HEAT TRANSFER IN A MULTISTAGE APPARATUS OF FLUIDIZED-BED TYPE

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Results are given on the heat transfer between the gas and the granular material in a multistage apparatus, and comparison is made with calculations.

In the present work we compare experimental measurements on heat transfer with calculated values obtained from the formulas of [2], and determine the change in the temperature gradients in various parts of a multistage as used in heat engineering and in the performance of various technical processes [1].

The tests were made on a particular type of multistage apparatus consisting of a combination of direct-flow parts with countercurrent flow of the heat carrier as a whole over the apparatus (Fig. 1a). In Fig. 1a four stages in the apparatus are shown; each stage is part of the pneumatic tube 3, 7, 11, or 15 (height 0.5 m and internal diameter 0.027 m) and a separator 4, 8, 12, or 16 of inertial collision type [3].

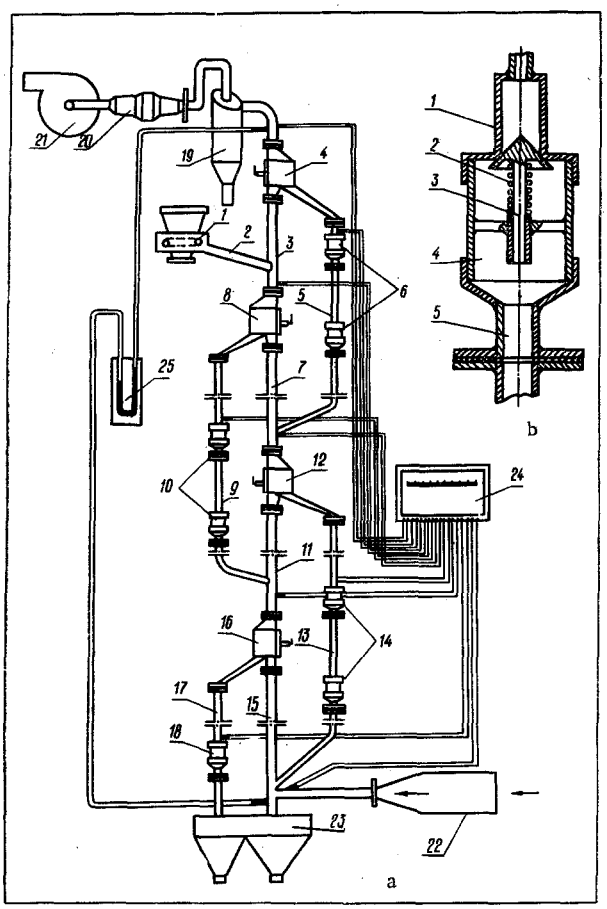

Fig. 1. a) The apparatus; b) baffle valve: 1), 5) nuts; 2) spring; 3) rod with valve; 4) body.

The heat-carrying gas comes from the oven 22, moves upwards from the bottom, passes in sequence through sections 15, 11, 7, and 3 of the apparatus, and is extracted by the fan 21. The amount of gas passing through the apparatus during the run was recorded by the RS-100 gas counter 20.

The polydisperse material is supplied by the hopper 1 and inlet 2 to the lower part of the upper stage 3 of the apparatus, and it is carried by the gas to the separator 4 where it leaves the flow and passes via the outlet 5 to stage 7, etc.

The material is collected in bunker 23 when it has passed through all stages of the apparatus. The small particles carried off by the gas flow are deposited in the cyclone 19. A suitable hydrodynamic ceiling is provided to organize the gas flow in the required direction in the transfer sleeves 5, 9, 13, and 17 (d_{tu} = 0.008 m), each of which has two baffles 6, 10, 14, and 18. The design of the baffle is shown in Fig. 1b. This disposition of the baffles facilitates production of the moving close-packed layer in the couplings, in which the temperature was monitored. Of course, the height of the moving close-packed layer should be arranged for each stage to avoid gas leak along the walls,

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on the basis of the characteristics of the material and the hydraulic resistance of the apparatus.

The two baffle valves in each transfer section provide for continuous transfer of the material as a whole through the apparatus.

The temperatures of the gas and the material were monitored by nine Chromel–Alumel thermocouples placed as shown in Fig. 1. These were read by the electronic potentiometer type ÉPP-09 shown at 24. The hot junctions recorded the gas temperature and were protected by thin copper grids to avoid contact with particles of the material.

As we have previously described [3] detailed measurements on the separator and the method of calculating the efficiency of particle removal, we do not consider these topics here.

The throughput was determined by weighing the material supplied to the hopper. The measurements were made with quartz sand with various mean particle diameters: $d_M = 0.3 \cdot 10^{-3}$ M, $d_M = 0.5 \cdot 10^{-3}$ M, $d_M = 0.75 \cdot 10^{-3}$ M.

The material flow concentration μ_c was varied within limits 0.2-0.5 kg/kg; the initial gas temperature was varied between 473 and 673°K in steps of 50-100°.

Hydrodynamic calculations are involved in complete characterization of such an apparatus; the resistance of the heat-transfer apparatus is the sum of the resistances of the parts consisting of tubes and separators; each of these aspects was examined separately and had been adequately discussed in the literature.

We measured the hydrodynamic resistance of the apparatus as a whole for systems with 2, 4, and 6 stages, the pressure being monitored by manometer 25. For initial gas sppeds varying between 12 and 25 m/sec, the resistance of the 2-stage apparatus was 60-65 mm of water, that of the 4-stage apparatus 90-100 mm, and that of the 6-stage apparatus 110-120 mm.

The heat-transfer experiments were conducted on an apparatus consisting of 2, 4, or 6 sections; the results were compared with calculated ones by deriving the latter as follows. The dimensionless temperature of the material is

$$\theta_M = \frac{1}{1+R}\left\{1 - \exp\left[-\frac{\alpha F_t}{W_M}(1+R)\right]\right. . \quad (1)$$

The dimensionless gas temperature is

$$\theta_g = 1 - R\theta_M, \quad (2)$$

where

$$\theta_M = \frac{\vartheta - \vartheta_i}{t_i - \vartheta_i}, \quad \theta_g = \frac{t - \vartheta_i}{t_i - \vartheta_i}, \quad R = \frac{W_M}{W_g}.$$

The true surface of the heat-transfer material in each part of the apparatus F_t, was determined via the following equation [4]:

$$F_i = kF_c[1 + \exp(-ch)], \quad (3)$$

where $F_c = [\mu V_{tu}\gamma_{g,av}\sigma$, $k = 1.8 + 6\gamma_M d_M$, $c = 0.92 - 0.6\gamma_M d_M$.

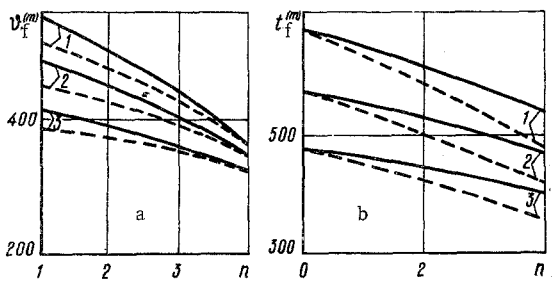

Fig. 2. Temperatures, °K, of material (a) and gas (b) in parts of the apparatus with initial temperatures t_i, °K: 1) 673; 2) 573; 3) 473. The broken lines are from experiment, and the continuous lines are from calculation.

It follows from (1) that θ_M for the conditions R = const, W_M = const is dependent on the mean heat-transfer coefficient α_{av} for each part of the apparatus and also F_t; F_t is the same for all parts of the apparatus [4]. We deduced α from the relation

$$\alpha = a \frac{(v_{rel})^{0.8}}{d_M^{0.2}} \cdot \frac{\lambda}{\nu^{0.8}}.$$

As the hydrodynamic conditions were the same in each part of the apparatus, α varied in the different parts only due to change in the gas temperature. The speed of the material at the start of each part was close to zero. Calculations showed that $\lambda/\nu^{0.8}\gamma_g^{0.8}$ deviates from the mean by 16.8% with a change in the heat-carrier temperature from 1273°K to 570°K. This means that we can assume that α_{av} = constant with an accuracy sufficient for practical purposes, and therefore θ_M and θ_g are also identical for all parts of the apparatus.

We derived θ_M and R for the initial gas temperature specified in the experiment and calculated the final and current gas temperatures and the temperature of the material as a whole over the apparatus by means of relationships derived in [2] for n = 2, 4, or 6.

Figure 2 shows the temperatures of the gas and the material in the various parts with n = 4. The observed curves lie somewhat lower than the calculated ones, but the two are of the same form.

We assumed in the calculations that there was no heat loss [2]; in the real apparatus of comparatively small size, heat loss to the medium cannot be neglected with ordinary insulation. In the present case the loss was ~ 20%, so the discrepancies between experiment and calculation increase with the initial gas temperature and the number of stages.

Figure 3 shows the gas temperature and material temperature for various values of n. There is a rapid fall in the gas temperature when the apparatus consists of two parts; a larger number of parts leads to redistribution of the temperature differences, and consequently the curve for the gas temperature varies less rapidly (Fig. 3b). Analogous curves apply for the values of the material temperature (Fig. 3a). The choice of the number of stages is influenced by the material flow rate and the initial gas temperature, as is clear from the above evidence, which shows that $\vartheta_f^{(6)}$ increases only slightly for apparatus consisting of 6 stages (Fig. 3).

Figure 4 illustrates the effects of the countercurrent flow over the apparatus as a whole as regards the temperature curves. The hot gas is supplied to part 1 and passes in sequence through parts 2-4 (n = 4). Point b_4^I corresponds to a final gas temperature at the outlet; the initial temperature in each part m equals the final temperature in part m−1, i.e., the curve $a_1^I b_4^I$ is continuous over the points a_2^I, a_3^I, a_4^I.

The material is supplied to part 4 at the temperature of the surrounding air. The initial temperature of the material in part m−1 is equal to the final temperature in part m, i.e., $a_3^{II} = b_4^{II}$, $a_2^{II} = b_3^{II}$, $a_1^{II} = b_2^{II}$. Material moves gradually through the apparatus and enters parts of higher temperature; although the temperature difference in each part is Δt = 100-120°, we have on the whole the countercurrent principle, which causes the final temperature θ_f to rise relative to the final temperature of the gas by 40°, while the mean temperature difference in this case (Δt_{av} = 180) is 14% above that for each section individually (Δt = 156).

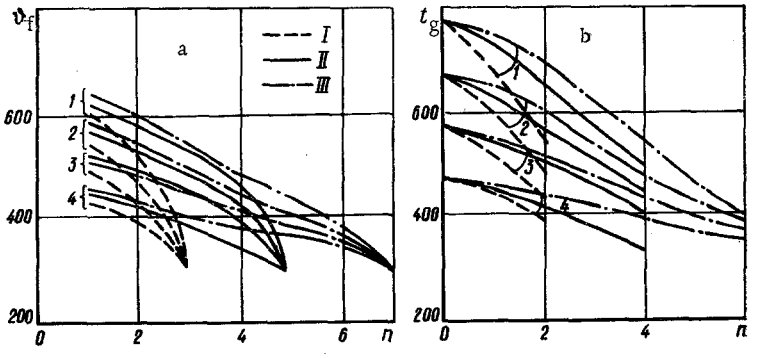

Fig. 3. Final temperatures of material (a) and gas (b) for various numbers of stages: I) n = 2; II) 4; III) 6 (1−773°K; 2) 673; 3) 572; 4) 473).

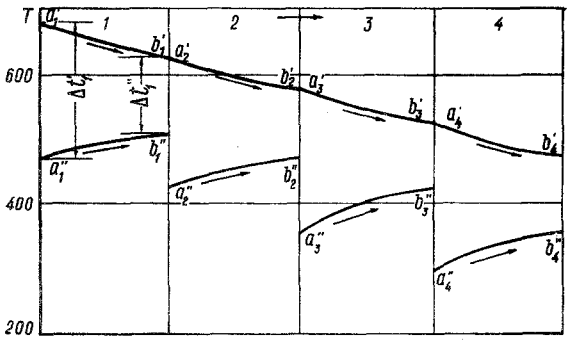

Fig. 4. Trends in gas and material temperatures (T, °K) in each part (the upper curve is for the gas).

The curves show that increase in the number of stages facilitates more complete use of the temperature difference as a whole; for instance, if t_i = 473°K, the difference between the initial and final gas temperatures is 80° for n = 2 but is 125° for n = 6; while for t_i = 673°K the corresponding figures are 180 and 290° for a material flow rate of μ_c = 0.4 kg/kg. In the first case one uses 17% of the temperature difference for n = 2 and 27% for n = 6 while in the second case one uses respectively 27 and 43%. The generally low use of the temperature difference is here due to the low values of μ_c that were used. The practical flow rate may be varied widely in apparatus of this type [5], and the exact value is determined from the equations for the heat balance with allowance for the hydrodynamics of the process.

The final temperatures of the material give the following picture: for t_i = 473°K, with n = 2 we have ϑ_f = 420°K, with n = 4 ϑ_f = 445°K, with n = 6 ϑ_f = 450°K; if t_i = 673°K then we have respectively ϑ = 538, 568, and 583°K.

These results confirm the conclusions [2] from analytical studies that increase in the number of stages results in further increase in the heating of the material but a decrease in the rate of heating.

Practical calculations are simplified by the use of the nomogram shown in Fig. 5, which was constructed by means of analytical relationships given in [2]:

$$\vartheta_f = \theta_M t_i \frac{\sum_{m=1}^{n} \left(\frac{1-\theta_M}{\theta_g}\right)^{n-m}}{\left(\frac{1-\theta_M}{\theta_g}\right)^{n-1} + \theta_M \sum_{m=2}^{n} \left(\frac{1-\theta_M}{\theta_g}\right)^{n-m}}, \quad (4)$$

$$n = -\frac{1}{\lg a} \lg\left[1 + \frac{1-a}{a} \frac{\vartheta_f (1-\theta_M)}{\theta_M (t_i - \vartheta_f)}\right],$$

where $a = 1-\theta_M/1-R\theta_M$.

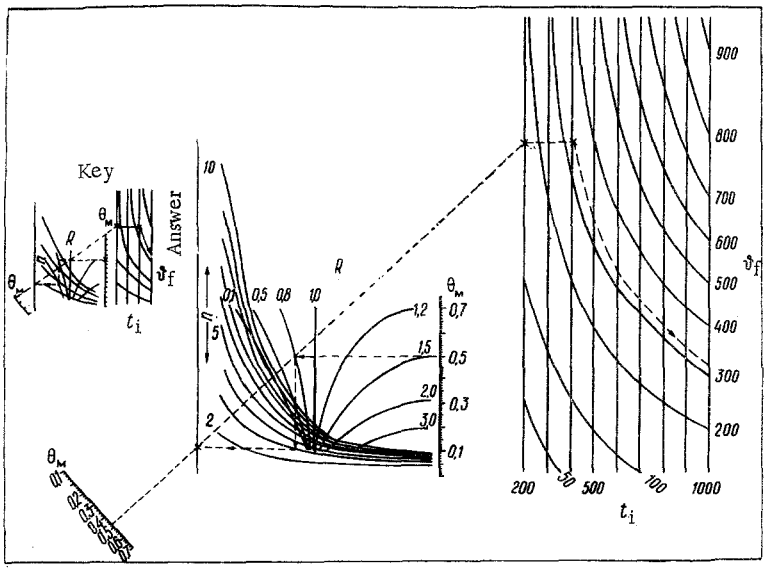

Fig. 5. Nomogram (ϑ_f and t_i, °C).

To use the nomogram one takes values of the ratio of the water equivalents as a mean for the whole apparatus $R = W_M/W_g$, the initial gas temperature t_i, and the dimensionless material temperature θ_M as reckoned from (1). From the selected number of parts one determines the final material temperature θ_f. The nomogram also enables one to determine any other quantity if the others are given. The accuracy of the results from the nomogram is about 3%.

NOTATION

F	is the heat-transfer surface;
d	is the diameter;
h	is the height of section;
t, ϑ	is the temperature of gas and material;
V	is the tube volume;
W	is the water equivalent;
α	is the heat-transfer coefficient;
γ	is the specific weight;
λ	is the thermal conductivity;
σ	is the specific surface of material;
ν	is the kinematic viscosity.

Subscripts

i, f	are the initial and final states;
M, g	are the material and gas;
av, t, c, rel	are the mean, true, calculated, and relative values.

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