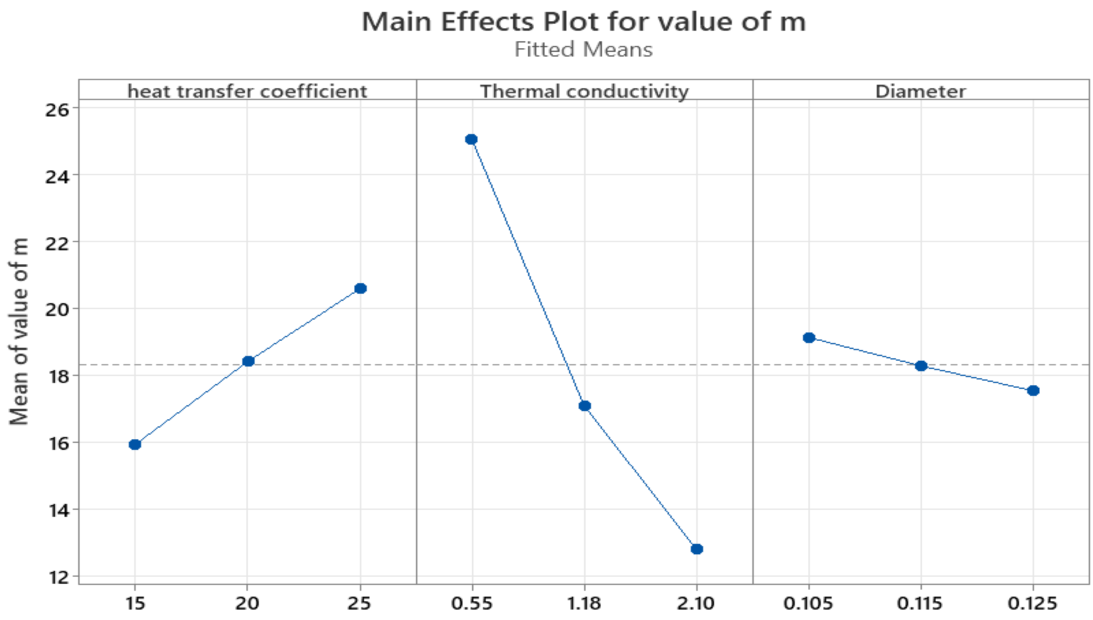

Fig.11 Main effects plot for mean S/N ratio of Temperature

In Fig. 11, the plots show the variation of heat transfer coefficient (HTC), thermal conductivity (TC), and diameter (D) with respect to the mean value of the "m" constant.

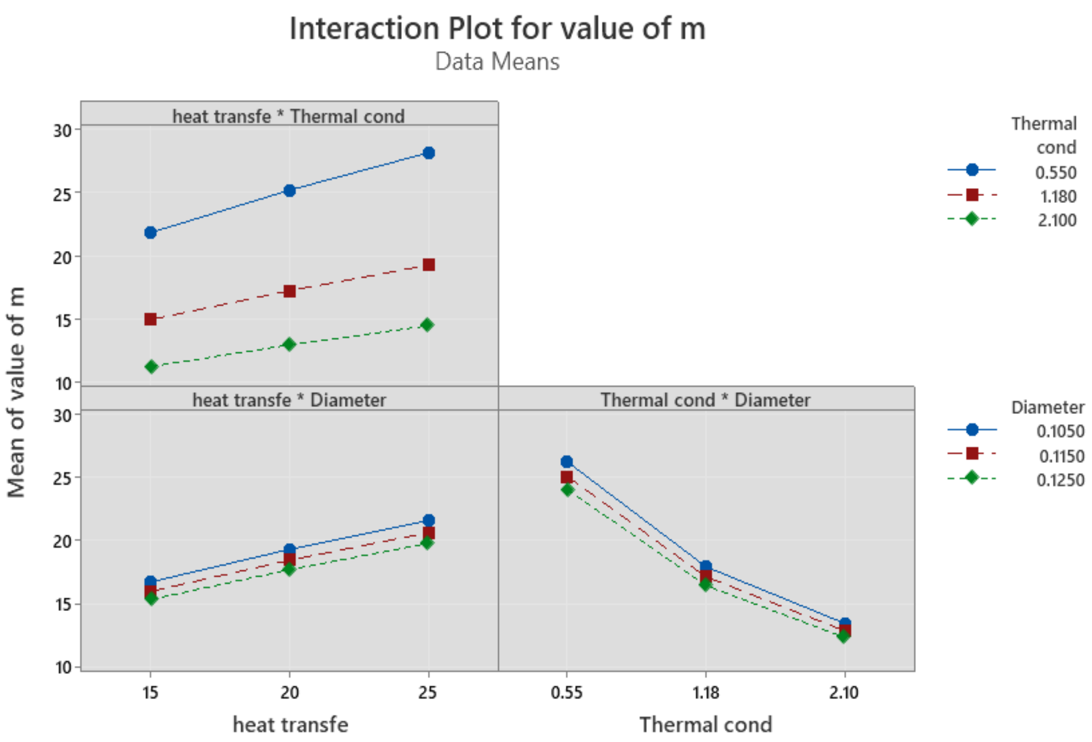

Fig.12 Main Interaction effects plot for the value of ‘m’ constant

F. Conclusion:

In the first phase analysis, it is going to be concluded during the selection of sensible heat storage materials for packed bed heat storage systems. We can make a selection based on this analysis. This analysis is helping to find out the parameters through which the temperature can be controlled at the desired level. This analysis is also helpful to find out the best sensible heat storage material for the sensible heat-based packed bed storage system.

In the second phase analysis of this research paper, various parameters that directly or indirectly affect the temperature variation along the length of different sensible heat storage materials are also optimised by using full factorial analysis to determine which parameters are correlated or not. Also helpful is finding out the relation and the contribution percentage of all relevant parameters in a variation in a value of 'm' constant. The value of the 'm' constant directly affects the variation of temperature in sensible heat storage materials.

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