DESIGN AND MANUFACTURING OF FORMING MOLDS FOR THERMAL STORAGE MATERIALS AND ANALYSIS OF THEIR THERMAL STORAGE STRUCTURES

by

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In response to the shortcomings of concentrated stress, difficult forming, and short service life of commonly used honeycomb ceramic thermal storage materials with square lattice holes, the author has developed a new type of low stress honeycomb ceramic thermal storage material by studying the structure, forming mold, and extrusion forming material of the thermal storage body. The author introduced the changes in specific surface area and porosity of heat storage materials with different geometric structures, and analyzed and compared the structural characteristics of two types of heat storage materials, namely heat storage balls and honeycomb bodies, under the premise of equal heat storage capacity. The trajectory of air-flow in the heat storage chamber was simulated using CFD software, and the pressure loss and centerline velocity changes of different shapes of honeycomb were analyzed. The flow characteristics, pressure distribution, and heat transfer performance of gas inside different shapes of honeycomb were calculated. The experimental results showed that the closer to the circular shape, the smaller the pressure loss of the centerline. The larger the equivalent diameter, the smaller the resistance along the path. From the perspective of cold pressure loss alone, regular quadrilateral holes and regular circular holes are the best choices for the shape of honeycomb openings. The centerline velocity of the equilateral triangle hole is the largest, indicating that the smaller the equivalent diameter is, the greater the average velocity at the outlet is. The resistance along the path of the round hole is the smallest, the regular quadrilateral hole is slightly larger, and the pressure loss of the equilateral triangle hole is the largest, which exceeds the round hole by nearly 1/3. Taking into account factors such as heat storage, specific surface area, flow characteristics, and heat transfer characteristics, quadrilateral honeycomb cells are the best choice.

Key words: *honeycomb, heat storage ball, opening rate, specific surface area*

Introduction

Energy is the material foundation for human survival, a necessary condition for social development and economic construction, and an important cornerstone for future human civilization innovation. Since the industrial revolution, the depletion of fossil fuels and the increasingly serious environmental and climate issues have made energy and environment a major issue in today's human society. Serious energy and environmental issues have brought huge hidden dangers to global economic and social development. Therefore, *developing new energy* is not only an urgent need for the current energy economy transformation, but also an inevitable

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choice for the sustainable development of human civilization [1]. In 2019, back propagation (BP) pointed out in the BP world energy resources statistical yearbook that the global demand for Primary energy increased by 2.9% in 2018, reaching the highest level since 2010. In 2018, carbon emissions reached 600 millionns, with a year-on-year growth rate of 2%, reaching the highest in recent years. However, according to the model, the speed of energy demand in 2018 should slow down under the trend of slightly weak economy and higher energy prices. Through in-depth analysis, the reason for the strong growth of energy demand is related to the abnormal weather in 2018. The energy demand for heating and cooling led to the growth of Primary energy consumption. Is extreme weather and continuously increasing carbon emissions a vicious cycle or a random event? It is worth pondering. According to the energy statistics of BP in 2018, the world's proven oil reserves in 2017 were 1.697 trillion barrels, which could provide 50.2 years of production based on the oil production in 2017. The proven reserves of natural gas is 193.5 trillion cubic meters, which can be exploited for 52.6 years based on the production level in 2017. The Proven reserves of coal can also meet the global production in 134 years. However, if the primary energy output in 2018 is taken as the calculation standard, the global oil can be exploited for 49.0 years, natural gas for 50.0 years, and coal for 128.5 years. Therefore, the transformation of the energy industry and society towards low carbon is urgent [2].

In this context, according to the vision of energy transformation and the basic strategic guidelines, and based on the low carbon economy theory of energy conservation and scientific energy use, the development of renewable energy will become an inevitable choice in the near future. In the 13th five year plan, it is pointed out that by 2020, the installed scale of wind power in China will reach over 210 million kW, and the installed capacity of solar power generation will reach over 110 million kW. Efforts will be made to promote the grid connection mechanism for wind and PV power generation, and action plans will be introduced to address wind, solar, and water waste, and it is proposed to control wind and light abandonment within 5% by 2020. Vigorously developing renewable energy as the main or core energy source for future development, this cannot be achieved without the national strategic policy and the support of corresponding technologies. For new energy sources such as wind power and PV with low energy density, thermal storage technology is one of the important technologies to improve the efficiency of new energy utilization and promote the sustainable development of renewable energy. Heat storage is a key component of regenerative burners, and the main types of heat storage used in China are heat storage balls and honeycomb bodies. Analyzing the structural parameters and gas-flow and heat transfer characteristics of different shaped heat storage bodies is of great significance for selecting suitable heat storage bodies and improving heat transfer efficiency.

Literature review

In response to China's vision and basic strategic guidelines for energy transformation, China vigorously promotes *carbon peaking and carbon neutrality*, incorporates *dual carbon* into the overall lay-out of ecological civilization construction, and advocates the use of clean energy. Solid heat storage technology plays an important role in replacing traditional coal-fired heating boilers and balancing power grids. Compared with other heat storage devices, solid heat storage devices have the characteristics of high heat storage temperature and large heat storage capacity, so they are vigorously promoted in promoting clean heating and reducing environmental pollution in China [3].

At present, scholars at home and abroad have carried out a lot of research on solid heat storage technology. Liu established a 2-D heat transfer model for the laying process of thermoplastic prepregs in ANSYS. Transient thermal analysis is conducted using the life and death unit technique. By analyzing the effects of mold temperature, laying speed, and heating temperature on the temperature field of the first layer of curved surface laying, the optimal processing parameters were obtained [4]. Wang believe that silicon carbide (SiC) ceramic materials have shown important application prospects in engineering and technology fields such as aerospace, nuclear energy, and automotive industry due to their excellent mechanical, thermal, and optical properties. In recent years, the requirements for high performance SiC ceramic components with complex shapes, such as lightweight space optical mirrors, have become increasingly stringent, which has driven the demand for ceramic processing technology. The traditional manufacturing techniques for SiC ceramic components include slip casting, isostatic pressing, and injection molding [5]. Waqar believes that ceramic-based molds can be used for cryogenic alloy parts, such as mounting brackets, which is possible with the aid of CAD modelling of casting molds, which allows instant printing of patterless molds [6]. The author's analysis of the structural parameters and gas-flow and heat transfer characteristics of different shaped heat storage bodies is of great significance for selecting suitable heat storage bodies and improving heat transfer efficiency.

Geometric structure analysis of heat storage body

According to the different shapes of heat storage bodies, there are mainly two types: heat storage balls and honeycomb bodies. According to the different shapes of openings, honeycomb bodies can be divided into four types: quadrilateral, circular, hexagonal, and triangular. The parameters used to measure the geometric structure of a heat storage body mainly include specific surface area and porosity. Specific surface area refers to the ratio of heat exchange area per unit length to volume in a unit body, while porosity refers to the ratio of porosity area to the cross-sectional area of the unit body. Table 1 lists the geometric parameter formulas for different forms of honeycomb.

Table 1. Formula for geometric parameters of heat storage body

	L	F	V	A_s	A_f	V_m
Square	a	$4a$	$(a+\delta)^2$	$\dfrac{4a}{(a+\delta)^2}$	$\dfrac{a^2}{(a+\delta)^2}$	$1-\dfrac{a^2}{(a+\delta)^2}$
	δ					
Regular triangle	a	$3a$	$\dfrac{\sqrt{3}(a+3.464\delta)^2}{4}$	$\dfrac{6.928a}{(a+3.464\delta)^2}$	$\dfrac{a^2}{(a+3.464\delta)^2}$	$1-\dfrac{a^2}{(a+3.464\delta)^2}$
	δ					
Round tube	d	πd	$(d+\delta)^2$	$\dfrac{\pi d}{(d+\delta)^2}$	$\dfrac{0.785d^2}{(d+\delta)^2}$	$1-\dfrac{0.785d^2}{(d+\delta)^2}$
	δ					
Regular hexagon	a	$6a$	$2.6(a+1.155\delta)^2$	$\dfrac{2.31a}{(a+1.155\delta)^2}$	$\dfrac{a^2}{(a+1.155\delta)^2}$	$1-\dfrac{a^2}{(a+1.155\delta)^2}$
	δ					

where L [mm] is the feature scale, F [mm^2] – the cross-sectional area of the unit flow channel, V [m^3] – the unit volume, A_s [mm^2] – the specific surface area, A_f [mm^2] – the opening rate, V_m [m^3] – the volume of the solid part per unit length of the unit body, d [mm] – the diameter, a [mm] – is the side length, and δ [mm] – the wall thickness.

Development of honeycomb ceramic heat storage body

- *Design of heat storage structure*: In response to the deficiency of stress concentration at the straight corner of the regular square honeycomb ceramic thermal storage body, the author designed a low stress honeycomb ceramic thermal storage body to reduce stress concentration at the straight corner of the lattice. The heat storage body is composed of four parts: honeycomb cell wall, honeycomb cell hole, cut corner of the heat storage body, and bottom foot of the heat storage body. The honeycomb cell hole is square, and the straight folding angle of the square cell hole is a rounded corner with a 90° arc transition. The shape of the heat storage body can be made into a rectangular cuboid or a cube according to requirements. The low stress honeycomb ceramic heat storage body is designed with a square lattice structure, maintaining the characteristic of high heat transfer specific area of the conventional square lattice honeycomb ceramic heat storage body. The structural feature of the 90° arc transition fillet of a square lattice hole avoids stress concentration at the straight bending angle of a conventional square lattice hole, ensures a smooth transition between the circular arc surface and the flat surface of the lattice hole, improves the distribution of mechanical stress during the extrusion forming process of the thermal storage body, enhances the comprehensive strength of the thermal storage body formed by extrusion, and achieves the goal of improving the production yield [7]. At the same time, it homogenizes the distribution of thermal stress during the use of the thermal storage body, slows down the damage process caused by the concentration of thermal stress at the straight corner of the square grid hole, improves the air-flow distribution and filling degree inside the grid hole, delays the melting rate of slag and hole wall inside the grid hole, and achieves the goal of extending the service life of the thermal storage body. The structural design of the chamfer of the heat storage body and the foot of the heat storage body ensures the alignment of the front and rear grid holes during the installation of the heat storage body, reducing the adverse effects of installation misalignment [8]. The advantages of heat transfer ratio of porous honeycomb ceramic heat storage body. The improved design of the transition surface structure of the square grid hole forming column edge and fillet alleviates the stress concentration of the 90° angle between the square grid hole walls of the heat storage body, improves the yield of the heat storage body production, delays the stress damage process of the heat storage body grid hole, reduces the degree of slag accumulation at the angle between the grid holes, and extends the service life of the heat storage body. The design of the inlet hole structure with a trumpet shaped inlet reduces the feeding resistance of the formed mud material. The three segment structure design of the lattice shaped column facilitates the rheological and transverse extrusion of the mud forming, reduces the processing stress caused by the surface roughness of the lattice shaped column, improves the density and extrusion yield of the honeycomb ceramic thermal storage body, improves the heat storage and release performance, and provides favorable conditions for increasing the area of the mud inlet channel of the mud inlet hole, facilitating the stable extrusion forming of the thermal storage body.

– *Design and preparation of extrusion forming molds*: In response to the problems of heat storage defects, complex forming process, and low yield caused by insufficient material supply during the extrusion forming process of conventional square lattice honeycomb ceramic heat storage bodies, based on the structure of low stress honeycomb ceramic heat storage bodies and referring to the design and research results of domestic honeycomb ceramic heat storage body extrusion forming molds, the extrusion forming mold was designed according to the ratio relationship of 1.1:1 between the die inlet and extrusion outlet. The designed low stress honeycomb ceramic thermal storage body forming mold is mainly composed of lattice shaped columns, mud discharge channels, metal bases, welding layers, mud inlet holes, and edge molds, among them, the grid hole forming column is composed of three sections: the square arc chamfer equal section section at the feeding end, the variable section section, and the square fillet transition equal section section at the discharging end. The feeding end is a trumpet shaped mud inlet, the mud inlet hole is a circular through-hole, the edge mold is a square or rectangular inner cavity equal section structure, and the included angle of the section is a natural processing chamfer.

– *Research on extrusion forming materials*: During the normal operation of a regenerative combustion system, the heat storage body periodically comes into contact with high temperature flue gas and ambient combustion air or gas. Through the heat storage and release of the heat storage body, the heat of the high temperature flue gas is transferred to ambient combustion air or gas, achieving the ultimate recovery of waste heat and high temperature preheating of ambient combustion air or gas, achieving the goal of efficient energy conservation. Therefore, the safe and stable operation of the heat storage body and the high strength heat exchange effect are the key factors that affect the efficient and energy-saving of the regenerative combustion technology. The heat storage system works under harsh conditions such as high temperature, iron oxide dust, and frequent temperature fluctuations for a long time, therefore, it is required that the thermal storage body have high fire resistance, high temperature structural strength, load softening temperature, as well as good thermal shock stability and resistance to iron oxide corrosion. As a heat storage carrier, the thermal physical properties of heat storage materials have a significant impact on their heat transfer efficiency, therefore, the raw materials with high specific heat capacity, thermal conductivity and density should be selected as far as possible to improve the heat storage/heat release capacity of the heat accumulator. Based on the aforementioned analysis, from the perspective of improving the service temperature of honeycomb ceramic thermal storage, alumina and mullite fine powder rich in Al_2O_3 are selected as the main raw materials for low stress honeycomb ceramic thermal storage, fully leveraging the advantages of Al_2O_3 based materials such as high melting point, high strength, high thermal conductivity, and low price. Considering the practical problems of high firing temperature, high thermal expansion coefficient, and poor thermal stability of Al_2O_3 based materials, on the premise of ensuring that the service temperature of the material is higher than 1400 °C to meet the service temperature requirements of the high temperature furnace, the thermal shock resistance of the material is improved by adding an appropriate amount of *hree stones* (sillimanite, Andalusite, Kyanite) and making use of the volume expansion effect of *three stones* during the mullitization process at high temperature to produce microcracks. Adopting various toughening techniques and additives, improving the composition and structure of ceramic grain boundaries, optimizing the micro-structure of materials, achieving the goal of reducing the sintering temperature and thermal expansion coefficient of Al_2O_3 ceramics, and improving the thermal shock resistance of thermal storage materials [9]. Add an appropriate amount of additives to the raw material ratio to improve the plasticity and flowability of the mud, facilitating the extrusion forming of the honeycomb thermal storage body. The designed formula is shown in tab. 2.

The square cross-section structure of the lattice forming column of the designed low stress ceramic heat storage mold retains the change in the specific surface area and opening rate of the square sphere. For the equal diameter sphere, there are two ways: square arrangement and monoclinic square arrangement. The opening rate of the square arrangement layer is a fixed value of 0.48. When using a positive arrangement, the specific surface area shows a decreasing trend as the diameter of the sphere increases.When the small balls are naturally stacked in the heat storage chamber, the total porosity after being filled by gravity is close to 0.39.

Table 2. Formula of low stress honeycomb ceramic thermal storage body extrusion material

Material name	Specifications	Content
Fused mullite	180 mesh	30-45
	324 mesh	10-24
White corundum	325 mesh	8-16
Kyanite	152 mesh	2-5
Sillimanite	325 mesh	3-6
Desilication zirconia	315 mesh	3-5
A-Al_2O_3 micro powder	–	5-10
Microsilica	–	3-8
Clay	–	2-4
Dispersing agent	–	0.5-1.5
Organic binder	–	5-9
Lubricant additives	–	1-3

Changes in specific surface area and porosity of different types of honeycomb cells

Figures 1(a) and 1(b) show the changes in specific surface area and porosity of a regular quadrilateral honeycomb as the opening area increases. The changes in other opening shapes are similar to those of a regular quadrilateral honeycomb. From the figure, it can be seen that as the opening area increases, the specific surface area of the honeycomb body shows a downward trend, while the opening rate shows an upward trend. As the area increases, the curve gradually becomes flat. When the wall thickness exceeds 2.0 mm, the trend of increasing specific surface area slows down. The opening rate is slightly different, as the opening area increases, the opening rate gradually increases, and the upward trend of the curve tends to be gentle.

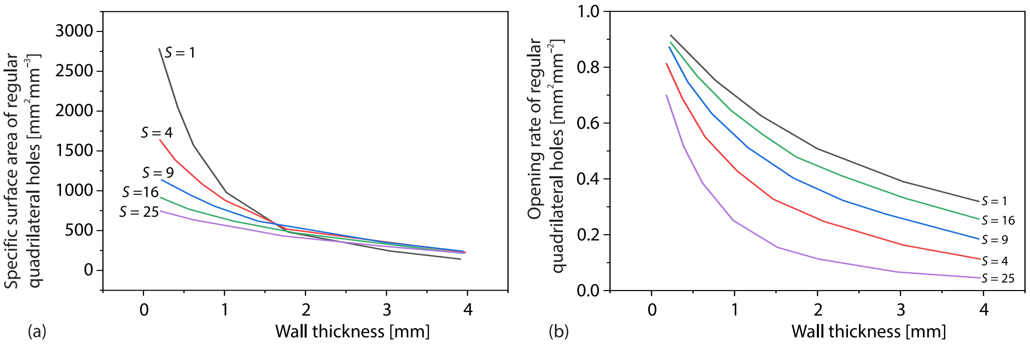

Figure 1. Specific surface area and porosity of regular quadrilateral holes; (a) specific surface area and (b) opening rate

Analysis of structural characteristics of different honeycomb structures with the same cross-sectional area

When the opening area is small and the wall thickness is thin, the specific surface area of the equilateral triangle hole reaches the maximum, as the cross-sectional area and wall thickness increase, the specific surface area rapidly decreases. When the cross-sectional area is greater than 9 mm^2 and the wall thickness is greater than 1.2 mm, the specific surface area and porosity reach the lowest. The specific surface area and porosity of regular hexagonal holes are smaller than those of square holes. The porosity of circular holes and regular quadrilateral holes is the same, but the specific surface area is smaller than that of regular quadrilateral holes. From this, it can be seen that under the same opening area, quadrilateral holes have the maximum specific surface area and opening rate. The maximum porosity indicates that the solid area has the largest volume and heat storage capacity. Comparing the two factors of heat storage and specific surface area, quadrilateral pores are the best choice [10].

Comparison of specific surface area of different types of heat storage bodies with the same opening rate

When the porosity is equal, the solid area is the same, ensuring the same heat storage capacity. The changes in specific surface area of different forms of honeycomb under the same porosity. Under the same cross-sectional area, the closer it is to a circular shape, the smaller its specific surface area. Under the action of gravity, the porosity of naturally accumulated equal diameter small balls is 0.39, and the specific surface area is 390. Compared with quadrilateral holes, under the premise of equal heat storage, when the side length of a square honeycomb is less than 4 mm, the smaller the side length, the greater the advantage of the specific surface area.

Numerical simulation of fluid-flow in different forms of heat storage chambers

Establishment of heat transfer models for different heat storage bodies

Inside the heat storage body, there is simultaneously heat release from flue gas or heat absorption from air and gas. There are three different forms of heat transfer between the surface of the heat storage body and the flue gas. The small balls are naturally stacked, and one channel of the honeycomb is selected as the fluid-flow area. The center is a gas channel, and the surrounding areas are solid areas, with a thickness of half of the normal wall. The surface in contact with the gas adopts gas-solid coupling boundary conditions, while the external part of the solid area adopts symmetric boundary conditions, and the rest adopts adiabatic boundary conditions.

Make the following assumptions:

- Ignoring the difference between smoke and air, replacing the physical parameters of smoke with the physical parameters of air.
- Neglecting the radiation heat transfer of smoke and air in the channel and only convective heat transfer.
- Neglecting the heat loss transmitted by the heat storage chamber to the outside world.
- The surface area and mass distribution of the heat storage body are uniform and the surface is smooth.

The control equations:

- Convective phase

$$\varepsilon\rho_f c_f \frac{\partial t_f}{\partial \tau} + \rho_f u_z c_j \frac{\partial t_f}{\partial z} = -a(t_j - t_z) \tag{1}$$

$$\rho_f = G_f \tag{2}$$

- For honeycomb bodies

$$(1-\varepsilon)\rho_s c_s \frac{\partial t_s}{\partial \tau} = \frac{\partial^2 t_s}{\partial \tau} + \frac{1}{r}\frac{\partial^2 t_s}{\partial r} + \frac{\partial^2 t_s}{\partial z} + a(t_f - t_s) \tag{3}$$

– For heat storage balls

$$\frac{1}{\alpha}\frac{\partial t_s}{\partial \tau}=\frac{\partial^2 t_s}{\partial \tau^2}+\frac{1}{r}\frac{\partial t_s}{\partial r} \tag{4}$$

where ρ_f is the free carge density, c_f – the current speed, and $\partial t_f/\partial \tau$ – the partial derivative of time.

The diameter of the small ball is 15 mm, and the structural parameters of the honeycomb are 9 mm^2 with an opening area and 1 mm wall thickness. Fluid velocity of 10 m/s, temperature of 1500 K, flow time of 30 seconds. The temperature of the solid area is 300 K.

Numerical simulation of gas-flow inside different heat storage bodies

With the fluid-flowing along the shortest radius of the curved surface, and its trace consisting of segments of small curves. This flow mode is the flow mode with the least resistance when the fluid-flows through multiple spheres, but the pressure loss in the heat storage chamber is still higher than that in the honeycomb heat storage chamber. Under the condition that the diameter of the regenerator, the diameter of the sphere and the gas inlet velocity are constant, the higher the height of the sphere, the greater the friction loss of the gas through the regenerative packed bed. Under the conditions of very low flow velocity and small height, the relationship between the Friction loss and the height is non-linear. At low velocity and low height, the smaller the height, the greater the friction loss per unit height:

Figure 2 shows the pressure loss diagram on the centerline of honeycomb bodies with different shapes. From the figure, it can be seen that the closer it is to a circular shape, the smaller the pressure loss on the centerline. The larger the equivalent diameter, the smaller the resistance along the path. From the perspective of cold pressure loss alone, regular quadrilateral holes and regular circular holes are the best choices for the shape of honeycomb openings. Figure 3 shows the centerline velocity diagram of honeycomb bodies with different shapes under the same operating parameters in cold state. The centerline velocity of the equilateral triangle hole is the largest, indicating that the smaller the equivalent diameter is, the greater the average outlet velocity is. The resistance along the path of the round hole is the smallest, the regular quadrilateral hole is slightly larger, and the pressure loss of the equilateral triangle hole is the largest, which exceeds the round hole by nearly 1/3.

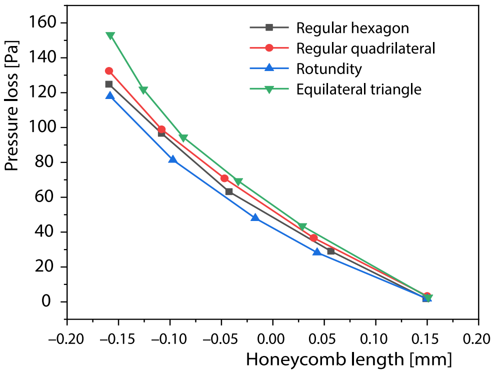

Figure 2. Pressure loss of gas-flowing through honeycomb bodies of different shapes

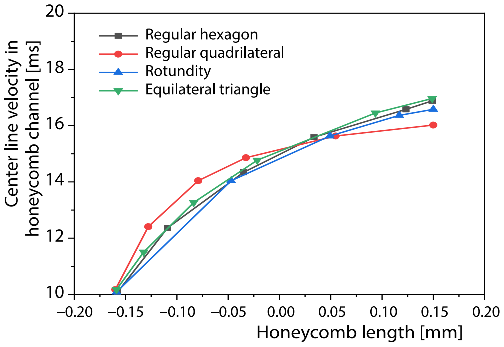

Figure 3. Centerline velocity of gas-flowing through honeycomb bodies of different shapes

Conclusion

The designed low stress honeycomb ceramic thermal storage body extrusion forming mold reduces the feed resistance of the formed mud, facilitates the rheological and lateral extrusion of the mud formation, and improves the density and extrusion yield of the honeycomb ceramic thermal storage body. The developed thermal storage body extrusion forming material has excellent plasticity and rheological properties, ensuring the smooth progress of the extrusion forming process. One of the prerequisites for a reasonable comparison of the geometric structure of a heat storage chamber is the consistency of its heat storage capacity. The equal opening rate can ensure that the solid volume in the same heat storage chamber is equal. When comparing heat storage bodies with different structures, the premise is that the opening rate is equal. The flow of gas in a small ball heat storage chamber advances along a spherical surface, and its flow trace is a curve connected by many small arcs. The gas has the shortest distance through the heat storage chamber. Compared with thermal storage balls, honeycomb bodies have advantages in pressure loss and specific surface area. When the opening rate is equal, the triangular honeycomb has the maximum specific surface area. When there are limitations on the area of the heat storage chamber and a large heat exchange is required, the triangular honeycomb can be used, but the opening area should not exceed 9 mm^2 and the wall thickness should not exceed 1.2 mm. The internal flow field distribution of honeycomb bodies with different opening shapes is similar, and regular quadrilateral holes have lower pressure loss and air-flow distribution, but the opening area should not be greater than 16 mm^2. Taking into account factors such as heat storage, specific surface area, flow characteristics, and heat transfer characteristics, quadrilateral honeycomb cells are the best choice.

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