THE STUDY OF HEAT TRANSFER CHARACTERISTICS IN SAND-BASED ENERGY STORAGE SYSTEMS

Lappeenranta–Lahti University of Technology LUT

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Yuanyue Zhao

Examiner(s): Associate professor, Payman Jalali

Lecturer, Liyao Xie

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

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Yuanyue Zhao

The Study of Heat Transfer Characteristics in Sand-based Energy Storage Systems

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Keywords: sand, storage, air, heat exchanger.

In this paper, a literature review of energy storage systems and the utilisation of sand batteries is presented. A two-dimensional model of the air-sand heat exchanger is established, and heat transfer efficiency and exergy are used as evaluation indexes to analyse the air flow and heat exchange within the sand bed. The influence laws of air flow rate and sand flow rate on the heat exchange capacity of the heat exchanger were obtained, providing a theoretical basis for the optimisation of the air-sand heat exchanger.

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Tässä artikkelissa esitetään kirjallisuuskatsaus energian varastointijärjestelmistä ja hiekkaakkujen hyödyntämisestä. Ilma-hiekka-lämmönvaihtimesta laaditaan kaksiulotteinen malli, ja lämmönsiirron tehokkuutta ja eksergiaa käytetään arviointiindekseinä analysoitaessa ilmavirtausta ja lämmönvaihtoa hiekkapedin sisällä. Saatiin ilma- ja hiekan virtausnopeuden vaikutuslait lämmönvaihtimen lämmönvaihtokykyyn, mikä antaa teoreettisen perustan ilma-hiekkalämmönvaihtimen optimoinnille.

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SYMBOLS AND ABBREVIATIONS

Roman characters

h	heat transfer coefficient	W/m^2K
A/a	area	m^2
T	temperature	K, ^oC
Q	heat	J
c	specific heat capacity	J/kg/K
q	mass flow rate	m/s
D	diameter of sand	m
x	horizontal direction	/
y	vertical direction	/
H	height of chamber	m
B	width of chamber	m
W	thickness of chamber	m
V	void volume	m^3
ex	exergy	J

Greek characters

Φ	convective heat transfer	W
ε	particle void ratio	/
η	efficiency	%

Subscripts

a	air
s	sand

m	mass flow
in	inlet
out	outlet

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1 Introduction

Energy has been an important driving force for the continuous economic growth of human societies and is inextricably linked to human survival and development. While natural fuels such as wood were mainly used in ancient times, coal resources have been heavily utilised in recent times. This shift has led to a dramatic change in the energy structure of the human world, driving productivity and rapid economic development. However, with the rapid development of the world's economy, human demand for energy has been increasing. The reserves of traditional fossil energy sources are dwindling, while the ecological environment is deteriorating. This has prompted the rapid development and widespread application of various new and renewable energy sources. Despite the huge potential of renewable energy, limitations from natural factors such as weather changes can lead to fluctuations and intermittency in energy supplies.

In recent years, the rapid development of energy storage technology has provided opportunities to solve these problems. Various energy storage technologies such as thermal storage, pumped hydro storage, and electrochemical storage can store energy when there is excess energy and release energy when there is energy shortage, thereby balancing energy supply and demand. Among them, the pumped storage energy utilization rate is 92.6%. Electrochemical energy storage also has a high utilisation rate of 5.3%. Thermal and compressed air energy storage, on the other hand, had a lower utilisation rate, which may be because they have large energy losses in the energy conversion process. (Sun, 2021).

Therefore, the rapid development of energy storage technology provides a possibility for the smooth development and large-scale application of new energy. In the future, with the continuous breakthrough and innovation of energy storage technology, the development level of new energy will be further improved. And it is of great significance to vigorously develop energy storage technology, which can effectively solve the problem of imbalance between energy supply and demand and promote the sustainable development of global energy. Energy storage technology involves converting excess energy into a storable form and releasing it again for use when needed. Currently, the main energy storage technologies include physical energy storage, chemical energy storage and electromagnetic energy storage, etc., of which physical energy storage can be further divided into two categories:

physical power storage and physical heat storage. Physical power storage technologies include pumped storage, compressed air storage, flywheel storage, and superconducting power storage, etc., while physical thermal storage technologies include sensible heat storage, latent heat storage, and phase change storage. In addition, chemical energy storage involves lead-acid batteries, lithium batteries, etc., while electromagnetic energy storage includes supercapacitor energy storage, etc. (Sun, 2021).

Among the various energy storage technologies, thermal storage is notable for its efficient use of thermal energy. Thermal storage technology uses certain materials to store excess thermal energy from solar radiation, industrial waste heat and low-grade waste heat sources and then release and utilise it when needed. This technology not only solves the problem of thermal energy supply, which is constrained by factors such as region, climate, and time, but also maximises the energy efficiency of the whole system. Among several heat storage methods, latent heat storage and phase change heat storage have attracted much attention, while sensible heat storage has been widely used in fields such as solar photovoltaic power plants. (Hasnain, 1998).

Therefore, it is of great significance to increase the research, development and application of energy and heat storage technologies. This can not only improve the structure of energy use and reduce the proportion of traditional fossil energy use, but also promote the development of clean energy and the sustainable use of energy. At the same time, the continuous innovation and application of energy storage technology will also promote the upgrading and transformation of the energy industry on a global scale, contributing to the construction of a clean, efficient, and sustainable energy system.

2 Thermal storage materials

Solar power generation is a technology that uses solar radiation energy to convert it into thermal energy, which is then used to generate electricity. Thermal storage systems play a vital role in energy utilization. It can solve the above-mentioned intermittent problems when using solar energy to ensure stable and continuous power generation of the system. In thermal storage systems, the choice of thermal storage materials has a significant impact on the performance of the system.

2.1 Importance and requirements of thermal storage materials

When selecting energy storage materials, material thermal properties and heat storage density are the first things to consider. Specific heat capacity and phase change enthalpy determine how efficiently a material stores thermal energy. A higher specific heat capacity means that the material can absorb or release more heat per unit mass, and a higher phase change means that the material can store or release more heat during the phase change process. The thermal storage material selected must be able to withstand long-term thermal cycling without instability, damage, or irreversible chemical reactions due to temperature changes. This stability can ensure long-term stable operation of the system, reduce maintenance and replacement costs, and thereby improve energy efficiency. Third, security is also a factor to consider. Non-toxic, non-corrosive and non-flammable materials can reduce safety risks during operation and protect operators and the surrounding environment. In addition, the operation is simple and easy to use, which can reduce system operation and maintenance costs and improve system operation stability. Finally, cost is an important consideration when evaluating thermal storage product performance. Simple and cheap equipment can reduce system construction and operating costs, making thermal storage technology more competitive and sustainable. And products that can be applied on a large scale can further reduce system costs and promote the widespread application and popularization of heat storage technology. (Sun, Yang, & Li, 2020).

In summary, excellent thermal storage materials should have superior thermal properties and thermal density, higher stability, safety, and low cost, which will provide important support

for the development and application of thermal storage technology and promote the sustainable development of renewable energy.

2.2 Commonly used heat storage materials

Molten salt is one of the most widely used heat storage materials at present. It has high thermal stability and relatively low cost and is often used in fields such as solar thermal power generation. Ceramics have great high-temperature resistance and chemical stability and are suitable for high-temperature heat storage systems. Thermal oil, usually organic oil, has proper thermal conductivity and can be used to transfer thermal energy or serve as a heat storage medium.

Sand, as an emerging thermal storage material, has the advantages of high thermal stability, low cost, non-toxic, non-corrosive, good oxidation resistance, etc. It has attracted much attention in the field of solar thermal utilisation and other areas and is often used in the thermal industry. High-temperature concrete with certain heat storage capacity is commonly used in heat storage tanks or heat storage systems of solar thermal power plants. Rocks have high heat capacity and thermal conductivity and can be used as the heat storage medium in geothermal heat storage systems. (Rathod & Banerjee, 2013).

The above-mentioned thermal storage materials have their own advantages, but sand has more multiple advantages as a thermal storage material and is therefore of interest in areas such as solar thermal power generation. Its high thermal stability allows it to withstand temperatures of up to 800°C or more without phase change, gasification, or chemical decomposition, making it an ideal thermal storage material. Its non-toxic and non-corrosive nature, low price and excellent oxidation resistance make it economical and environmentally friendly while providing long-term stability (Zhu et al., 2018) & (Knott et al., 2014). Sand does not require complex pre-treatment, is widely distributed on the earth and is easy to access and utilise, and its volumetric specific heat capacity advantage also allows it to store large amounts of heat during thermal storage. Taken together, sand has great potential as an emerging thermal storage material, and its research and application in the field of renewable energy is expected to expand further. As the development of solar thermal power generation and other fields, the research and application of sand as a new type of thermal storage

material is also advancing, and sand provides more options and possibilities for the development of renewable energy fields. (Suhil Kiwan and Soud 2020).

3 Sand-based thermal energy storage

As mentioned before, the potential of sand as a thermal energy storage material is mainly derived from its good thermophysical properties. Sand has a high specific heat capacity and can effectively absorb and store thermal energy. Meanwhile, sand has high thermal stability and can keep its physical and chemical properties stable at high temperatures for a long time. Silica-based minerals in sand, such as quartz, are particularly suitable for use as thermal storage media at high temperatures because they maintain structural integrity after prolonged thermal cycling. Many researchers have investigated whether sand can be used as a thermal storage medium and the thermal storage property.

3.1 Literature review for sand as a thermal storage material

Sand is recognised as a cost-effective thermal storage material in the design of dual-media shell-and-tube thermal storage units. The reason for this is that sand has excellent fluidity and matches well with the thermal expansion of the prefabricated pipes. By saturating the sand with a thermally conductive fluid, the heat transfer efficiency can be significantly improved. This is because the heat-conducting fluid fills the pores of the sand, creating a continuous heat transfer path. This approach not only enhances the thermal management capability of the system, but also keeps the system economical and sustainable due to the low-cost and environmentally friendly nature of sand. (Xu et al., 2017).

By investigating the thermal conductivity, thermal resistance and abrasion resistance of different types and sizes of solid particles, as well as their critical velocities and pressure drops in an air-sand thermal converter, Baumann et al. obtained the conclusion that quartz sands have low thermal abrasion resistance, which limits the temperature range in which they can be used, while industrial ceramics, such as alumina or bauxite, are insensitive to thermal cycling. (Baumann et al., 2011). Diago et al. investigated the feasibility of desert sand as a thermal storage material by analysing its composition, thermal stability, particle size distribution and optical properties. It was analysed that desert sand can be used as a work mass for direct solar energy absorption and as a thermal storage medium for heat storage. (Diago et al., 2018).

In the study of sand as a heat storage medium. Warerkar et al. studied the flow and heat transfer characteristics of sand during heat exchange with air in an air-sand heat exchanger and concluded that direct contact heat transfer between air and sand has high efficiency when sand is used as a heat storage medium in a tower-type solar sand heat storage system (Warerkar et al., 2011). Schwaiger et al. investigated the process of heat exchange between sand and air in a fluidised bed heat exchanger, where the process of energy release from the sand can be carried out in a fluidised bed heat exchanger containing internal ducts in which the sand is fluidised for more efficient heat transfer (Schwaiger et al., 2014). Riyadh white sand has better heat transfer properties compared to other types of sand, and small spherical particles of corundum and mullite have better heat transfer properties (Nguyen et al., 2014). Gimeno-Furio et al. studied the use of black silica sand as solid particles in a combined system to improve the solar absorption characteristics using a carbon coating method. (Gimeno-Furio et al., 2020).

Schlipf et al. analysed the thermal storage performance of a filled-bed system when small particles such as silica sand, quartz sand, and basalt were used as thermal storage materials, respectively, and concluded that the small-particle materials have good thermal storage potential. (Schlipf et al., 2015). Iniesta et al. designed a gravity combined solar energy receiving and storage system using sand particles as heat collection, heat transfer and storage medium. They also experimentally tested mass flow rate of sand with different particle sizes and different angles of the material receiver, and analysed the optimisation of the system device and what kind of sand is more suitable as the heat storage medium. (Suhil Kiwan & Soud 2020).

3.2 Application of sand-based thermal storage technology

In recent years, soaring international gas prices brought about by changes in the international situation have affected the energy security of countries. In response to climate change and the energy crisis, countries have also come up with a variety of different energy storage solutions.

The sand heat transfer and storage system developed by American Solar Holdings, Inc. is called "Sand Shifter". The system utilises two silos as storage tanks filled with both hot and cold sand and connected by a transport mechanism. A heat transfer pipe is arranged around

the transport mechanism, where a high temperature fluid is introduced into the pipe to transfer heat to the cold sand, and the heated sand is then transported to the hot silo for storage and utilisation. Both the hot and cold sand are cycled through the two silos to form a complete thermal energy storage system. (*Geni.org*).

In Finland, Polar Night Energy has developed an innovative technology that uses sand as a thermal storage medium, demonstrating the feasibility of using sand for high-temperature thermal storage. The 'sand battery' system stores large amounts of thermal energy by heating sand to temperatures of 500°C or more, which can be released through a heat exchange system when needed for heating or converted into electricity. This method of energy storage not only improves the efficiency of renewable energy use, but also reduces dependence on fossil fuels, with significant environmental and economic benefits. However, despite the high heat retention capacity of sand, how to effectively minimise heat loss while maintaining high operating temperatures, as well as ensuring the long-term economics of the system, remains a major challenge for the technology to overcome.

A Norwegian company, EnergyNest has developed a patented thermal energy storage technology called Heatcrete®. The technology makes use of a specially formulated concrete, consisting of vegan concrete, quartz sand and other additives, to store heat energy stably at high temperatures for long periods of time. The main strengths of Heatcrete are its high-energy density and its ability to withstand multiple high-temperature heating and cooling cycles without degradation, making it an ideal large-scale thermal energy storage solution for the industrial and renewable energy sectors. Heatcrete technology also excels in terms of environmental friendliness and cost-effectiveness, with the use of sustainable materials and low overall system maintenance costs, contributing to increased energy efficiency and a reduced environmental impact. Heatcrete provides an effective energy management and optimisation tool for energy-intensive industries, especially when integrating intermittent renewable energy sources, such as solar and wind, into the grid, showing its great potential for regulating grid supply and demand. (Hoivik et al., 2017)

4 Simulation study of air-sand heat exchanger

In this chapter, a detailed study of the flow and heat transfer characteristics of an air-sand heat exchanger is presented. By establishing a two-dimensional model of the air-sand heat exchanger, the flow and heat transfer characteristics of the air and the killing knife are investigated.

4.1 Geometric model

Air-sand heat exchanger structure is shown in Figure 1 and Figure 2. Higher temperature air enters from the horizontal channel, passes through the filter and enters the sand bed, where it exchanges heat in direct contact with the lower temperature sand that moves slowly from top to bottom. The sand is heated to a certain temperature and then removed from below the sand bed. Air with residual heat is discharged through the right filter.

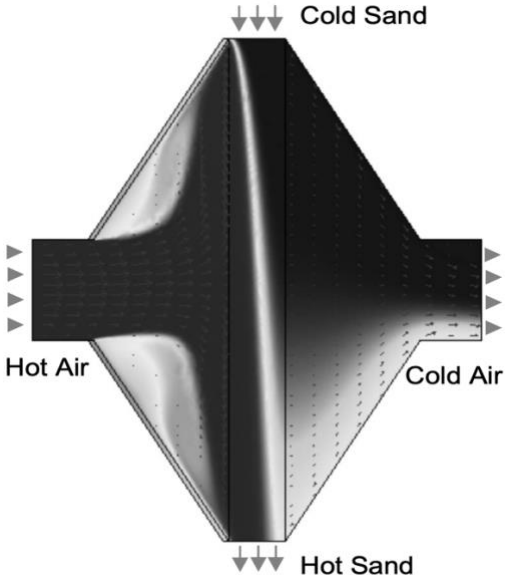

Figure 1. Steady state air temperature and air flow field simulation (Warerkar et al., 2011).

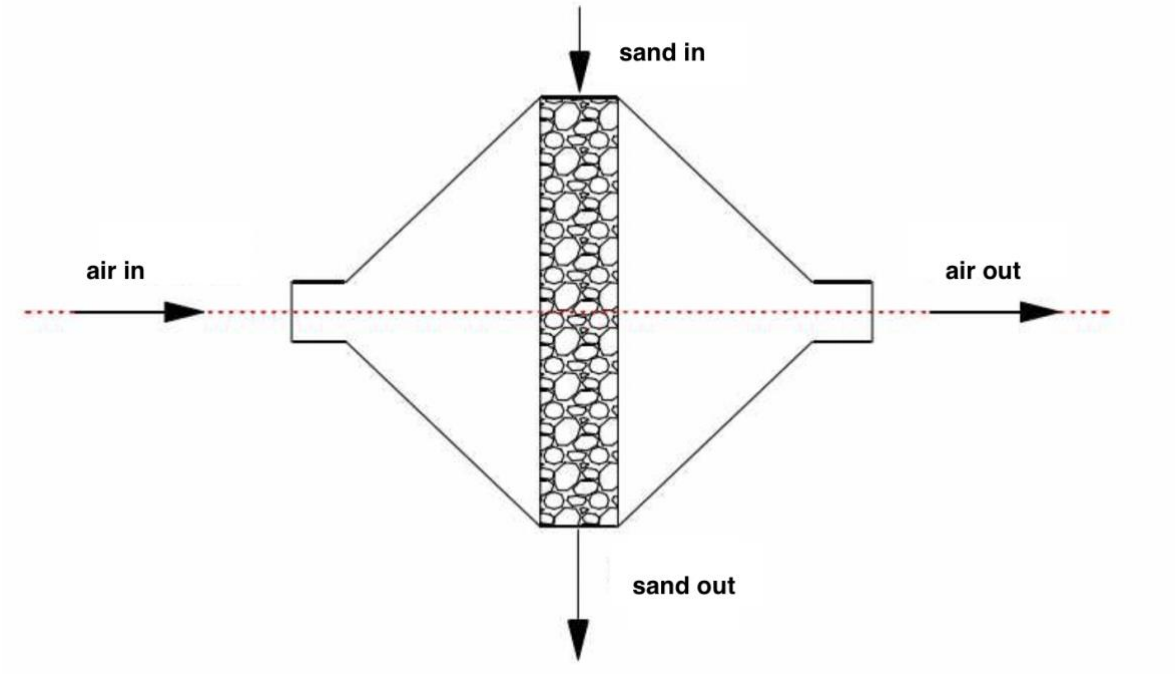

Figure 2. Schematic diagram of heat exchanger (Danyuan, 2021).

Due to the small grain size of the sand, the contact area of gas flowing over the surface of the particles is high, i.e., the heat transfer surface area is high. This leads to an increase in the rate of heat transfer. In addition, the contact friction that occurs between the gas and the solid particle during the flow also enhances the heat exchange, which accelerates the heat transfer rate. So thermal equilibrium between gas and solid can be reached in a short time.

The sand used in this thesis has a small particle size and void ratio. Relative dynamic distance and mobility of the particles in the heat exchange chamber are large. These result in relatively small contact surfaces between particles and short contact times. So, heat conduction and radiative heat transfer between and within the particles are usually considered to have a relatively small effect on the overall heat exchange process. In the case of a large temperature difference between air and sand, the air generally flows faster than the sand moves within heat exchanger. When the hot air flows over the surface of the sand, it rapidly warms up the sand. Due to diffusivity of air flow, the hot air can exchange heat with the low-temperature sand in all directions, resulting in a rapid increase in the temperature of the sand. Therefore, major heat transfer in the heat exchanger is convective heat transfer between air and solid phases, while the influence of heat conduction and radiation heat transfer is relatively small. Newton's cooling equation is the basic equation for convective heat transfer:

$$\Phi = hA\Delta T \qquad (1)$$

where Φ is the convective heat transfer power in Watts, h is surface heat transfer coefficient, A is contact area, and ΔT is difference in surface temperature between the two objects.

4.2 Modelling

4.2.1 Assumptions

To establish a reasonable mathematical model of the air-sand heat exchanger, it is necessary to make the following assumptions.

(1) Air and sand flows do not affect each other's state of motion. The flow is uniformly distributed.

(2) Sand particles are regarded as spherical, which are homogeneous and consistent porous media. Sand falls vertically in the heat exchanger chamber, and the void ratio does not change during the falling process.

(3) Neglect the heat transfer between particles.

(4) The walls of the heat exchanger chamber are adiabatic, and heat loss is neglected.

(5) No chemical reaction occurs between the substances participating in the heat exchange.

4.2.2 Heat exchange model

During heat exchange between air and sand, the exothermic heat Q_a of air is:

$$Q_a = q_{m,a} c_{p,a} \left(T_{a,in} - T_{a,out}\right) \quad (2)$$

where $T_{a,in}$ is air side inlet temperature, $T_{a,out}$ is air side outlet temperature, $q_{m,a}$ is mass flow of air and $c_{p,a}$ is specific heat capacity of air.

During heat exchange between air and sand, the absorption quantity Q_s of air is:

$$Q_s = q_{m,s} c_{p,s} \left(T_{s,out} - T_{s,in}\right) \quad (3)$$

where $T_{s,in}$ is sand side inlet temperature, $T_{s,out}$ is sand side outlet temperature, $q_{m,s}$ is mass flow of sand and $c_{p,s}$ is specific heat capacity of sand.

Average heat exchange rate of the heat exchanger is:

$$\bar{Q} = \frac{Q_a + Q_s}{2} \quad (4)$$

4.2.3 Model reasoning

Heat transfer area is divided into several microelements in both horizontal and vertical directions (i.e., x-direction and y-direction). The length of each microelement in the vertical direction is dy, and in the horizontal direction is dx. One of the microelements is selected for the study in deriving the mathematical model of the temperature field. The heat exchange model is shown in Figure 3. Height and width of the heat exchanger chamber are H and B respectively. d is height of the micromeres from inlet of sand, and b is length of the micromeres from inlet of hot air.

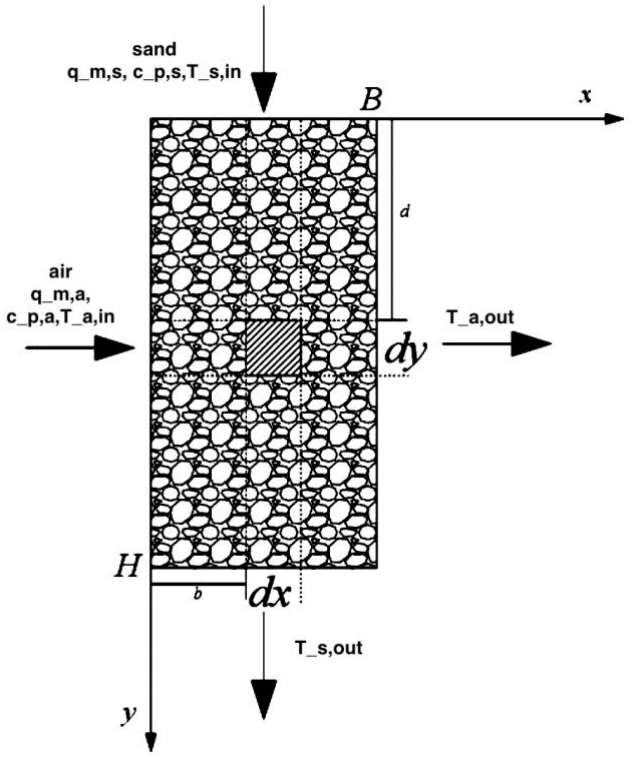

Figure 3. Heat exchange model (Danyuan, 2021).

According to heat transfer equation, heat change in the body of each microelement is:

$$dQ = ha(T_g - T_s)dV = ha(T_g - T_s)dxdyW \quad (5)$$

where V is total volume of the heat exchange chamber, W is thickness of the heat exchange chamber, h is convection heat transfer coefficient. a is effective surface area of sand particles in the bed per unit volume, which can be presented as:

$$a = \frac{6(1-\varepsilon)}{D} \tag{6}$$

where ε is particle void ratio and D is average diameter of sand particles.

$$\varepsilon = \frac{V_{\text{void}}}{V_b} = 1 - \frac{\rho_b}{\rho_p} \tag{7}$$

where V_{void} is void volume of the sand particles, V_b is total volume, ρ_b is packing density, and ρ_p is the bulk density.

The sand particles inside microelement body absorb heat and the temperature keeps increasing along the y-axis. Heat absorbed by sand in the microelement body is:

$$dQ = (1-\varepsilon)\frac{dx}{B} q_{m,s} c_{p,s} dT_s \tag{8}$$

Combine Equation (5) and Equation (8). Considering that air is mixed vertically due to the porous nature of sand particles, the air temperature varies much more horizontally than vertically. Integrating both sides of the equation gives the temperature distribution of the sand particles as:

$$T_s = T_a - \left(T_a - T_{s,in}\right) e^{-\frac{haBW}{(1-\varepsilon) q_{m,s} c_{p,s}}} \tag{9}$$

During heat transfer, sand gains heat and increases in temperature. The air loses heat and decreases in temperature. From the law of conservation of energy, the heat transfer process can be obtained to satisfy the following equation.

$$(1-\varepsilon) q_{m,s} c_{p,s} \frac{dx}{B} \left(T_{s,out} - T_{s,in}\right) = -\varepsilon q_{m,a} c_{p,a} dT_a \tag{10}$$

Combining Equations (9) and (10) and integrating both sides of the equation, the temperature change of air can be obtained as:

$$T_a = T_{s,in} + \left(T_{a,in} - T_{s,in}\right) \exp\left[\frac{(1-\varepsilon) q_{m,s} c_{p,s} b}{\varepsilon q_{m,a} c_{p,a} B}\left(e^{-\frac{haBW}{(1-\varepsilon) q_{m,s} c_{p,s}}} - 1\right)\right] \tag{11}$$

Heat exchange characteristics between gases and solids in a heat exchanger can be accurately described by the heat transfer coefficient. This can be obtained from the conservation of heat exchange energy between sand and air:

$$h = \frac{q_{m,a} c_{p,a} (T_{a,in} - T_{a,out})}{BHW \Delta T} \tag{12}$$

where ΔT can be expressed as log mean temperature (Ding et al., 2008):

$$\Delta T = \frac{(T_{a,in} - T_{s,out}) - (T_{a,out} - T_{s,in})}{\ln\left(\frac{T_{a,in} - T_{s,in}}{T_{a,out} - T_{s,in}}\right)} \tag{13}$$

4.2.4 Evaluation indicators

Heat transfer efficiency is a measure of capacity for heat transfer. It is defined as the ratio of the actual temperature difference of the heat exchanger to the maximum temperature difference that can be achieved. To analyse the law of change of heat more comprehensively, the air-sand heat exchanger heat transfer efficiency is divided into solid-phase heat transfer efficiency and gas-phase heat transfer efficiency respectively (Feng et al., 2019), to study the sand and air heat changes. Solid-phase efficiency is to describe the efficiency of sand from the air to absorb heat. Gas-phase efficiency describes the efficiency of heat transfer from air to sand.

The solid-phase heat transfer efficiency is expressed as:

$$\eta_s = \frac{T_{s,out} - T_{s,in}}{T_{a,in} - T_{s,in}} \tag{14}$$

The gas-phase heat transfer efficiency is expressed as:

$$\eta_a = \frac{T_{a,in} - T_{a,out}}{T_{a,in} - T_{s,in}} \tag{15}$$

Total heat transfer efficiency is:

$$\eta = \frac{|T_{in} - T_{out}|_{max}}{T_{a,in} - T_{s,in}} \tag{16}$$

where $T_{s,in}$ is sand inlet temperature, $T_{s,out}$ is sand outlet temperature, $T_{a,in}$ is air inlet temperature and $T_{a,out}$ is air outlet temperature.

As mentioned before, heat transfer between air and sand in a heat exchanger is essentially a transfer between gas and solid phases. The intensity of transfer would directly affect outlet temperature of air and sand. Exergy can be used as an evaluation index for the optimization of the operating parameters of the air-sand heat exchanger. The exergy of stable fluid is:

$$ex = h - h_0 - T_0(s - s_0)$$

$$= \int_{T_0}^{T} c_{\mathrm{p}}\mathrm{d}T - T_0\left(\int_{T_0}^{T} \frac{c_{\mathrm{p}}\mathrm{d}T}{T} - R_{\mathrm{g}}\ln\frac{p}{p_0}\right)$$

$$= \int_{T_0}^{T}\left(1 - \frac{T_0}{T}\right)c_{\mathrm{p}}\mathrm{d}T + T_0 R_{\mathrm{g}}\ln\frac{p}{p_0} = ex(T) + ex(p) \qquad (17)$$

According to this equation, exergy can be divided into temperature exergy and pressure exergy. As hot air flows through the sand bed, heat is transferred to sand, resulting in a decrease in air temperature. The difference in temperature before and after the air flows through sand bed is referred to as temperature exergy change. Also, because the hot air is subject to resistance as it passes through the sand bed, it requires the fan to provide sufficient pressure to allow the air to pass through the sand bed layer. To overcome this resistance, the fan needs to consume energy, and we define this energy consumption as the pressure exergy change. Sum of temperature exergy changes and pressure exergy change is the air side exergy change. This value reflects the combined effect of resistance and heat transfer as the air passes through the sand bed. Therefore, it is important to use air-side exergy change as an evaluation index of air flow and heat transfer in the heat exchanger. Because pressure changes are small relative to temperature changes, the effect of pressure exergy can be neglected. So, exergy of air changes is (Madhu et.al, 2018):

$$\Delta Ex_a = q_{m,a}c_{p,a}\left(T_{a,out} - T_{a,in}\right)\left[1 - \frac{T_0}{T_{a,out} - T_{a,in}}\ln\frac{T_{a,out}}{T_{a,in}}\right]$$

$$= -Q_{\mathrm{a}}\left[1 - \frac{T_0}{T_{a,out} - T_{a,in}}\ln\frac{T_{a,out}}{T_{a,in}}\right] \qquad (18)$$

where T_0 is surrounding temperature, which is about 300K.

Flow of sand can be considered as unforced motion, so the exergy changes of sand is:

$$\Delta Ex_s = q_{m,s}c_{p,s}\left(T_{s,out} - T_{s,in}\right) - T_0 q_{m,s}c_{p,s}\ln\frac{T_{s,out}}{T_{s,in}}$$

$$= Q_s - T_0 q_{m,s} c_{p,s} \ln \frac{T_{s,out}}{T_{s,in}} \quad (19)$$

Exergy efficiency is the ratio of absorption exergy to input exergy:

$$\eta_{ex} = \frac{\Delta Ex_s}{\Delta Ex_a} \quad (20)$$

4.3 Simulation parameters

Table 1 shows main parameters and values set in the simulation experiments. The dimensions of the heat exchanger are referred to Warerkar et al. Physical parameters related to air and sand change considerably with temperature. Specific heat capacity of air and sand can be expressed by the following equation (Yuanmin&Jianmeng&Bin, 2020):

$$c_s = 315.89 + 1.7655T_s - 0.004T_s^2 + 6 \times 10^{-6} T_s^3 \quad (21)$$

$$c_a = 955 + 0.14T_a + 3.8 \times 10^{-5} T_a^2 + 2.1 \times 10^{-10} T_a^3 \quad (22)$$

Table 1. Basic parameter for simulation.

Ambient Temperature	T_0 [K]	300
Ambient pressure	p_0 [Pa]	101325
Air inlet temperature	T_a,in [K]	800
Sand inlet temperature	T_s,in [K]	300
Average diameter of sand	D [mm]	1.63
Sand bed void ratio	ε	0.42
Heat exchanger height	H [mm]	500
Heat exchanger width	B [mm]	50
Heat exchanger thickness	W [mm]	100

4.4 Simulation results

Figures 4 and 5 show the effects of air flow rate versus sand flow rate on average air outlet temperature and average sand outlet temperature. When the sand flow rate is fixed, average outlet sand temperature and air temperature increase gradually with the increase of air flow

rate. When air flow is fixed, with the gradual increase of sand flow, the average outlet sand temperature and wind temperature gradually decrease.

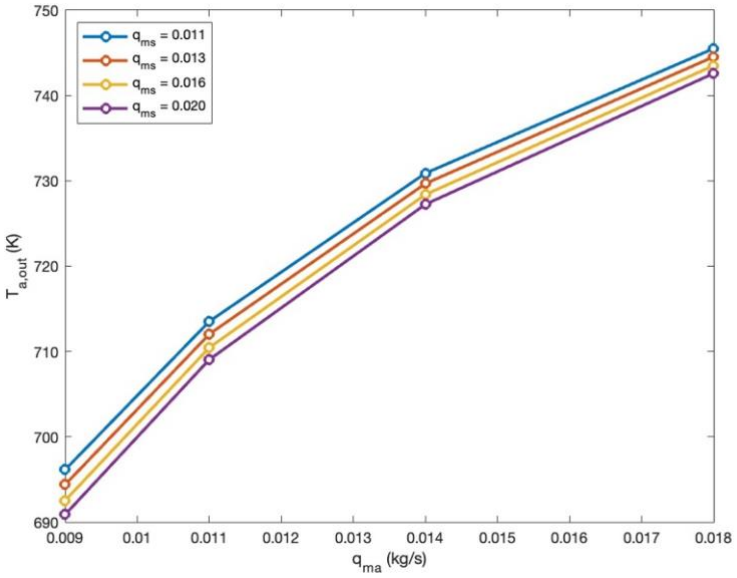

Figure 4. Air outlet temperature versus air mass flow rate at different sand mass flow rates.

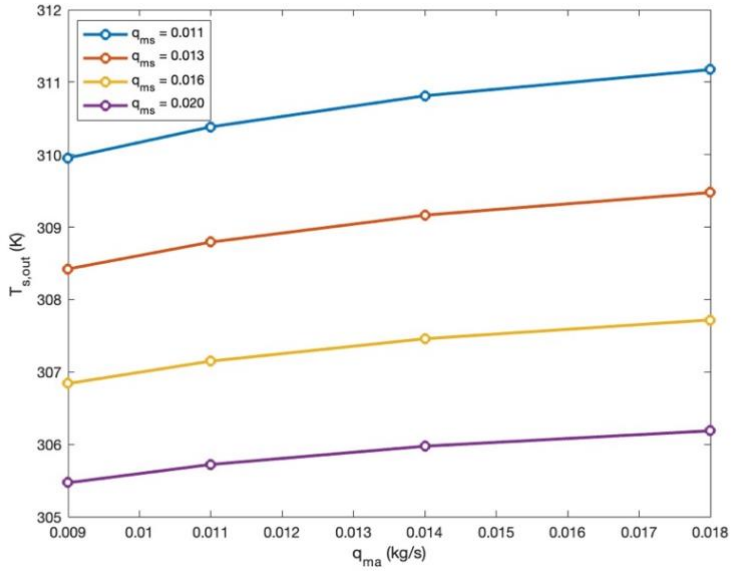

Figure 5. Sand outlet temperature versus air mass flow rate at different sand mass flow rates.

Figure 6 and Figure 7 show the influence of air flow rate and sand flow rate on solid-phase efficacy and gas-phase efficacy, respectively. From Figure 6, solid-phase efficiency is directly proportional to air flow and inversely proportional to sand flow. From Figure 7, the

gas-phase efficiency is inversely proportional to the air flow rate and positively proportional to the sand flow rate. Therefore, the solid-phase efficiency is inversely proportional to the gas-phase efficiency, and the solid-phase efficiency and gas-phase efficiency only reflect the ratio of actual heat transfer capacity and ideal heat transfer capacity of the sand side or air side.

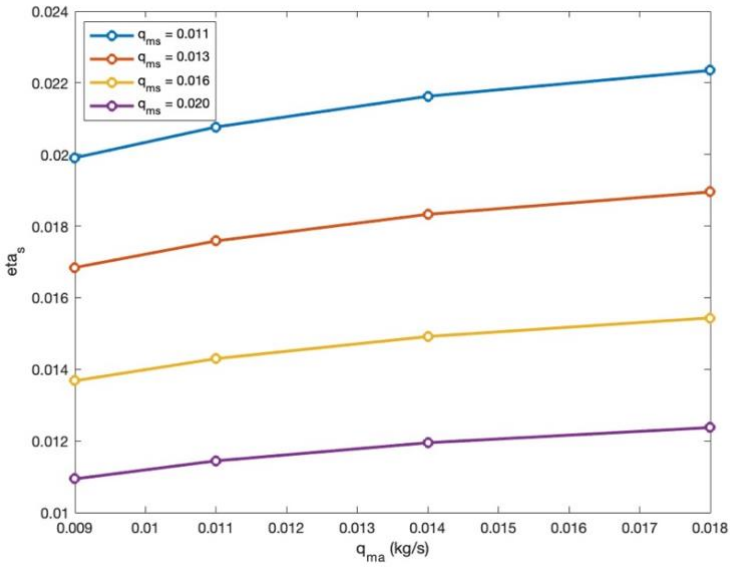

Figure 6. Solid phase heat transfer efficiency for different air and sand mass flow rates.

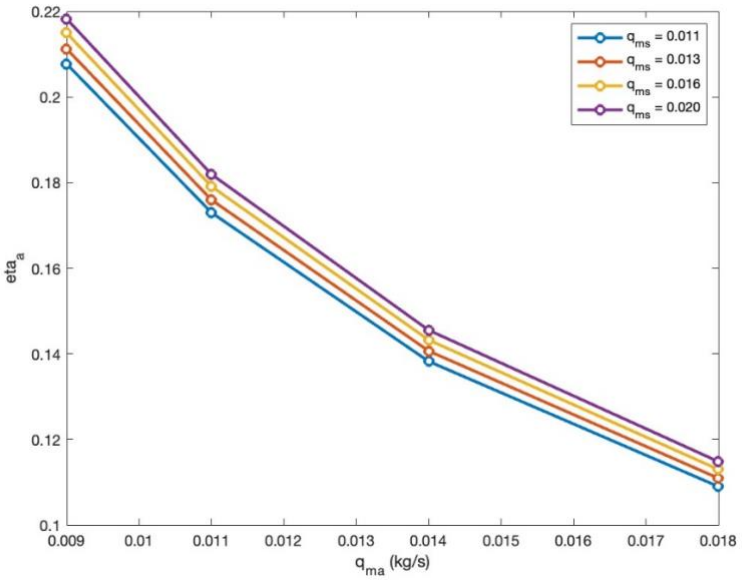

Figure 7. Gas phase heat transfer efficiency for different air and sand mass flow rates.

What causes the above temperature changes and effectiveness changes is that as the air flow rate increases, more hot air enters the air-sand moving bed heat exchanger per unit time. This increases the disturbance between the hot air and the sand, intensifying the heat transfer between the two. As a result, the sand outlet temperature increases and consequently the solid phase effectiveness increases. However, the increase in air volume per unit time reduces its residence time in the heat exchanger. This causes some of the heat in the hot air to be discharged through the heat exchanger into the pipeline without participating in the heat transfer with the sand. The higher the air flow rate, the more heat is lost, which results in an accelerated tendency for the air outlet temperature to increase, resulting in a decreasing gas-phase efficiency.

Figure 8 and Figure 9 show the change in exergy. At a constant sand flow rate, an increase in air flow rate will increase the sand outlet temperature, the sand side outlet exergy increases, and the sand side exergy change increases. At a constant air flow rate, an increase in the sand flow rate will increase the sand side exergy change. While increase in sand flow rate will decrease the sand outlet temperature and decrease the sand side change. And the sand outlet temperature decreases on the sand side exergy change effect is greater than the sand flow increase, so the sand side change gradually decreases.

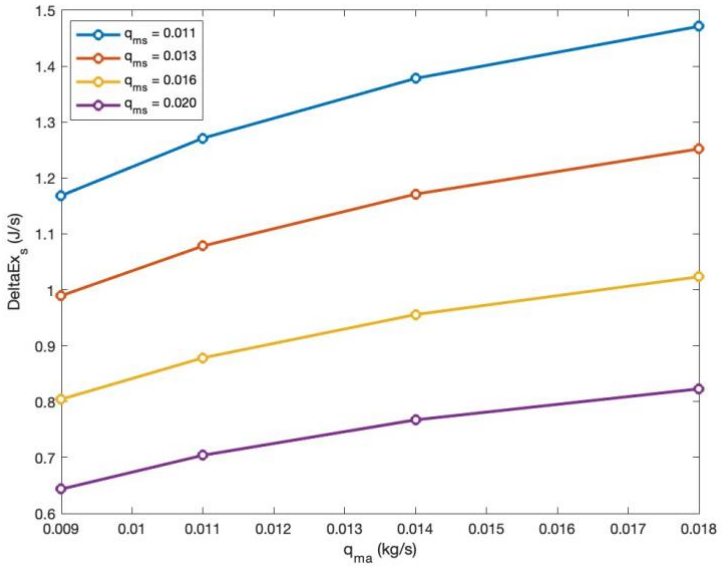

Figure 8. Exergy changes in sand for different air and sand mass flow rates.

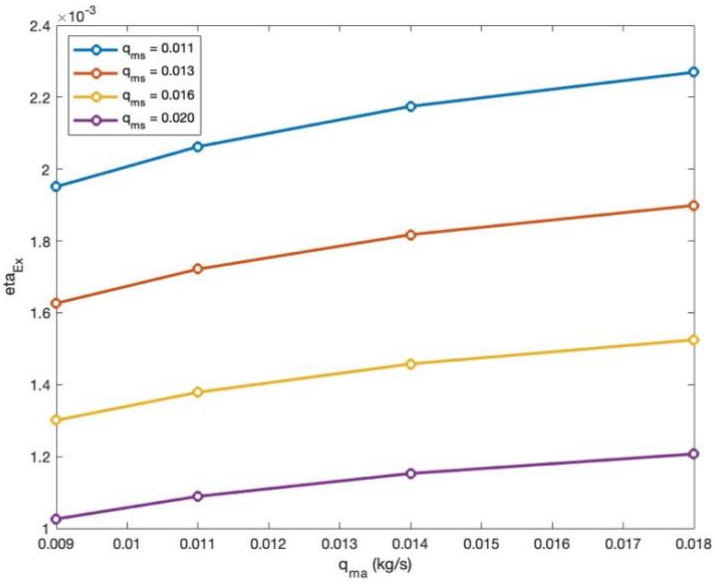

Figure 9. Efficiency of exergy for different air and sand mass flow rates.

5 Conclusions

This thesis presents a comprehensive study of sand as a heat transfer medium and the simulation of an air-sand heat exchanger. The physical parameters of sand as well as the flow and heat transfer characteristics of air-sand heat exchanger under different operating conditions are studied through simulation. The main conclusions are as follows:

(1) Sand has good heat transfer properties as a heat transfer work material and can be used as a packing material in heat exchangers.

(2) The air-sand heat exchanger simulation study shows that the temperature inlet and outlet changes are affected by the sand-air flow ratio.

(4) The complexity and non-uniformity of the flow within the heat exchanger exists and further research is required to optimise the design and improve the performance.

Future research can be carried out in the following aspects:

(1) Further optimise the measurement method of physical parameters of sand to improve the accuracy and reliability of experimental data.

(2) The simulation study of the air-sand heat exchanger can consider more influencing factors, such as the flow velocity distribution of the heat exchanger medium and the optimal design of the heat exchanger structure.

(3) Combine experiments and numerical simulations to carry out performance testing and validation of the heat exchanger to verify the accuracy of the simulation results.

(4) Explore the effects of different types of sand on the performance of the heat exchanger and the optimal design of the sand filling layer to improve the heat transfer efficiency and stability of the heat exchanger.

(5) Apply the air-sand heat exchanger in practical engineering, such as solar thermal energy utilisation, air purification, etc., and explore its performance and economic benefits in practical applications.

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Appendix 1. Main code of modelling

```
syms Ts Ta
for i = 1:length(q_ms_values)
    q_ms = q_ms_values(i);
    for j = 1:length(q_ma_values)
        q_ma = q_ma_values(j);

        c_s = 315.89 + 1.7655 * Ts - 0.004 * Ts^2 + 6 * 10^(-6) *
Ts^3;
        c_a = 955 + 0.14 * Ta + 3.8 * 10^(-5) * Ta^2 + 2.1 * 10^(-10)
* Ta^3;


        deltaT = ((Ta_in - Ts_sol) - (Ta_sol - Ts_in)) / log((Ta_in -
Ts_in) / (Ta_sol - Ts_in));
        h = (q_ma * c_a * (Ta_in - Ta_sol)) / (B * H * W * deltaT);


        Ta_eq = Ts_in + (Ta_in - Ts_in) * exp(((1-epsilon) * q_ms *
c_s ) / (epsilon * q_ma * c_a ) * (exp(-h * a * B / ((1-epsilon) *
q_ms * c_s)) - 1));
        Ts_eq = Ta - (Ta - Ts_in) * exp(-h * a * B * W/ ((1-epsilon)
* q_ms * c_s));

        [Ts_sol, Ta_sol] = vpasolve([Ts == Ts_eq, Ta == Ta_eq], [Ts,
Ta]);

        c_s_val = subs(c_s, Ts, Ts_sol);
        c_a_val = subs(c_a, Ta, Ta_sol);
        eta_s = double((Ts_sol - Ts_in) / (Ta_in - Ts_in));
        eta_a = double((Ta_in - Ta_sol) / (Ta_in - Ts_in));
        DeltaEx_a = double(-q_ma * c_a_val * (Ta_sol - Ta_in) * (1 -
T0 / (Ta_sol - Ta_in) * log(Ta_sol/Ta_in)));
        DeltaEx_s = double(q_ms * c_s_val * (Ts_sol - Ts_in) - T0 *
q_ms * c_s_val * log(Ts_sol/Ts_in));
        eta_Ex = DeltaEx_s / DeltaEx_a;

        Ts_results(i, j) = double(Ts_sol);
        Ta_results(i, j) = double(Ta_sol);
        eta_s_results(i, j) = eta_s;
        eta_a_results(i, j) = eta_a;
        DeltaEx_s_results(i, j) = DeltaEx_s;
        eta_Ex_results(i, j) = eta_Ex;
    end
end
```