STEAM FILTRATION IN A DISPERSE-LOAD BED

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UDC 532.546:547.912

The filtration of saturated steam in a disperse load is investigated experimentally. The possibility of the appearance of three modes of the process is shown and their conditions are determined.

A rather large number of experimental and theoretical reports have been devoted to the investigation of the process of vapor condensation in capillary-porous bodies and disperse loads. However, cases of heat and mass exchange confined to diffusional transfer only or to diffusional–filtration transfer, but at small pressure gradients, as in [1], e.g., are considered in them, as a rule. At the same time, condensation processes, in which filtration transfer is dominant, are inadequately studied. All the same, their investigation has great practical importance, especially in connection with the prospect of the efficient use of vapor-thermal treatment of beds for the intensification of oil extraction.

Attention is attracted first of all by the rather low level of the experimental work known from the literature, in which only the vapor pressure at the entrance to the load and the temperature, in the best case the temperature distribution over the path of vapor motion, were measured, as a rule. Naturally, this is inadequate either for an understanding of the physical picture of the process, or for the adoption of basic assumptions simplifying the analytical solution of the problem, or for a test of the equations obtained.

Below we present the results of an experimental investigation of the distributions of pressure, moisture content, and temperature over the height of a vertical cylindrical load during the filtration through it of saturated steam, and an attempt is made to analyze them from the standpoint of a model representation of the process.

Experimental Installation

The tests were conducted on an installation consisting of a steam generator, a column containing quartz sand, and the units for the measurement and automatic recording of the quantities being measured.

The EDA-22 steam generator, equipped with a system for automatic monitoring of the liquid level and maintenance of an assigned pressure of saturated steam, provided an output of up to 26 kg/h at a pressure of 0.6 MPa.

The column containing the bed of disperse material, sand, consisted of a vertical cylindrical tube 0.066 m in diameter and 0.250 m high, a grating supporting the bed and providing a uniform steam distribution at the entrance to the load and mounted between the flanges of the tube and the chamber below the grating, and a valve for switching the steam. The chamber below the grating, with a volume of about 5 cm^3, was itself a part of the valve for switching the steam to the entrance of the bed or dumping it to the atmosphere (for the preliminary ventilation, warming, and stabilization of the operation of the steam generator). Its small volume made it possible to obtain the assigned value of the steam pressure below the grating almost instantly after switching the steam to the entrance to the load. There were nipples distributed on diametrically opposite sides along the height of the cylindrical tube with a spacing of 5 cm, starting with 2.5 cm above the grating, for the introduction of thermocouples, moisture-content detectors, and pressure intakes into the bed.

The temperature below the grating and in cross sections along the height of the column was measured with Chromel–Copel thermocouples. The junctions obtained in welding them were pickled in a hydrochloric acid solution down to a diameter of 0.1 mm, in which case the time

A. V. Lykov Institute of Heat and Mass Exchange, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 38, No. 5, pp. 847-852, May, 1980. Original article submitted September 4, 1979.

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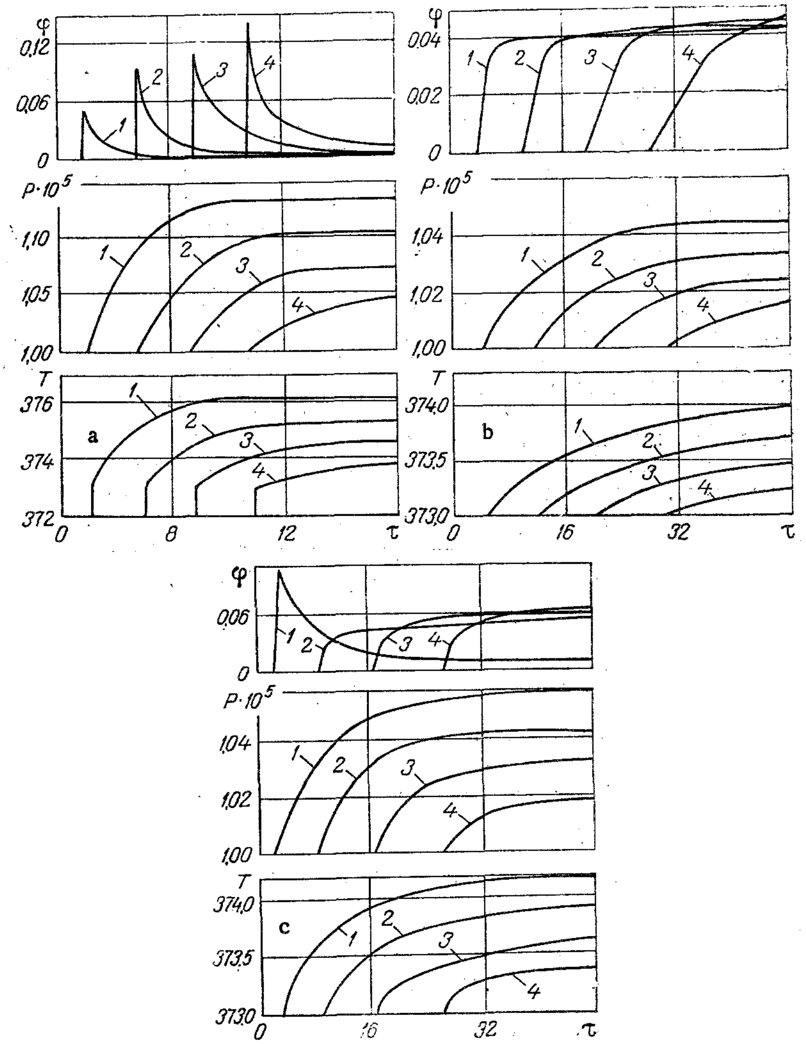

Fig. 1. Time variation of moisture content φ, kg/kg, pressure P, N/m², and temperature T, °K, over load height during filtration of saturated steam: 1) H = 2.5 cm; 2) 7.5; 3) 12.5; 4) 17.5 cm.

of heating of a thermocouple from 20 to 100°C did not exceed 0.5 sec. The saturation was determined with detectors operating on the principle of the measurement of the electrical conductivity of a base section. Preliminary calibration assured a measurement accuracy with an error of no more than 2.5%.

The pressures were measured with capacitive membrane manometers, for which the material and the membrane sizes were chosen in accordance with [2, 3]. Thus, the manometers made it possible to measure pressure variation with a frequency of up to 100 Hz (the natural frequency of the membrane was 4000 Hz) with a minimum sensitivity of 0.1 kPa in the range of up to 300 kPa and with a sensitivity of 0.5 kPa in the range of up to 0.3 MPa (the pressure sensitivity and accordingly the measurement range could be regulated within these limits). To avoid steam condensation in the intake tubes the latter were filled with silicone.

The steam flow rate was determined with an electrical rotameter of the RÉ-0.025 ZhUZ type, the measurement range of which was expanded by fabricating a new conical insert. Calibration assured accuracy in measurements of the flow rate with an error of no more than 7%.

All the measured quantities were recorded in the course of the experiments using an N-700 loop oscillograph and a four-channel recorder of the "RECORDER" type. The synchronization of the latter and the plotting of the time scale on the oscillograms were accomplished with a generator of sinusoidal signals of the P 104 type. The start of the supply of steam was marked on both oscillograms by brief pulsed shifts.

Before the start of each experiment the sand was baked in an electric muffle furnace at a temperature of 500°C for 3-4 h and then cooled in a desiccator.

Experimental Results and Their Analysis

Graphs typical of each of the three modes of filtration of saturated steam, characterizing the time variation of the moisture content, pressure, and temperature at the measurement points over the height of the bed, constructed from the data of the oscillograms, are presented in Fig. 1a-c.

The experiments conducted showed that in the filtration of saturated steam in a disperse-load bed three modes are possible, differing in the character of the process, which can be classified conditionally as one-phase filtration when only the steam is moving, two-phase filtration when movement of the steam and the condensate occurs, and transitional filtration when two-phase filtration is observed up to a certain height of the load and then only steam moves. The following relation can be used to predict the filtration mode:

$$L = \frac{4 - \dfrac{\Delta P}{\gamma H}}{d_e}, \tag{1}$$

where $d_e = 0.75$.

According to the experimental data, the mode of one-phase filtration is observed at $L < 4500$, two-phase filtration at $L > 7000$, and transitional filtration at $4500 < L < 7000$.

Curves characteristic of the filtration process at $L > 7000$ are shown in Fig. 1a. In this case the filtration mechanism is the following.

Upon reaching the developed heat-exchange surface, which is represented by the disperse load, the saturated steam condenses intensively, filling the interstitial volume of the bed with condensate to a moisture content corresponding evidently to the amount of steam which, having condensed, is required to heat the bed to a temperature equal to the saturation temperature at the initial pressure in the load, with allowance for the heat losses to heating the walls confining the load and to the ambient medium. In the case of quartz sand this value is about 4%.

Under the action of the pressure gradient the condensate formed starts to move with the newly entering steam, thus creating the two-phase flow. In the process, since the condensate occupies only part of the interstitial space in a cross section of the load, the steam outruns the liquid and condensates at its front. In view of the fact that in this narrow condensation zone the pressure falls almost to the initial pressure, the condensate moving in the load rolls, as it were, on the newly formed condensate, as a result of which the fraction of condensate in a cross section grows as the stream moves (which is indicated by the readings of the saturation sensors). Moreover, the condensate cools in the process of heating the particles, as well as due to heat losses, which causes a decrease in its temperature below the equilibrium temperature, as a result of which the steam in contact with it partially condenses, raising (restoring) the temperature of the condensate and increasing the saturation at the front of the stream. Under the corresponding conditions (a relatively low velocity of motion of the condensation front and a considerable height of the load) it is possible that complete filling of a cross section with condensate was also observed in the experiments. In this case the stream will consist of two zones, as it were: condensate and steam. Then, heating the load as the stream advances, the condensate will be cooled, thereby creating the conditions for steam condensation in its rear part. The zone of moving condensate, which was relatively narrow in two-phase flow, will widen. As a result, a pattern develops which was also observed by the authors of [4], who concluded on the basis of thermocouple readings that three zones exist in steam filtration in a disperse load: of cold water, hot water, and a zone of saturated steam.

To determine the depth of the zone of steam condensation, we set up special tests in which the temperature was recorded from the readings of thermocouples located at distances of 3 mm from the grating and from each other. At all steam flow rates down to 2 $kg/m^2 \cdot sec$ each successive thermocouple began to record a temperature rise only after the preceding

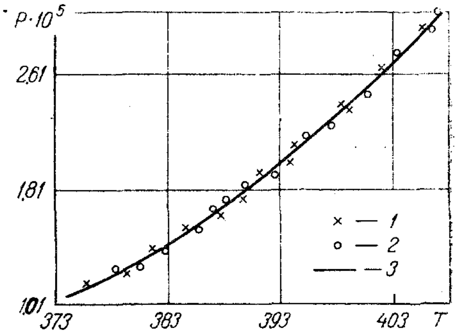

Fig. 2. Temperature dependence of steam saturation pressure. Experimental (1, 2) and calculated (3) data for steady (1) and nonsteady (2) filtration.

reading reached marks of not less than 100°C, in which case the rate of rise was within the limits of the inertia of a thermocouple. From this we can conclude that the steam condensation takes place in a very narrow zone, and the condensation process is limited not by heat and mass exchange but by the rate of arrival of steam in the condensation zone. This is also indicated by the fact that there is almost no steam ahead of the condensate front, which can be judged from the readings of the thermocouples and the saturation detectors, as well as from the results of a comparison of the data on the steam flow rate determined by weighing the sand before and after the steam filtration (when the condensate front reached the upper boundary of the bed) and recorded by the saturation detectors and the electric rotameter.

On the basis of the foregoing, we can assume, as in [6, 7], that local thermal equilibrium exists during steam filtration through a disperse load, and also that the pressures in the liquid film of condensate and in the vapor phase are the same. In this case the condition $\mu_w(T, P) = \mu_s(T, P)$ must be satisfied and, according to [9],

$$d\mu = -\bar{S}dT + \bar{V}dP, \tag{2}$$

from which

$$\frac{dP}{dT} = \frac{\bar{S}_s - \bar{S}_w}{\bar{V}_s - \bar{V}_w}, \tag{3}$$

which is equivalent to the Clapeyron–Clausius equation

$$\frac{dP}{dT} = \frac{\lambda}{T(\bar{V}_s - \bar{V}_w)}, \tag{4}$$

which, according to [8], can be represented in the following form:

$$\ln P = -\frac{A}{T} + B\ln T + CT + \ldots + \text{const}. \tag{5}$$

With an error not exceeding 1% we can be confined to the first two terms and obtain the following temperature dependence of the pressure of the saturated steam:

$$P = CT^B \exp\left(-\frac{A}{T}\right). \tag{6}$$

We determine the coefficients A, B, and C by setting up and solving a system of three equations based on the tabular data of [5].

Thus, for pressures of from 2336 Pa to 1 MPa we obtain the equation

$$P = 1.94 \cdot 10^{22} T^{-3.82} \exp\left(\frac{6407}{T}\right), \tag{7}$$

which establishes the relation between the saturation pressure and the temperature with an error of no more than 0.7%.

The experimental data for the cases of nonsteady steam filtration (when the condensation front was within the load) and steady steam filtration (after the condensation front reached the top level of the bed) and their comparison with tabular and calculated (from Eq. (7)) values of the pressure and temperature are presented in Fig. 2. The maximum deviation does not exceed 3%, which testifies to the correctness of the initial assumptions.

It can be assumed with a sufficient degree of approximation that beyond the condensation front (behind it) the steam filtration takes place in accordance with Darcy's law, which is indicated by the equality, within the limits of the experimental accuracy, of the coefficients of permeability determined for different sections between the cross sections in which the pressure sensors were mounted for the entire region lying behind the front and for the load as a whole after the passage of steam through it.

Graphs characteristic of the mode in which the steam filtration was conditionally called one-phase earlier are presented in Fig. 1b. In this case, i.e., when $L < 4500$, the following mechanism of the process can be proposed on the basis of the data of Fig. 2. In contrast to the mode represented in Fig. 1a motion of the condensate hardly takes place (more accurately, evidently, the velocity of its motion is quite low compared with the velocity of motion of the condensation front). The newly arriving steam condenses intensively at the interface between the dry and moist sand, filling the interstitial volume of the bed to a moisture content of about 4-4.2%, which corresponds to the amount of steam required, by condensing, to heat the bed to a temperature equal to the saturation temperature at the initial pressure in the load, with allowance for heat losses. Thus, the mode of one-phase filtration is characterized by a uniform distribution of condensate over the entire volume of the load.

The transitional mode, for which the process shown in Fig. 1c is typical, represents a kind of symbiosis of the modes presented in Fig. 1a and b, i.e., at the initial time, when the pressure gradient is rather large, the forming condensate moves along with the stream, repeating a process similar to that shown in Fig. 1. Subsequently, the velocity of its motion slows and then becomes negligibly low. From this time the character of the filtration becomes similar to the mode shown in Fig. 1b.

NOTATION

P, steam pressure; T, steam temperature; S_s, steam entropy; S_w, entropy of boiling water; μ_w, chemical potential of boiling water; μ_s, chemical potential of steam; V_s, specific volume of steam; V_w, specific volume of boiling water; γ, specific weight of disperse medium; d_e, equivalent diameter; λ, heat of phase transition; φ, moisture content of disperse medium.

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