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THERMAL CONDUCTIVITY OF PELLETIZED CERAMIC PACKINGS

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The results of an experimental study of the thermal conductivity of various pelletized packing systems with pellets 1-4 mm in diameter in the temperature interval 100-1600°C are examined. A formula is derived for the thermal conductivity.

The thermal conductivity of pelletized packing systems was measured by the stationary method in a cylinder with an internal electrical heater on the apparatus previously described in [4, 5].

The heater was a tungsten rod, 8 mm in diameter, surrounded by a thin walled ceramic tube.

Table 1

Characteristics of Materials Investigated

Pellet material	Aluminum oxide					Zirconium dioxide	Cast iron
Diameter, mm	3.2 ± 0.6	2.2 ± 0.1	1.7 ± 0.3	1.7 ± 0.3	1.0 ± ± 0.25	1.5 ± ± 0.25	1.5 – 4
Density g/cm^3	2.6	3.6	3.6	2.8	3.6	4.5	—
Bulk weight of pellets, kN/m^3	10	20	19	13	18	25	50
Porosity of packing with account for open porosity of pellet material, %	55	40	40	60	40	45	40

In this method the thermal conductivity is determined from the radial heat flow through the packing, which is located in the gap between two coaxial thin-walled cylinders, and from the temperature difference between these cylinders, using the formula for an infinite cylinder.

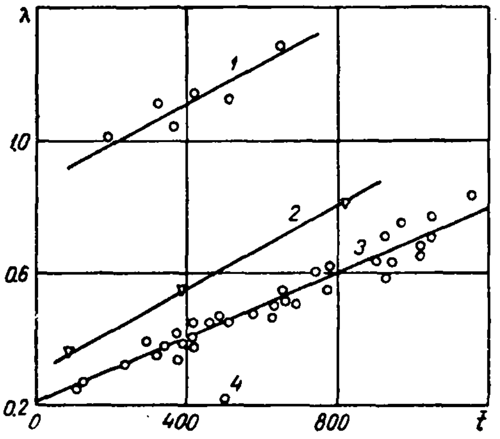

Fig. 1. Temperature dependence of thermal conductivity of pelletized aluminum oxide packings (d = = 1.7 mm) in different gases: 1) Helium, 2) air, 3) argon, 4) vacuum.

To reduce end heat losses, the cylinder assembly was divided vertically by thin fireclay discs into three equal independent sections. The height of the assembly was 270-290 mm, its outside diameter 35-40 mm; auxiliary thermal insulation was added at the end faces. Temperature measurements were made with chromel/alumel, platinum/platinum-rhodium, and tungsten/iridium thermocouples.

The basic data on the packings investigated are presented in Table 1.

The initial materials Al_2O_3 and ZrO_2 may contain up to 1% CaO and SiO_2. The sintering temperature of the ceramic pellets was approximately 1650±50°C.

The theoretical minimum porosity of a system of spherical particles of the same diameter is 25.95%. Measurements on metallic spheres give a porosity significantly greater than the theoretical, approximately 40% [6]. For the materials investigated the porosity of the packing, including the open porosity of the pellet material, was even greater – 40-60%. The thermal conductivity of the packing strongly depends on the filler gas [3] (Fig. 1). Analytically, for the temperature interval 100-1000°C these relations may be written:

$$\begin{aligned} &\text{for helium} \quad \lambda=0.87\,(1+0.69\cdot 10^{-3}t),\\ &\text{for air} \quad \lambda=0.30\,(1+2.08\cdot 10^{-3}t),\\ &\text{for argon} \quad \lambda=0.21\,(1+2.34\cdot 10^{-3}\,t). \end{aligned} \tag{1}$$

The small difference in thermal conductivity for packings in atmospheres of argon and air is explained by the approximate equality of the thermal conductivity of these gases. Thus, at 100°C the thermal conductivity of air is only 1.5 times greater than that of argon. The thermal conductivity of helium at the same temperature is approximately 5.6 times greater than that of argon. Accordingly, the thermal conductivity of the pellets in a helium medium is significantly greater than in air and argon (Fig. 1).

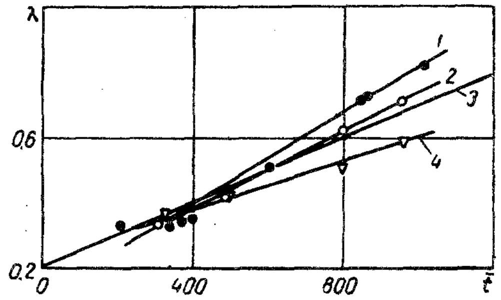

Fig. 2. Temperature dependence of the thermal conductivity of pelletized aluminum oxide packings with different pellet diameters in an argon medium: 1) d = 3.2 mm, 2) 2.2 mm, 3) 1.7 mm, 4) 1.0 mm.

For particles with an appreciable difference in dimensions in different directions the particle distribution may have a significant influence on the thermal conductivity of the system, this influence being the greater, the higher the temperature level and the solid-gas thermal conductivity ratio [7].

If all the particle dimensions are approximately the same, then it can be assumed that, for random packing, the shape of the particles does not, as a rule, have much effect on the thermal conductivity.

The thermal conductivity of pelletized packings is influenced to some extent by gas convection, particularly in systems with large particle size. At constant temperature, the change in the convective contribution to heat transfer for the range of pellet diameters examined (1-4 mm) may be disregarded to a certain approximation [6]

The experimental temperature dependence of the thermal conductivity of pelletized aluminum oxide packings with different pellet diameters is shown in Fig. 2.

Over the temperature range 200-600°C the data for all pellet diameters are quite similar. With increase in temperature, the increase in thermal conductivity is more intense for large diameters. Obviously, this is connected with the screening effect on radiative heat transfer, i.e., the greater the number of granules per unit length, the lower the contribution of radiation to the overall heat transfer.

The temperature dependence of the thermal conductivity for different sizes of pellets in an argon medium in the temperature interval 100-1000°C can be expressed approximately in the form

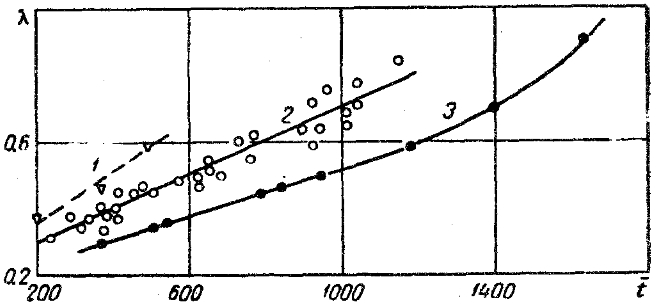

Fig. 3. Thermal conductivity of pelletized packings in an argon medium. 1) Cast iron d = 1.5-4 mm; 2) aluminum oxide d = 1.7 mm; 3) zirconium dioxide d = 1.5 mm.

$$\begin{aligned}\lambda&=0.13\ (1+5.35\cdot10^{-3}t),\\ \lambda&=0.14\ (1+4.25\cdot10^{-3}t),\\ \lambda&=0{,}21\ (1+2.34\cdot10^{-3}t),\\ \text{and}\quad \lambda&=0.23\ (1+1.6\cdot10^{-3}t)\end{aligned} \tag{2}$$

where d = 3.2, 2.2, 1.7, and 1.0 mm, respectively.

Investigation of a number of materials showed that the thermal conductivity of a granular system depends only slightly on the thermal conductivity of the starting material (Fig. 3). Thus, the thermal conductivities of cast iron, aluminum oxide, and zirconium dioxide packings at ~300°C differ by a factor of less than 1.5, whereas the thermal conductivities of cast iron and zirconium dioxide at these temperatures differ by a factor of more than 10.

Likewise, the density of the pellet material has little influence on the thermal conductivity of the packing (Fig. 4). The graph shows that the results for two densities are in close agreement.

These conclusions are confirmed by the data on the thermal conductivity of pelletized materials obtained by other authors. Thus, the thermal conductivity of hollow steel balls (diameter 8-9 mm) at room temperature in air is 0.23-0.27 W/m°C, the thermal conductivity of lead shot (solid, d = 1.55 mm) is 0.29 W/m°C [2].

The slight influence of the thermal conductivity and density of the solid phase can be explained by the presence of a marked contact thermal resistance between particles [8, 9]. The greatest contribution to the thermal conductivity of the system is that made by the gaseous medium, and at high temperatures (> 1000°C) by radiation. However, this does not mean that the starting material of the solid phase has no effect on the thermal conductivity of the packing. Its influence may be exerted through the roughness, roundness, and hardness of the pellet surface (hence the form of contact) and the emissivity of the material (particularly important at high temperatures).

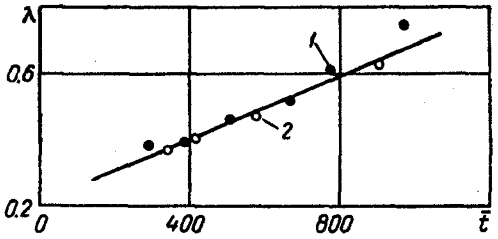

Fig. 4. Thermal conductivity of pelletized aluminum oxide packings, d = 1.7 mm, at packing densities of: 1) 3.5 g/cm^3; 2) 2.8 g/cm^3.

With increase of temperature the thermal conductivity of granular materials increases. This is connected with an increase of the thermal conductivity of the gaseous medium and radiative heat transfer.

At the packing volumes and pellet diameters examined, increase of the convective contribution to over-all heat transfer may evidently be neglected. It is known that the formula describing the development of convection currents contains the product of the Grashof and Prandtl numbers [6]. According to the kinetic theory of gases [12], this product is directly proportional to the temperature drop and inversely proportional to the fourth power of the absolute temperature. This suggests even the possibility of a slight decrease in convection currents with increase in temperature.

In the temperature interval 100-1000°C various granular ceramic materials have an almost linear dependence of thermal conductivity on temperature. At higher temperatures the increase in thermal conductivity becomes steeper (Fig. 3).

The formulas of Bogomolov and Rassel [3, 6] are those most frequently used for calculating the thermal conductivity of loose materials. Comparison of the experimental results with calculations (Table 2) shows that the Bogomolov formula is suitable only for media with low thermal conductivity, such as argon and air, and the Rassel formula for media with high thermal conductivity, for example, helium.

Table 2*

Thermal Conductivity of Pelletized Al_2O_3 Packings with d = 1.7 mm

Medium	t, °C	λ_{exp} (data of Fig. 1)	Thermal conductivity λ_i according to:			$\frac{\lambda_i - \lambda_{exp}}{\lambda_{exp}}$ 100 %		
			Bogomolov	Rassel	(5)			
			$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$
Argon	200	0.31	0.30	0.16	0.31	−3	−48	0
	600	0.51	0.47	0.25	0.50	−8	−52	−2
	1000	0.70	0.66	0.34	0.69	−6	−51	−1
Air	200	0.42	0.46	0.25	0.38	10	−60	−10
	600	0.67	0.72	0.38	0.57	8	−43	−15
	1000	0.92	0.99	0.49	0.76	8	−47	−17
Helium	200	0.99	2.38	1.27	1.37	140	28	38
	600	1.23	3.86	1.66	1.56	210	35	27

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*Calculation carried out for a porosity of 40% using tabulated data on the thermal conductivity of the starting materials [9, 10].

The derivation of a general theoretical formula describing the thermal conductivity of pelletized packings taking account of the different factors is very complex. Therefore, for practical calculations, it is convenient to use the experimental data and make a number of simplifications to obtain an approximate semi-empirical formula reflecting the influence of the main factors. It is known that the thermal conductivity of systems of pellets is composed of contributions due to the thermal conductivity of the solid phase, the gaseous medium (allowing for convection), and thermal radiation, that is, in general

$$\lambda=\lambda_1+\lambda_2+\lambda_3. \qquad (3)$$

Considering that the actual contact area in a pellet system is small [8, 9], one would expect the influence of the thermal conductivity of the solid phase on the thermal conductivity of the system to be slight. This conclusion is confirmed by the experimental data. In fact, the thermal conductivities of packings of different pelletized materials in the same gaseous medium at low temperatures, where thermal radiation can be neglected, are approximately the same. Therefore it may be considered that the contribution to the over-all thermal conductivity made by the thermal conductivity of the solid phase (contact thermal conductivity) is approximately constant. To be specific, we will take as this quantity the thermal conductivity of cast iron pellets in vacuum at 0°C [3], i.e., $\lambda_1 = 0.07$ W/m°C.

It is natural to suppose that the contribution of the gaseous medium to the over-all thermal conductivity of pelletized packings is proportional to the thermal conductivity of the gas, i.e., $\lambda_2 = a\lambda_0$. From an analysis of the experimental data (Fig. 1), extrapolated to 0°C, an average value of the constant $a = 8.4$ was found for different gaseous media. It was further assumed that the increase in the thermal conductivity of pelletized packings with increase in temperature is entirely due to radiative heat transfer. In general form the contribution of thermal radiation to the thermal conductivity of pelletized packings may be written

$$\lambda_3 = f\,(t,\ d,\ \varepsilon,\ p). \tag{4}$$

The porosity of different packings after compaction is roughly constant. Therefore, in our case the dependence on porosity was not examined. The emissivity of the material was also assumed constant.

It is known that the radiative thermal conductivity (conductivity due to radiation [6]) is proportional to T^3. However, taking account of the linear character of the change in the thermal conductivity of pelletized packings of constant diameter in the interval 0-1000°C (Fig. 2), it was found that $\lambda_3 \sim \sqrt[3]{d}\,t$.

In this case the proportionality factor is equal to $0.4 \cdot 10^{-3}$. Thus Eq. (3) can be written in the form

$$\lambda = 0.07 + 8.4 \cdot \lambda_0 + 0.4\sqrt[3]{d}\,t\,10^{-3}. \tag{5}$$

Formula (5) can be used for the approximate calculation of the thermal conductivity of ceramic and metallic (Tables 2 and 3) pelletized packings 1-4 mm in diameter in different gaseous media and in a vacuum over the temperature range 0-1000°C.

Table 3

Thermal Conductivity of Pelletized Cast-Iron Packings

Medium	t, °C	λ_{exp} (data of [3])	λ_{calc} according to (5), diameter 1.7 mm	$\frac{\lambda_{calc} - \lambda_{exp}}{\lambda_{exp}} \cdot 100\%$
Vacuum	200	0.15	0.17	13
	400	0.23	0.26	13
Argon	200	0.32	0.31	−3
	400	0.47	0.40	−15
Air	200	0.46	0.38	−17
	400	0.66	0.47	−29
Helium	200	1.45	1.37	−6
	400	1.68	1.46	−13

Formula (5) does not reflect the influence of the emissivity of the material, the form of contact between particles, or the porosity. The greatest influence, particularly at high temperatures, may be that of thermal radiation.

NOTATION

λ – thermal conductivity of pelletized packing; λ_0 – thermal conductivity of gas at 0°C; a – a constant; λ_1, λ_2, λ_3 – contribution to over-all thermal conductivity of packing of thermal conductivitv of solid phase, gaseous medium (including convection), and radiation, respectively; t – mean temperature in °C; T – temperature in °K; d – pellet diameter; ε – emissivity of material; p – porosity.

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