CHARACTERISTICS OF HEAT TRANSFER FROM A SURFACE TO A FLUIDIZED BED UNDER PRESSURE

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The effect of pressure within the 0-30 atm g range on the heat transfer from a surface to a fluidized bed has been studied at temperatures within the 150-1000°C range and with a gas of various compositions.

For the development of intensive endothermal processes and for the design of necessary engineering apparatus it is desirable to have data on the characteristics of heat transfer between an 800-1000°C hot surface and a fluidized bed under pressure during such processes as conversion, gasification, or pyrolysis.

In consideration of this, the authors have studied the effects of temperature, pressure, and gas composition on characteristics of heat transfer from a surface to the fluidized bed in which it is immersed. The tests covered a wide range of temperatures (150-1000°C) and pressures from 0.5 to 30 atm g.

The test stand is shown schematically in Fig. 1. It consisted of an apparatus 1 for measuring the heat transfer in the fluidized bed, with an electrical furnace for external heating, a tubular cooler 2, a heater for the carrier gas 3, and appropriate inspection-measuring-regulating instruments.

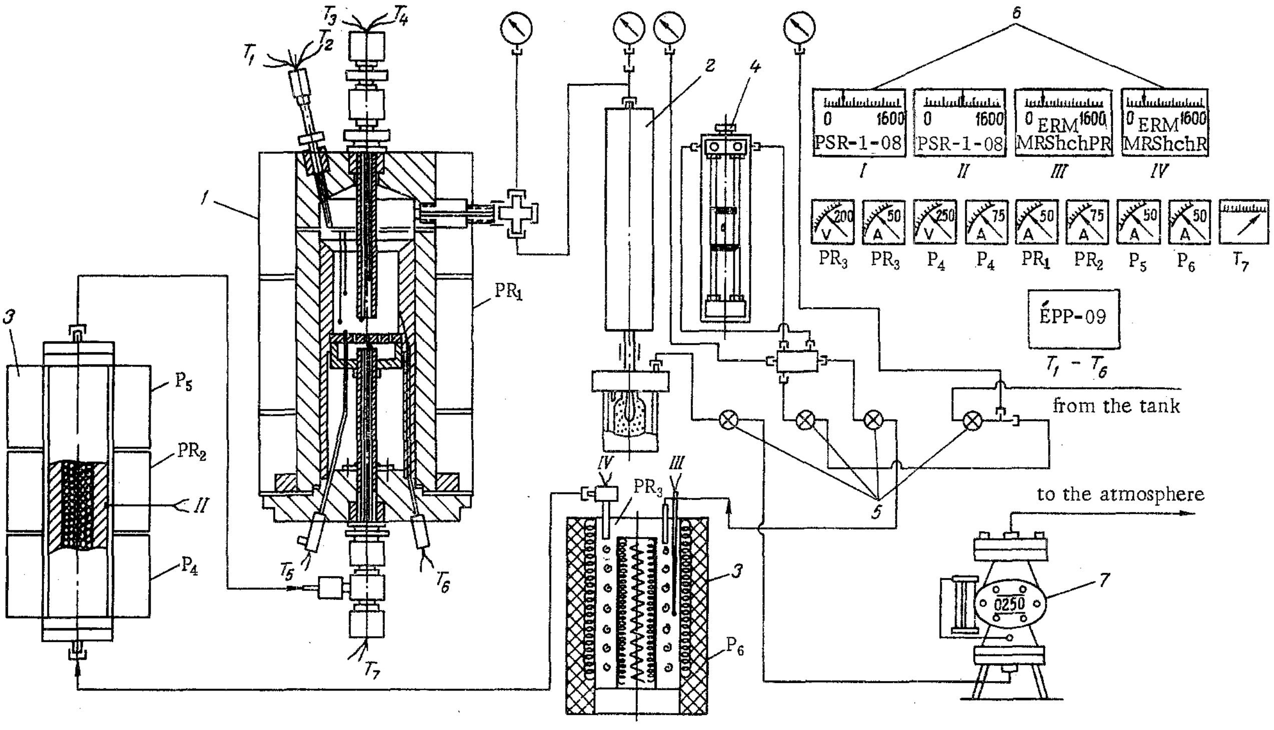

Fig. 1. Schematic diagram of the test stand: 1) apparatus for studying the heat transfer; 2) tubular cooler; 3) gas heater; 4) differential manometer with diaphragm; 5) set of regulating valves; 6) inspection-measurement panel; 7) model RS-40 gas counter.

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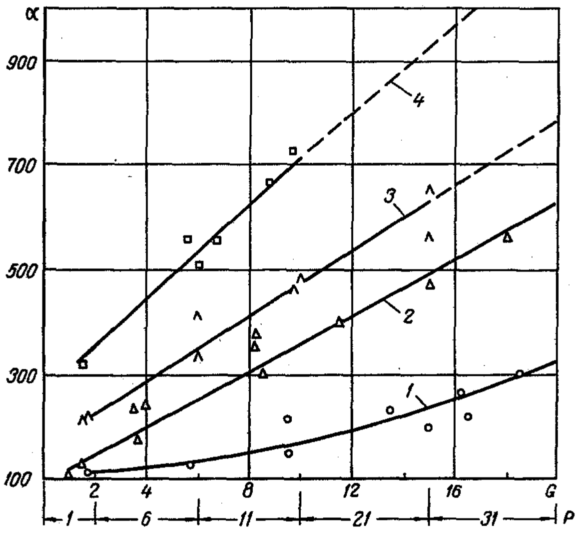

Fig. 2

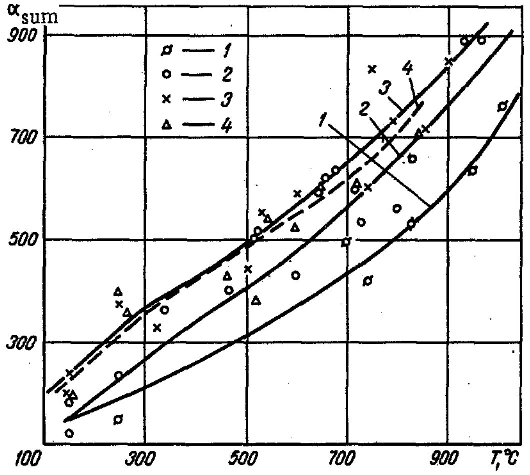

Fig. 3

Fig. 2. Heat-transfer coefficient α (kcal/m^2 · h · °C) as a function of the pressure P (atm a) or the mass rate of injection (kg/h), at $H/H_0 = 1.5$ and $d_{av,p} = 0.52$ mm: 1) $T_{m,b} = 120\text{-}150$°C and N_2 carrier gas, 2) $T_{m,b} = 230\text{-}250$°C and N_2, 3) $T_{m,b} = 200\text{-}250$°C and 55% N_2 + 16% CO_2 + 29% H_2, 4) $T_{m,b} = 220\text{-}260$°C and 35% N_2 + 25-30% CO_2 + 35-40% H_2.

Fig. 3. Overall heat-transfer coefficient α_{tot} as a function of the temperature (°C) at $H/H_0 = 1.5$ and $d_{av,p} = 0.52$ mm: 1) P = 0.5 atm g, 2) 5 atm g, 3) 10 atm g, 4) 20 atm g; fluidizing gas N_2 at $T_w = 700$°C, 50% N_2 + 50% CO_2 at $T_w = 700\text{-}1100$°C.

The experiment was performed with two types of apparatus differing, essentially, with regard to the heating range. The inside diameter of both was 44 mm.

The first apparatus was suitable for testing at a 200-400°C wall temperature and under 50 atm g. Temperatures inside the bed were measured with Chromel–Copel thermocouples at three different heights and two points each per bed section. The apparatus had been designed for a visual observation of the bed behavior through a special viewing window and thus for allowing the same bed expansion λ = const in tests at different temperatures and pressures.

Tests in the second apparatus were performed at 40-1000°C wall temperatures and pressures up to 50 atm g. The wall temperature in each apparatus was measured with thermocouples attached to the heat emitting surface. Temperatures inside the fluidized bed were measured at three points along the height and across the section with Pt/PtRh thermocouples connected to model ÉPP-09 class 0.5 potentiometers. The thermocouple readings were recorded every 1.5-3 sec.

With the aid of model PSR-1 potentiometers, the temperature of the outer walls in each apparatus was maintained constant for each test series.

The initial mixture was made up of gas and various size comminuted GIAP-3 catalyst particles. Particle fractions 0.40-0.63 mm and 0.63-1.0 mm were used for the experiment.

The fluidizing gases were nitrogen and an approximately 50 : 50 mixture of nitrogen and carbon dioxide, also nitrogen with hydrogen and carbon dioxide in the following ratios: 1) 16% CO_2, 55% N_2, 29% H_2 and 2) 25-30% CO_2, 35% N_2, 35-40% H_2.

Prior to the heat transfer tests, the hydraulic characteristics of the fluidized bed were determined with the given catalyst particles at normal temperature and at 0.5, 5.0, 10, 20, and 30 atm g pressures.

The heat-transfer coefficient α was calculated by the well known formula $Q = \alpha F \Delta t$ and heat balance equation $Q = Gc_p\Delta T$.

The tests were run at almost the same expansion factor $\lambda = 1.5\text{-}1.6$ with $H_0 = (1.0\text{-}1.1)D_i$ and gas flow rates from 1 to 18 kg/h.

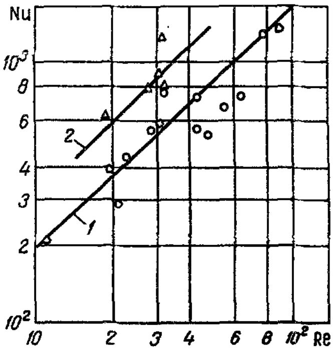

Fig. 4. Relation Nu = f(Re): 1) $T_{m,b}$ = 250°C; 2) 800°C.

The effect of pressure on the heat transfer was studied over the 120-260°C temperature range with two different compositions of the carrier gas, namely nitrogen and the $N_2 + CO_2 + H_2$ mixtures, and the effect of surface temperature was studied over the 0-20 atm g range of pressures with two different compositions of the carrier gas: N_2 at T_W = 300-800°C and $N_2 + CO_2$ at T_W = 750-1100°C.

When the pressure was raised from 0 to 30 atm g (or, which is equivalent, as the draft was increased accordingly), with other conditions remaining the same (λ = const, T = const, and $d_{av,p}$ = const), the heat-transfer coefficient increased, even though the linear velocity of the gas stream decreased, as is shown in Fig. 3. Thus, with the pressure increasing from 0 to 30 atm g at a 150°C bed temperature, α increased correspondingly from 115 to 300 kcal/m^2 · h · °C. An analogous trend of α was observed at a bed temperature $T_{m,b}$ = 220-260°C and various gas compositions, also at a varying average particle size.

It must be noted that within the test range of pressures and temperatures we did not reach the maximum value of the heat-transfer coefficient α, because the experiment was performed at rather low linear velocities of the gas stream on the ascending portion of the $\alpha = f(G, P)$ characteristic.

The feasibility of increasing α by increasing the gas density at linear velocities lower than under atmospheric pressure was mentioned also in [1, 2, 3].

The tendency of α to increase with higher pressure P can, evidently, be explained by the increasing mass rate of gas flow during a constant bed expansion, which allows the fluidized bed to remove heat from the immersed surface. At the same time, the increasing pressure affects the hydrodynamic characteristics of the fluidized bed and thus, evidently, also the heat transfer characteristics. Under these circumstances the bed becomes more isotropic, the rate of particle circulation increases, and the volume of gas bubbles contained in the bed decreases sharply [4]. These factors, according to the theoretical model of heat transfer proposed by S. S. Zabrodskii [5], contribute to a uniform and steady heat removal.

The physical properties of the gases have a definite effect on the heat-transfer coefficient. The thermal conductivity of the gas plays a particularly important role here [6]. This fact, which had been established earlier under atmospheric pressure and moderate ambient temperatures (15-20°C), was confirmed in our tests with the bed heated to 220-260°C under pressures within the 0-20 atm g range. Results of this study are shown in Fig. 2 (curves 3 and 4). Tests have shown that the presence of hydrogen in the mixture has the effect of increasing the thermal conductivity and, consequently, of increasing the quantity of heat removed from the developed catalyst surface. The higher the hydrogen content in the mixture is, the higher becomes the heat-transfer coefficient α. A comparison with data obtained in tests with nitrogen shows that the heat-transfer coefficient in this case was higher at the same mass rates of carrier gas flow. For instance, at G = 10 kg/h (P = 11 atm a), α = 350 kcal/m^2 · h · °C when nitrogen was used (curve 2), α = 460 kcal/m^2 · h · °C when mixture No. 2 was used (curve 3), and α = 720 kcal/m^2 · h · °C when mixture No. 1 was used (curve 4).

This circumstance is particularly important for setting up the methane vapor conversion process.

Under actual conditions the thermal and the thermocatalytic processes in a fluidization bed take place at higher temperatures, namely within the 800-1000°C range. For this reason, we performed tests to establish the effect of temperature on the heat-transfer coefficient at pressures in the 0-20 atm g range.

As the bed temperature rises, the radiative component of the heat-transfer coefficient increases. Within the 500-1000°C range, according to the data in [7, 8], 10-35% of the heat may be transmitted from the bed to a surface and vice versa by radiation.

Under our test conditions, under pressure, the overall heat-transfer coefficient $\alpha_{tot} = \alpha_{conv} + \alpha_{rad}$ was determined, because the α_{rad} component could not be easily determined separately.

According to Fig. 3, the heat-transfer coefficient increased with rising temperature. Thus, as the mean temperature in the bed rose from 300 to 900°C under 5, 10, and 20 atm g pressure, the absolute value of α_{tot} increased approximately 2.4-2.7 times.

It is to be noted that the trend of the α_{tot} increase with increasing pressure was maintained at any bed temperature.

At temperatures above 300°C the difference between the wall temperature and the mean bed temperature increased more sharply with increasing pressure. At $T_{m,b}$ = 600°C, for instance, Δt increased from 45 to 157°C as the pressure was increased from 0 to 20 atm g. The increase in Δt with an increasing mass rate of gas injection, at other fluidization bed parameters remaining the same, can apparently be explained by the inadequate supply of heat from the furnace to the heat transfer surface coinciding with a rapid removal of heat through the bed to the cold gas, also by the slight bed expansion. Properly correlating these factors, one may expect a further increase in the heat-transfer coefficient α at the same environmental and flow conditions.

Considering this established relation between the increase in α_{tot} and the temperature rise, with other conditions remaining unchanged (the same $d_{av,p}$, H/H_0, and P atm g), and considering the increase in α with an increasing hydrogen content in the carrier gas, one may assert that under actual conditions of an endothermal process (e.g., vapor-catalytic conversion of gaseous hydrocarbons) at a mean bed temperature within 850-900°C and under pressures within 10-30 atm g the overall heat-transfer coefficient may reach 1100-1800 kcal/m^2 · h · °C.

The data pertaining to the heat transfer from a hot surface to the fluidized bed with nitrogen as the carrier gas have been generalized into a Nu = f(Re) relation. The test results obtained at mean bed temperatures 250 and 800°C are shown in Fig. 4.

On the basis of these test data, we derive an empirical formula for calculating the heat-transfer coefficient within the 200-1000°C range of temperatures and under up to 30 atm g pressures, with the Reynolds number $Re \leq 100$,

$$Nu = 42.17\,Re^{0.9}\,T_{m,b}/250,$$

with $T_{m,b}$ denoting the mean temperature in the fluidized bed and 250°C being the lowest temperature used in calculating the heat-transfer coefficient α.

NOTATION

α	is the heat-transfer coefficient, kcal/m^2 · h · °C;
Q	is the quantity of heat received by the gas, kcal;
G	is the mass rate of gas flow, kg/h;
T_w	is the wall temperature;
$T_{m,b}$	is the mean-integral bed temperature;
c_p	is the specific heat of the gas, kcal/kg · °C;
$\Delta t = T_w - T_{m,b}$;	
ΔT	is the mean temperature difference between gas leaving and entering the fluidization bed;
d	is the diameter of bed particles, mm;
H	is the height of fluidized bed, mm;
H_0	is the height of stationary bed, mm;
D	is the diameter of the apparatus, mm;
P	is the pressure inside the apparatus, atm gage;
λ	is the bed expansion factor, H/H_0;
Re	is the Reynolds number referred to diameter D.

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