

Investigation of the Flowability and the Thermal Behavior of Sand /Basalt-Mixture in Moving Bed Heat Exchanger (MBHX) as Heat Transfer Medium for Concentrating Solar Tower Plants

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Abstract

The present study investigates experimentally heat recovery from particle-based Thermal Energy Storage (TES) by using different bulk material (Sand, Basalt, and Mixture). A newly developed Moving Bed Heat Exchanger (MBHX) was used for this purpose. The present work focuses on solar thermal power plants applications to find economic and efficient heat transfer and heat storage medium. In the experimental investigations, the performance assessment of a prototype was carried out with a detailed look on the granular flow behavior as well as its overall thermal efficiency. The tested heat transfer mediums are only Sand, only Basalt and a Sand/Basalt mixture. The results showed that the mixture has best thermal performance among other tested materials within the heat exchanger. The effectiveness of the MBHX and the overall heat transfer coefficients of the heat exchanger are measured and documented. The test results showed that the MBHX effectiveness was improved when using the Sand/Basalt mixture by 45.5% and 33.3% than using only Sand and Basalt as heat transfer fluid, respectively. Moreover, the powder flow test results show that the mixture has a better flowability than having only Sand or Basalt.

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Keywords: Thermal Energy Storage (TES), Moving Bed Heat Exchanger (MBHX), Effectiveness.

Nomenclature

A_s	Surface area	m^2
c	heat capacity ratio	-
c_p	specific heat capacity	J/kg.K
D_i	inner diameter of tube	m
D_o	outer diameter of tube	m
h	convection heat transfer coefficient	W/m ² .K
h_i	inner convection heat transfer coefficient	W/m ² .K
h_o	outer convection heat transfer coefficient	W/m ² .K
K	thermal conductivity	W/m.K
L	length of tube	m
N	number of tube bundles in the MBHX	-
Pr	Prandlt number	-
Q	rate of heat transfer	W
St_h	horizontal distance	mm
St_v	vertical distance	mm
T	Temperature	K
t_c	contact time	S
V	Velocity	m/s
ϵ	effectiveness of heat exchanger	-

1. Introduction

Concentrating Solar Power technologies (CSP) have a considerable potential for implementation in sunny regions and have relatively good conversion efficiency from solar radiation to electrical energy. CSP technologies generate electricity by concentrating the direct solar radiation on to a small absorber area, where a Heat Transfer Fluid (HTF) is heated up and this energy is ultimately transferred to the steam. Electricity is then generated by an electric generator, which is driven by a steam turbine with the efficiency limited by the Carnot cycle.

The ease of integration Thermal Energy Storage (TES) [1; 2] makes Concentrating Solar Power (CSP) dispatchable and unique among all other renewable energy-generating alternatives. A TES system that offers efficient heat energy storage can be considered an important intermediate step for on-demand electricity generation. Depending on the size of the TES system, it is able to mitigate the short load fluctuations and shift or

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extend the energy supply. Thermal Energy Storage (TES) is one of the few energy storage technologies that have proven to be an economically feasible large-scale storage solution. Thermal Energy Storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used later for heating and cooling applications and power generation.

CSP with TES presents advantages if it supplies electricity at times of greatest need, which generally has the highest electricity tariff [3; 4]. Furthermore, TES is a key technology for solar thermal energy utilization and the improvement of the cycle operation efficiency. Using an energy storage system in a solar thermal power plant has many advantages, such as obtaining higher annual solar contribution, reduction of part-load operation, power management and buffer storage to improve the plant dispatchability [5]. Three fundamental types of thermal energy storage processes are commonly presented in the literature; sensible, latent, and thermochemical. Many different mediums are available within each type. With sensible heat storage, energy is stored by changing the temperature of a material. Most sensible heat systems employ water, rocks earth, or ceramic bricks as the thermal storage material and water, air, or possibly oil as the heat transfer fluid. Sand is among the most promising materials that could be used for sensible energy storage. It has been very attractive recently for its availability and low cost [6; 7].

Thermal Energy Storage (TES) based on a flowable granular material made of ceramics or natural stones allows for a load following operation of a central receiver

solar power plant at high process temperatures ($> 600^{\circ}\text{C}$). In such a system, the granular mass is used both as heat transfer and storage medium in a closed cycle. The particles can be heated either directly (see Fig. 1) in a direct absorption receiver [8] or indirectly by air coming from a volumetric air receiver [9]. Such a system depends on a heat exchanger to generate steam from a solar heated particle stream. The Moving Bed Heat Exchanger (MBHX) is a promising technology option for this component. MBHX offers low parasitic loads, a good part load behavior, a little need for maintenance, a compact design and low financial investment and operation expenses [10]. The purpose of the present paper is to evaluate the performance of moving bed heat exchanger (MBHX) with innovative solid particles of Sand & Basalt mixture where the particles working as a heat transfer medium and a thermal heat storage. Sand, Basalt and their even mixture (Sand/Basalt) are tested as a heat transfer fluids by using an experimental Moving Bed Heat Exchanger (MBHX) that is developed and tested at the Institute for Thermodynamics of the German Aerospace Center (DLR). The aim of the present research paper is to investigate the flowability and the thermal performance of the three potential HTFs. To achieve this goal, several experiments are conducted: (1) measuring the flowability of the materials, (2) measuring the flow interaction between the material and the designed MBHX using PIV technique, (3) measuring thermal properties of the materials and (4) measuring the thermal performance of the MBHX in real flow case using the selected materials.

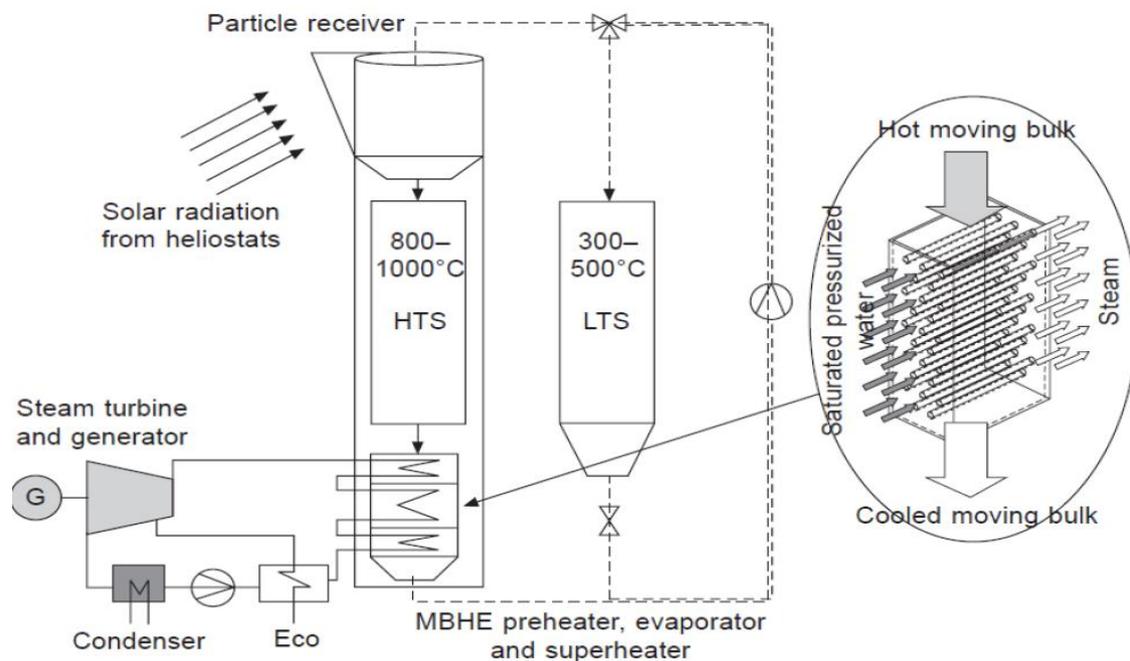


Fig. 1. Central receiver solar power plant with particle storage and integrated moving bed heat exchanger

2. Analysis of Tested Materials and Pre-Experiment

2.1. Rheological Properties

As mentioned earlier, three different material combinations are tested as working fluid in the systems under consideration; only sand, only Basalt and a mixture of 50% Sand and 50% Basalt. At the first stage, the material flow behavior was tested to check its suitability to circulate in the system, in general, and in the heat exchanger in particular. Material with high “flowability” is desired while cohesive material is to be avoided especially when the material flow is driven by gravity, which is the case in the MBHX. The “flowability” of the bulk material inside the MBHX has its direct effect on the heat transfer process between the bulk material and the walls of the tube bundles of the heat exchanger since it controls the speed of the solid material inside the heat exchanger. Thus, it affects the design of the tube bundle distribution in the MBHX.

The rheological properties of bulk material determine its flow behavior. The ring shear cell apparatus, which is known as “Powder Flow Tester”, is used to measure both major principal consolidation and unconfined failure stresses to obtain knowledge about the nature of flowability of the materials. The standard classification of powder flowability uses the flow factor index ffc , as shown below:

- $ffc < 1$ Non flowing
- $1 < ffc < 2$ Very cohesive
- $2 < ffc < 4$ Cohesive
- $4 < ffc < 10$ Easy flowing
- $10 < ffc$ Free flowing

The data obtained are demonstrated in Fig. 2, which classifies the “flowability” of bulk materials. As shown in Fig. 2, Basalt has the lowest “flowability” while Sand and Basalt mixture has the highest “flowability”. Furthermore, according to the flowability classification regions in Fig. 2, Basalt suffers from cohesiveness and thus is not favorable in the MBHX. However, it can be noticed that the presence of Basalt in the sand improves the flowability of the sand. Whereas, sand and Mixture flowability lies in a sector where $ffc > 10$, the flowability of Basalt fluctuates between $ffc = 2$ and $ffc = 4$. Accordingly, Basalt has the least flowability.

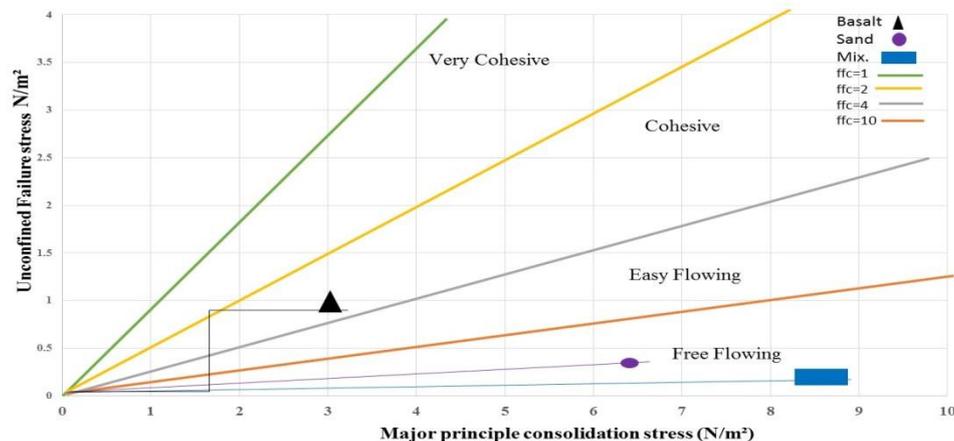


Fig. 2. Powder flow function of Sand, Basalt, and Mixture [12]

2.2. Design Concept of the MBHX

The MBHX conceptual design is based on a heat exchanger with a staggered tube bundle arrangement operated in cross-counter flow configuration. A CSP-adapted design requires a specific tube bundle arrangement, which strongly depends on the rheological properties of promising bulk material. The design procedure is described in [10]. For the thermal characterization experiment, a stainless steel MBHX prototype has been constructed in DLR laboratories, integrated with a fully transparent acrylic glass mock-up for flow investigations. The acrylic glass side is chosen so that PIV measurements can be conducted via this transparent side. A prototype with a certain distribution of tubes was used, as shown in Fig. 3. Baumann *et al.* [10 to 12] used two prototypes of different distribution. The geometric data of the test configurations of mock-ups can be found in Table 1.

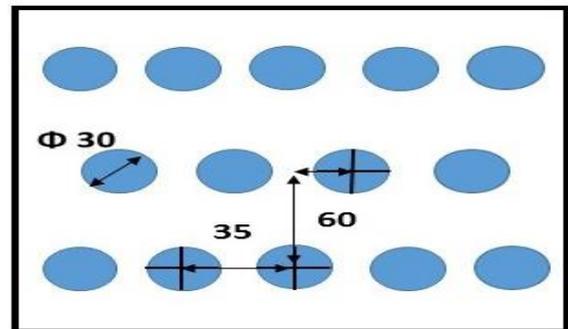


Fig. 3. Configurations of the MBHX tube bundle used in the acrylic glass model for PIV measurements

Table 1. Geometric details of the two designs of MBHX

Experimental purpose (PIV)	Tube bundle
Ro[mm]	30
Number of tubes	45
A [m ²]	-
St,v [mm]	60
St,h [mm]	35

Therein, A is the effective heat transfer area and R_o is outer radius of the tube, S_v and S_h are the vertical and horizontal tube pitch, respectively [10 to 12].

To characterize the flow behavior of the granular medium around the acrylic glass tube bundle, Particle Image Velocity (PIV) is applied. This measurement technique has been successfully applied to granular flows before (e.g., in [10 to 12]). The set-up includes a high-speed camera, a halogen bulb lamp for illumination of the plane of interest and an external computer for data processing. The set-up is illustrated in Fig. 4. Details and specifications of equipment used are available in Reference [10 to 12].

The mock up was filled with sand (Table 2) and the velocity measurement inside the mock-up of tube bundle was conducted using the PIV measurements as shown in Fig. 5. The captured pictures were analyzed by using two software packages (Image J and Matlab). The results are shown in Fig. 6. It was found that the velocity of the particles of sand was 4 mm/s. Fig. 5 and Fig. 6 show the formation of a stagnation area and void zones at the top and at the bottom of each tube, respectively. In the stagnant zone, which often has a triangular-like shape, the particles are almost motionless. The stagnant zone is a

thermally insulating area in comparison to those regions in which particles are flowing. It should be noted that the same experiment was conducted by Baumann *et al.* [11; 12] before and the same phenomena (stagnation zones and voids) was observed.

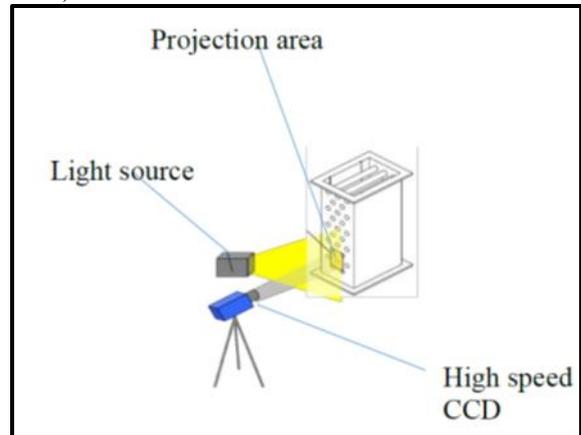


Fig. 4. Simplified representation of the PIV measurement setup

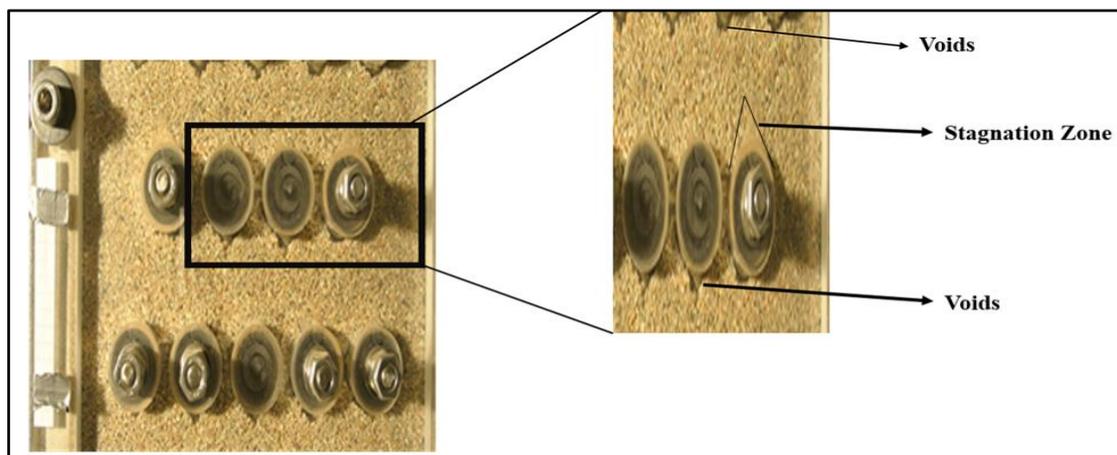


Fig. 5. Stagnation zones and voids at the upper and lower parts of tube

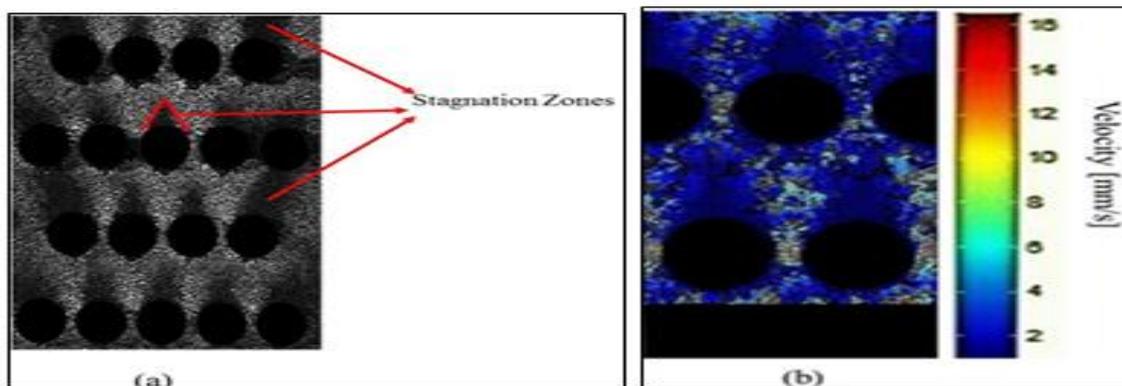


Figure 6. pictures' analysis of the PIV test. (a) Image J analysis. (b) Matlab analysis

The velocity of sand inside the mock-up was measured to be 4mm/s. This reassures the results obtained by Baumann, who investigated the performance of the MBHX by using two different arrangements of the tube bundles. One of these arrangements with $S_h = 40$ mm and the other one with $S_h = 60$ mm, with inlet velocities ranging between 0.3 mm/s – 3mm/s [10 to 12]. Baumann found that the MBHX with a narrower horizontal distance has a higher velocity then the heat transfer process increase according to equations (1) and (2) [12 and 17]. Therefore, in this mock-up, the horizontal distance was decreased by 5mm, as shown in Fig. 3, and the inlet velocity increased to 4 mm/s. These observations indicate that the extension of the stagnant zone is affected by the tube bundle arrangement [10 and 12]. The stagnant zone is a thermally insulating area in comparison to those regions in which particles are flowing [13 to 16].

Table 2. Sand properties

Material	Particles Diameter [mm]	Density [Kg/m ³]	Form factor fp
Sand	0.8± 0.18	1456.8	1.15

$$h_o = \frac{2\sqrt{(Kc\rho p)so}}{\sqrt{\pi}\sqrt{t_c}} \tag{1}$$

$$t_c = \frac{S_R}{v} \tag{2}$$

where, t_c it is the contact time and (h) is the convection heat transfer coefficient. Accordingly, the relationship between (h) and the reciprocal value of (t_c) in the model indicates that, the shorter the contact time the better will be the heat transfer process. Therefore, increasing velocity means that the heat transfer also increases.

3. Thermal performance Experimental Setup

For the thermal performance assessment, a test rig was constructed at the Institute of Technical Thermodynamics at DLR. The test rig consists of a tube chain conveyor, a heated storage bin and a replaceable MBHX test device. Twenty-four heating plates are inserted inside the storage bin. The heating plates inside the storage bin can heat up the bulk up to approximately 500°C depending on the flow rate. The maximum heating power is 38 kW. The centerpiece of the lab is the moving bed heat exchanger. In the MBHX, the hot particles are driven gravitationally through the shell space, while, a cold mineral thermal oil is flowing inside the heat exchanger pipes using a pump, as shown in Fig. 7. The heat is then transferred from the bulk material to the cold fluid. The cooled bed –bulk material- is transported using a conveyor device back into the storage tank where it is heated again.

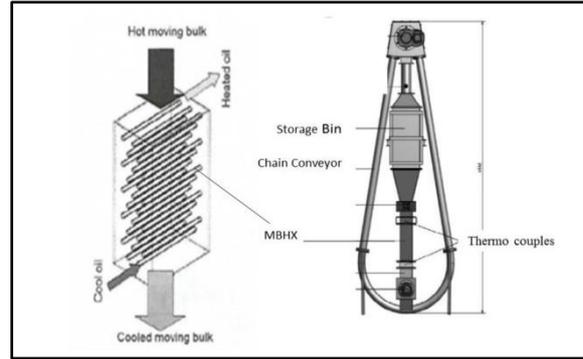


Fig. 7. Components of the Experimental setup and the MBHX [10]

For the thermal characterization experiment, a stainless steel prototype of MBHX has been constructed at the Institute of Technical Thermodynamics at DLR. The geometric properties of the MBHX are listed in Table 3.

Table 3. Geometric properties of the heat exchanger

Parameters	Stainless steel prototype
Outer Diameter [mm]	26.9
Number of Tubes	25
Area [m ²]	0.61
Horizontal distance S_{h} [mm]	23.3
Vertical distance S_{v} [mm]	31.1

3.1. Bulk-Side System Components

In the storage container, 24 electric heating panels are arranged in parallel. The heating plates reach a maximum surface temperature of about 500 °C to heat up the bulk material flowing between the plates. The temperatures of these plates are controlled by controlling the electric power supplied to each plate heater. Depending on the flow rate the outlet temperatures of the bulk material reaches up to about 400 °C. There are 25 thermocouples fixed to measure the temperature of the bulk material before and after crossing the heat exchanger, as shown in Fig. 8. A special feedback control system is designed for this purpose using a software installed on a computer that control the heaters temperature to heat the bulk material to the desired value.

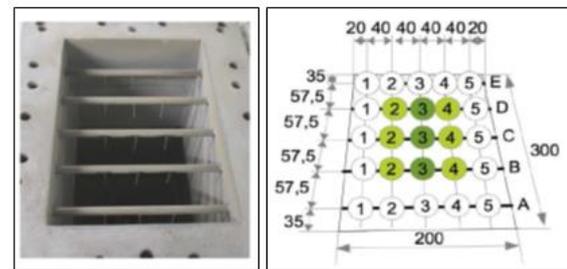


Fig. 8. Grid for thermocouples locations at the inlet and outlet of MBHX shell [10 to 12]

In this experiment, the three different materials of interest are used to evaluate their thermal performance in the MBHX. The physical properties of selected materials used in the experiment are shown in Table 4.

Table 4. Properties of tested materials

Material	Diameter [mm]	Density [kg/m ³]	Form Factor (-)	c _p [kJ/Kg K]	K [w/m k]	Melting point [°C]
Quartz Sand	0.8±0.18	1456.8	1.15	0.83	1.79	1700
Basalt	1.77±0.56	1422	1.21	0.84	2.11	1200
Mix. (Basalt/Sand)	0.6±0.4	1439.4	1.18	0.835	1.95	1450

3.2. Liquid-Side System Components

This side includes all components related to the flowing of the fluid. The working fluid used is the mineral thermal oil "Mobiltherm 603". In unpressurized operation, its operating temperature may reach maximum of 300°C. Compared to water/steam as the working medium, the thermal oil allows single-phase operation and hence easier for energy accounting, simpler for assessment of heat transfer coefficient and the possibility to operate under atmospheric pressure. The thermal oil operates in two cycles: heating by the heat exchanger (by the moving bed), and cooling by an auxiliary external cooler down to 200 °C. At the inlet and outlet of the oil tube, two redundant resistance thermometers are mounted.

4. 4. Results and Analysis

Thermal test was conducted for each of the selected material (Sand, Basalt and Mixture). The rate of heat transfer between the bulk material and oil inside the tubes of the heat exchanger could be found from the equation:

$$\dot{Q} = \dot{m} c_p \Delta T \quad (3)$$

The relation above can be applied to both working mediums: oil or solid particles. The outer surface of the heat exchanger is perfectly insulated. Therefore, the thermal losses to the surrounding are negligible (approx. 1%) [10, 12]. Thus, it can be assumed that the rate of heat transfer from hot medium (bulk material) equals to the rate of heat transfer to cold fluid (oil). The thermal properties of the oil are shown in Table 5. Heat exchangers usually operate for long periods with no change in their operating conditions. Therefore, they can be modeled as steady-flow devices. As such, the mass flow rate of oil remains constant, and the properties such as temperature and velocity at any inlet or outlet remain the same. To calculate the performance of the MBHX with each one of the selected materials, the effectiveness–NTU method was

used. This method is based on a dimensionless parameter called the heat transfer effectiveness ε :

$$\varepsilon = \frac{\dot{Q}_{actual}}{\dot{Q}_{max}} = \frac{(\dot{m}c_p)_s (T_{si} - T_{so})}{(\dot{m}c_p)_{min} (T_{si} - T_{fi})} \quad (4)$$

For all experiments conducted $(\dot{m}c_p)_{min} = (\dot{m}c_p)_s$, thus, Eqn. 4 becomes:

$$\varepsilon = \frac{(T_{si} - T_{so})}{(T_{si} - T_{fi})} \quad (5)$$

The MBHX is a shell and tube heat exchanger so the NTU is determined by [18]:

$$NTU = \frac{1}{\sqrt{1+c^2}} \ln\left(\frac{2/\varepsilon - 1 - c\sqrt{1+c^2}}{2/\varepsilon - 1 - c + \sqrt{1+c^2}}\right) \quad (6)$$

Then overall heat transfer coefficient can be found by [18]:

$$NTU = \frac{UA_s}{(\dot{m}c_p)_{min}} = \frac{UA_s}{(\dot{m}c_p)_s} \quad (7)$$

It is important to specify which of the selected materials (Sand, Basalt, and Mixture) have better performance as a heat transfer and storage medium. The heat transfer surface area, A_s , is calculated as follows:

$$A_s = \pi D_o L N \quad (8)$$

Table 5. Thermal oil properties

Property	c _p [kJ/Kg.K]	K [W/m.k]	v [m ² /s]	ρ [kg/m ³]	M [kg/m.s]	Pr
Value	2.60	0.12	1*10 ⁻⁶	738	0.000744	16.12

The values of the overall heat transfer coefficient for the three tested combinations are calculated and plotted in Fig. 9 and Fig. 10. The results show that the Mixture (Sand and Basalt) has the highest value of U. It can be seen in the figures that the sand/Basalt mixture is the best bulk material among the tested materials to be used in the MBHX as heat transfer and storage medium.

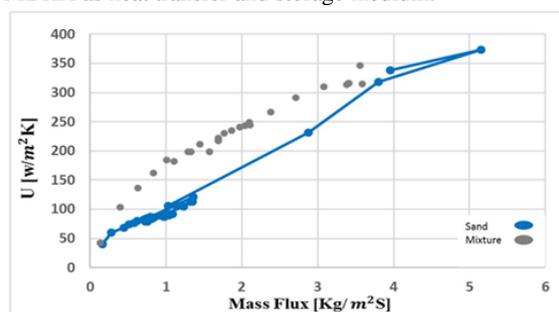


Fig. 9. Overall heat transfer coefficient for Mixture and Sand

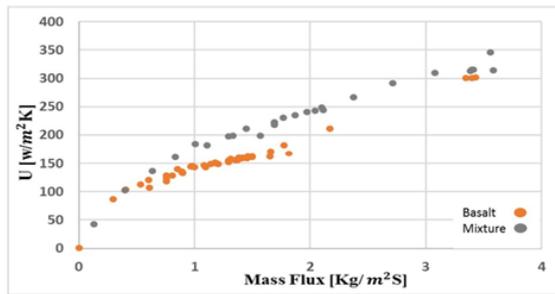


Fig. 10. Overall heat transfer coefficient for Mixture and Basalt

Figures 9 and 10 show clearly that the overall heat transfer coefficient of the mixture is the highest most of the times. For example, Fig. 9 at $[2 \text{ kg/m}^2 \text{ S}]$ mass flux the Sand has the highest value of overall heat transfer coefficient. This was $160 \text{ [W/m}^2 \text{ K]}$ for sand and $250 \text{ [W/m}^2 \text{ K]}$ for mixture. The only time that the sand values exceed those of the mixture are observed at value at $5.3 \text{ [kg/m}^2 \text{ S}]$ mass flux where the overall heat transfer coefficient $350, 380 \text{ [W/m}^2 \text{ K]}$ for mixture and sand, respectively, as shown in Fig. 9. This is attributable to the sand inversion phenomenon because the sand is a quartz compound and usually these compounds suffering from inversion at high temperature [12]. This phenomenon was also observed in another research project named "sandstock" in the UAE, where sand was investigated as a storage media "nonflowable" by Diago *et al.* [7]. Multiple tests on different sand samples from the desert of the UAE were conducted. The results show that all the samples are stable up to $1100 \text{ }^\circ\text{C}$ [7]. They also noticed some samples experienced color changes after multi-cycling. The color of the sand becomes lighter which may affect the absorptivity of this material.

At $[2.3 \text{ kg/m}^2 \text{ S}]$ mass flux in Fig. 10 the overall heat transfer coefficient for mixture was approximately $210 \text{ [W/m}^2 \text{ K]}$ for Basalt and $250 \text{ [W/m}^2 \text{ K]}$ for mixture. In both Figures (9 and 10), the values of the overall heat transfer coefficient increase with the increase in mass flux and this is resulted by the increase of the particles velocity inside heat exchanger. This leads to reduce the contact time of the particles on the wall of the tubes, and thus, increasing the rate of heat transfer process between the wall of the tubes and the bulk material according to equations 1 and 2 mentioned above.

Based on the above test results and observations, it can be concluded that using the Sand/Basalt mixture as heat transfer medium shows an improvement in the MBHX effectiveness of 45.5% compared to using only sand and 33.3% compared to using only Basalt.

5. Conclusions

The main objectives of the present study was to investigate the suitability of adding Basalt to the sand to form a bulk material working as a heat transfer and storage medium in Moving Bed Heat Exchanger (MBHX) to be used in CSP Solar Tower plants. PIV measurements are conducted to compare the suitability of using sand as a working fluid in MBHX by measuring the flow behavior around the tube bundles for MBHX. PIV measurements showed that the voids and stagnation zones formed with all materials in the heat exchanger. The rheological properties

of Sand, Basalt, and Mixture were tested and documented. The results showed that the Mixture has the best flowability. The thermal performance of the selected material was measured by measuring the effectiveness of the heat exchanger. It is found that using the 50% Basalt and 50% sand mixture in the MBHX results in a higher heat exchanger effectiveness than that when only using Sand or Basalt in MBHX. The improvements were quantified to be 45.5% and 33.3% compared to only sand and only Basalt, respectively.

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