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Preliminary Design and Analysis of Regenerative Heat Exchanger

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Heat regenerators transfer heat from one gas to another, with by storage in solids. This type of heat exchanger is used primarily when heat has to be transferred between enormous amounts of gases, when the gases are dirty and liable to plug up the recuperative heat exchangers, or when the gas is too hot or reactive. Regenerative heat exchanger can provide at the same volume much higher heat transfer area and lower friction factor than recuperative heat exchanger. Furthermore, regenerative heat exchanger has in most cases better efficiency and its construction is much simpler.
The calculation of this type heat exchanger is relatively complicated. Moreover, a suitable and adequately accurate calculation method is not freely available. Those are the main reasons why the companies are not interested in this type of heat exchanger. On the grounds of requirements from companies we started to deal with design of regenerative heat exchangers and creation of suitable calculation model that would cover all their requirements.
The various possibilities of regenerative heat exchanger applications will be described in the paper. For various types of geometries of heat transfer surface their advantages and disadvantages will be described. On the basis of measurements of several types of heat transfer surfaces geometries their possibilities of heat absorption and amount of pressure drop will be compared. The mathematical models for calculation of these heat exchangers will be the main issue of the paper. The possibilities of improvement and extension of the simple calculation model will be also described/introduced. This model can be used for preliminary calculation of regenerator for given purpose.
Simultaneous using of regenerator as heat exchanger and a reactor in which, for example, can take place cleaning of waste gas will be discussed.
The possibility of simultaneous use of regenerative heat exchanger as the reactor, where cleaning of waste could take place, will be considered.

1. Introduction

A regenerator is a type of heat exchanger where both fluids pass alternately over storage material and is used to improve an energy efficiency not only in high temperature processes. This type of heat exchanger can be used also in heat recovery systems. A hot gas passes through channels of a storage material and gives up part of a heat to the storage material. The hot gas is then switched off and a cold gas passes through the same channels and the heat is regenerated from the storage material to the gas. Various materials and shapes can be used as storage materials.
Regenerators are divided into two groups: fixed-bed and rotary regenerators. In a fixed-bed regenerator (see Figure 1), a single fluid stream has cyclical or reversible flow. Valves are employed to switching of flowing the hot and cold gas streams.

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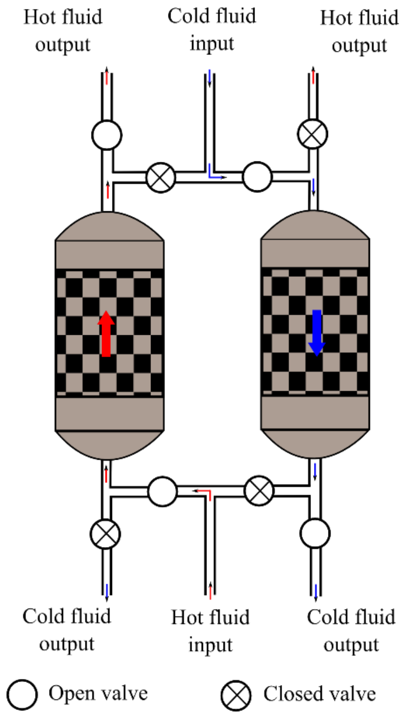


Figure 1: Function of fixed-bed regenerative heat exchanger

In rotary regenerators (see Figure 2), the storage material rotates continuously through two counterflowing streams of fluids. Only one stream flows through a section of the storage material at a given time. However, both streams eventually flow through all sections of the storage material during one rotation.

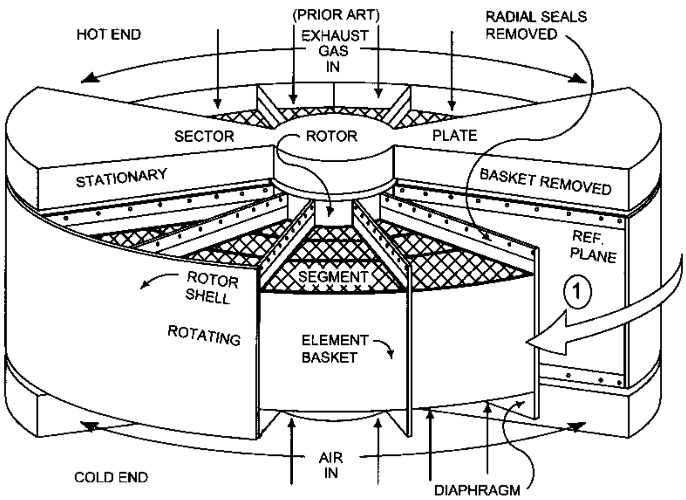


Figure 2: Function of rotary regenerative heat exchanger (Hastings N., 2013)

Fixed-bed regenerators are normally operated in pairs. It means that two or more regenerators are used in parallel because of the requirement for continuous stream of the gas. During one part of a cycle, the hot gas flows through one of regenerators and heat up the storage material, while the cold gas flows through and cools down the storage material in the second regenerator. Both gases directly contact storage material in the regenerators, although not both at the same time since each is in a different regenerator at any given time. After a sufficient amount of time, the cycle is switched so that the cooler storage material in the second

regenerator is preheated with the hot gas, while the hot storage material in the first regenerator exchange their heat into the cold gas. This cycle is permanently repeated.
The advantages of regenerators over recuperators are that they have a much higher surface area for a given volume. Hence, the regenerator usually has a smaller volume and weight than an equivalent recuperator. It means, regenerators are more economical in terms of materials and manufacturing. The storage material of regenerators also has a degree of self-cleaning characteristics, reducing fluid-side fouling and corrosion. Regenerators are thus ideal for gas-gas heat exchange.

2. Application of regenerative heat exchangers

The recovery of waste heat is a necessary part of improving process efficiency in high temperature applications or energy demanding processes. For example, a waste heat contained in exhaust gases from various processes can be used to preheat combustion air or other process medium. This preheating can significantly improve the efficiency of given process.
The advantages of regenerators over recuperators are higher efficiency, the high temperature of the input gas and the much higher surface area for the given volume. One of disadvantages connected with regenerators is mixing both streams after the flow is switched. But, in those applications where these regenerative heat exchangers are used, the impact of this mixing of fluids is generally not significant.
Rotary regenerators and regenerators with fixed-bed have different applications and differ in some of their advantages and disadvantages relative to recuperative heat exchangers. Rotary regenerators can be designed to withstand gas temperatures up to 500 °C. Rotary regenerators are employed in chemical plants, in ships, and in electricity generating stations for the utilization of the waste heat in a preheating air for combustion (Hewitt et al., 1994). Rotary regenerators are also used for lower temperature processes, for example, in air conditioning applications.
Fixed bed regenerators can be designed to withstand gas temperatures up to 1,400 °C and are especially used to provide high temperature process gasses in the glass and steel industries, in power plants and in waste heat recovery systems (Zarrinehkafsh and Sadrameli, 2004). At this level of the temperature, the storage material must be made from a ceramic material, which has a low thermal conductivity.

3. Basic equation for calculation of regenerative heat exchangers

3.1 Theoretical model of heat transfer calculation of regenerators

The performances of the regenerator include resistance characteristics and thermal characteristics. Therefore, it is necessary to know how to calculate a pressure drop and a heat transfer in this type of heat exchanger.
We want to deal with the fixed-bed regenerator in our research. In this reason, only methods for calculation of this heat exchanger type will be described. A heat transfer rate in regenerators is a function of many interdependent parameters, such as a sphere diameter and a height of the fixed bed, gas and air velocities, and a reversal time, and temperatures of the cooled and preheated gas. These parameters were described by (Schack, 1965) and (Kern, 1950).
The simplest calculation method is based on a mathematical model according to (Hausen, 1983). The regenerator effectiveness is only dependent upon four dimensionless parameters (two parameters for hot fluid and two parameters for cold fluid):

- reduced length Λ - is an indication of "thermal size" of the regenerator in relation to thermal load.

$$\Lambda = \frac{\alpha A}{\dot{M}_g \, C_{p,g}} \tag{1}$$

- reduced period Π - is the period duration, of a heating or cooling part of the cycle to which it refers.

$$\Pi = \frac{\alpha A (P - L / u)}{m_m C_{p,m}} \tag{2}$$

These parameters can be used for design purposes of regenerators. This simple method is not sufficiently accurate. Therefore, this model is not suitable for real design of the regenerative heat exchanger.
The exact mathematical models of regenerators are based on partial differential equations representing the spatial and temporal variations of the temperature of the gas, T_g, and of the storage material, T_m.
(Zarinekafash and Sadrameli, 2004) derived the governing differential equation under some assumptions for the fluid phase:

$$M_g C_{p,g}\left(\frac{\partial T_g}{\partial x}+\frac{\varepsilon}{u}\frac{\partial T_g}{\partial t}\right)=\rho_s C_{p,m}(1-\varepsilon)\frac{\partial T_m}{\partial t}=-k_m A\frac{\partial T_m}{\partial y}=-\alpha A\left(T_m-T_g\right) \quad (3)$$

In a case the internal resistance to heat transfer of the storage material exist, a heat balance on a solid phase becomes:

$$\rho_m C_{p,m}\frac{\partial T_m}{\partial t}=k_m\nabla^2 T_m \quad (4)$$

The boundary and initial conditions are need to solve the differential equation. These conditions can be find in (Zarinekafash and Sadrameli, 2004) or in (Sadrameli and Ajdari, 2015).

3.2 Theoretical model of pressure drop calculation in the regenerators

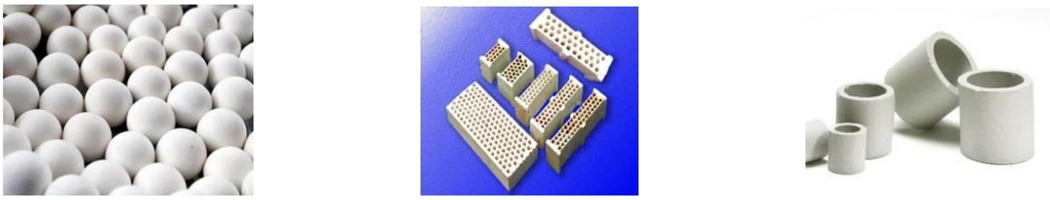
The primary reference for the calculation of pressure drop in packed beds is proposed by (Ergun, 1952), see Eq(5).

$$\frac{\Delta p}{H}=1.75\left[\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho U^2}{d_p}\right]+150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu U}{d_p^2} \quad (5)$$

This method is widely used for evaluation of the pressure drop and considered to be satisfactory over the range of flow rates encountered in the regenerator, resp. in the packed bed.
However, some researchers consider coefficients, 1.75 and 150 in this equation, do not provide good results. (Hicks, 1970) considered these two coefficients are not constants but are the functions of Reynolds number. (Bradshaw and Myers, 1963) found their measured values of the pressure drop for the bed of Celite cylindrical packing, are half as the results calculated by Ergun's equation. (Handly and Heggs, 1968) also found that Ergun's equation was not applicable to predict the pressure drop of irregular bed packed with sphere, cylinder, ring or plane. (MacDonald et al., 1979) considered the two coefficients are 180 and 1.8 respectively for the bed of spherical packing. (Yu et al., 2002) determined these two coefficients are 203 and 1.95 respectively for the randomly packed bed of uniform spheres (ball packed-bed regenerator).

4. Types of storage materials

The storage material can be made from different type of material. Because solids have a very large heat capacity compared to gases, they are used as an intermediary storage of the heat. Their selection depends on given conditions and requirements, especially temperature. For very high temperature should be use the ceramic storage material. For low or moderate temperatures, the heat storage material can be made of metal, e.g., steel or aluminium.
There are also exist many types of storage material (see Figure 3). For large regenerators can be use bricks. It is also possible to build the packing of molded bricks. For smaller regenerator can be use honeycombs, spherical particles, monolith, woven-screen or Raschig rings.



(a) Spherical particles[1] (b) baffle bricks[2] (c) Raschig rings[3]

Figure 3: Some types of geometry of storage materials

[1](JiangXi JinTai Special Material Limited, 2016a), [2](VERTIX Co., 2016), [3](JiangXi JinTai Special Material Limited, 2016b)

According to (Hewitt et al., 1994) honeycombs are less sensitive to a dust and they have the very low pressure drop. On the other hand, balls and rings have a higher heat transfer coefficient, but they are sensitive to blocking by dust and the pressure drop is very high. (Duprat et al., 2001) calculated that the fixed bed of particles gives both the highest efficiency and the highest pressure drop, whereas the monolith gives the lowest ones. The results of these calculations are shown in the Table 1.

Table 1: Comparison of heat transfer efficiency and pressure drop of heat exchangers working under the same operating conditions: L = 0.3 m, D = 0,14 m, W = 50 kg/h, tc = 50 s. (Duprat et al., 2001)

Storage material	ε	α (m-1)	η (%)	Δp (Pa)
Monolith	0.89	3,230	90.7	126
Woven screens	0.725	3,210	97.9	1,225
Spherical particles	0.5*	3,000	99.0	7,290

*dp = 1 mm

5. Future works

Currently, a testing equipment is preparing. Our goal is measurements of characteristics of various storage materials to finding out their effect on the heat transfer and pressure drop. On the basis of these measurements we would like to improve the simplified calculation model. These measurements should be also to provide the information which storage material is suitable for various requirements.
In other step we want to test this regenerative heat exchanger in collaboration with Eveco Brno, s.r.o. company in real operation or pilot plant. In the last step we would like to consider possibility of application of regenerative heat exchanger as heat exchanger and a reactor simultaneously. For example, the regenerative heat exchanger could be serve to cleaning of flue gas stream.

6. Conclusion

In the paper, the fixed-bed regenerative heat exchanger is described. Other research is necessary to propose the suitable and adequately simple calculation method for design this type of heat exchanger. Therefore, the testing equipment is preparing. Our goal is measurements of the characteristics of various fixed-bed to finding out their effect on the heat transfer and pressure drop. It means, we need to measure the temperatures at the input and output from the exchanger, time to warm up to given output temperature and pressure drop.
We would like to employ the regenerative heat exchanger also as the reactor simultaneously. It means, the regenerative heat exchanger should be serve to heating or cooling of the gas stream and also for example to cleaning of the flue gas stream.

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Nomenclature

Latin symbols

A	heat transfer area, m^2
C	specific heat capacity, J/(kg.K)
dp	diameter of particles/balls, m
H	height of bed, m
k	thermal conductivity, W/(m.K)
L	bed length, m
m	mass of material, kg
M	mass velocity, kg/s
P	period, s
t	time, s
T	temperature, K
u	fluid velocity, m/s
U	fluid velocity based on empty column cross-section, m/s
x	axial distance
y	direction normal to the matrix surface

Greek letters

α	heat transfer coefficient, $W/(m^2.K)$
Δp	pressure drop, Pa
ε	average void fraction, -
ρ	fluid density, kg/m^3

Subscripts

m	matrix
g	gas

References

Bradshaw R.D., 1963, Myers J.E., Heat and mass transfer in fixed and fluidized beds of large particles, AIChE.J., 9(5), 590-598.

Ergun S., 1952, Fluid flow through packed columns, Chem. Eng. Prog. 48.

Handly D., Heggs P.J., 1968, Momentum and heat transfer mechanisms in regular shaped packings, Trans. Inst.Chem.Eng. 46 (9) T251-T259.

Hastings Nathan., 2013, Contact seal system and method for rotary air ducts. Inventor: Hastings Nathan. United States Patent Application Publication. US 2013/0327495 A1. 2013

Hausen H., 1983, Heat Transfer in Counter Flow, Parallel Flow and Cross Flow, McGraw Hill, New York.

Hewitt G.F., Bott T.R., Shires G.L, 1994, Process heat transfer, CRC Press : Begell House, Boca Raton.

Hicks R.E., 1970, Pressure drop in packed beds of spheres, Ind. Eng. Chem. Fund. 9, 500.

Duprat F., Lopez G., 2001, Comparison of performance of heat regenerators: Relation between heat transfer efficiency and pressure drop. Int. J. Energy Res., 25: 319–329. DOI:10.1002/er.681

JiangXi JinTai Special Material Limited, 2016a, Inert Ceramic Ball <www.ceramic-honeycombs.com> accessed 03.05.2016

JiangXi JinTai Special Material Limited, 2016b, Ceramic Raschig Ring <www.ceramic-honeycombs.com> accessed 03.05.2016

Kern D.Q., 1950, Process Heat Transfer, McGraw hill: New York.

MacDonald F., Ei-Sayed M.S., Mow K., Dullien F.A.L., 1979, Flow through porous media – the Ergun equation revised, Ind. Eng. Chem. Fundam. 18(3), 199-208.

Sadrameli S.M., Ajdari H.R.B., 2015, Mathematical modelling and simulation of thermal regenerators including solid radial conduction effects, Appl. Therm. Eng., 76, 441-446.

Schack A., 1965, Industrial Heat Transfer, Chapman and Hall: London.

VERTIX Co., 2013, Honeycomb Ceramic Filters <www.vertix.co/> accessed 03.05.2016

Yu J., Zhang M., 2002, Study on performance of the ball packed-bed regenerator: experiments and simulation, Appl. Therm. Eng., 22, 641–651, DOI:10.1016/S1359-4311(01)00116-8

Zarinekafsh M.T., Sadrameli S.M., 2004, Simulation of fixed bed regenerative heat exchangers for flue gas heat recovery, Appl. Therm. Eng., 24(2), 373–382.