Intensification of heat and mass transfer of the gas channel of the multi-temperature condensation filter

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Abstract. The principle of operation and features of hydrodynamics and heat-mass transfer in the working channel of a multi-temperature condensation filter for gas purification are described. Promising methods of gas flow purification using porous surfaces are described. The modeling and comparison of the laminar air flow in channels of various shapes: in a flat channel, in a channel with webs and in a spiral channel are performed. An analysis of their effectiveness is carried out.

1. Introduction
The issue of purifying gas streams from various mechanical and chemical impurities is of particular interest, since, in addition to purifying gas to obtain a purified stream as an end product, it is often necessary to capture valuable suspended particles contained in the purified gases. These requirements for the purification of streams can be implemented with a sufficient degree of efficiency in a multi-temperature condensation filter [1], the working channel of which is formed by walls having different temperatures (figure 1).

Figure 1. Diagram of a working channel for a multi-temperature condensation filter: a – cold wall; b – hot wall; c – gas input; d – gas output

The gas stream is purified by supplying a contaminated gas stream to a working channel at different temperatures. During its passage a zone of stable supersaturation is formed in the purified stream, which promotes the formation and growth of liquid droplets on various inclusions contained in the stream. Part of the moisture with trapped inclusions is deposited on the colder wall of the working channel and is discharged outside. The rest is captured behind the working channel quite simply, the channel moisture droplets on suspended particles significantly coarsen.
Currently, an increasingly promising direction in the purification of gas streams is the use of various developed surfaces with sorbing properties. So, in works [2-4], the processes of creation, application and development prospects of various polymer membranes for gas purification are described. The works [5-7] describe the use of various organometallic frameworks for gas separation and adsorption. Let us look at some of these examples below.

The work [8] describes the application of various membranes in industry, and shows examples of modifications of membrane surfaces that improve the reaction processes on these surfaces (figure 2).

![Figure 2](image)

**Figure 2.** Schematic representation of some examples of surface modification membranes: (A) bare membrane, (B) etched membrane, (C) porous coated membrane, (D) catalyst particle deposition, (E) catalyst particle activated porous coating, and (F) protective layer.

Quite a lot of attention has been paid to work investigating CO$_2$ scrubbing on developed surfaces. In [9], various nitrogen-doped microporous coals were shown to demonstrate a high degree of CO$_2$ absorption (up to 197 mg / g) at 273 K and a pressure of 1 bar. The effective pore size was also determined to be 0.84 nm giving the best CO$_2$ uptake results. Work [10] described the creation of a cost-effective adsorbent in the form of porous anthracite carbons, created by a combination of KOH activation and treatment with urea to capture CO$_2$ and separate CO$_2$ / CH$_4$. The work [11] described the use of spongy pulp of a sunflower stem for the production of highly efficient porous carbon with the prospect of using it as a sorbent for CO$_2$, radioactive iodine, and oily / organic water pollution.

In devices such as a multi-temperature condensation filter (figure 1), a significant role is played by the efficiency of heat and mass transfer between the gas flow and the walls of the working channel [12, 13] with the purified gas flow. Thus, it becomes necessary to solve the problem of intensifying heat and mass transfer processes in the working channel.

The heat and mass transfer may be enhanced by using various developed surfaces [14-17], showing high efficiency due to the improvement of hydrodynamic and heat exchange indicators at the flow of liquids and air flows in the channels.

The purpose of this work is to assess the influence of developed surfaces and channel configuration on hydrodynamics and heat transfer in the channel.

2. Problem statement

One of the clearest ways to obtain a picture of the distribution of velocities, temperatures, etc., used in various studies [18-21], is the modeling of processes in software packages. In this work, we will use the COMSOL Multiphysics package to simulate a stationary gas heating process in a laminar gas flow through channels of various shapes.

It is required to make an approximate simulation of the gas heating process in laminar flow in channels of various shapes (figure 3) with the following similar data:
- three steel ducts of various shapes (flat duct, webed duct, spiral duct);
- conditionally constant rectangular channel section - 5mm x 20mm and channel length - 120mm;
- constant temperature of the channel walls - 80 °C;
- working environment - air;
- air temperature at the inlet - 20 °C;
- air velocity at the channel inlet – 1 m/s.
When constructing a mathematical model, a number of assumptions were made: the flow is three-dimensional stationary; there is no initial hydrodynamic section at the channel entrance; there is no heat exchange with the environment; the thermophysical properties of the flow are taken to be constant and equal to the average values in the investigated temperature range.

The modeling used the interfaces "Heat Transfer in Solids and Fluids" and "Laminar Flow" with built-in solvers.

3. Results and discussion

As a result of the simulation, the values of temperatures and velocities were obtained in different regions for the three considered channels: for a flat channel (a, d), a channel with protrusions (b, e), a spiral channel (c, f) (figure 4).

On a flat channel: a gradual uniform heating of the gas is observed. The maximum temperature is observed in the near-wall regions, in the corners and at the exit from the channel, which corresponds to the laminar flow regime. The average temperature at the outlet from the channel is 69.1 °C (figure 4, a). The maximum gas flow velocity is reached in the central region of the channel, while in the near-wall regions the velocity is insignificant and increases slightly closer to the exit from the channel (figure 4, d). The pressure drop across the channel is approximately 2.1 Pa.
Figure 4. Simulation results: flow lines with temperature changes for a flat channel (a), a channel with protrusions (b), a spiral channel (c); cross-sections for visualizing flow velocities in a flat channel (d), a channel with protrusions (e), a spiral channel (f)

Through the channel with protrusions: a sharper heating of the gas is observed than in the flat channel. Thermal stabilization of the flow occurs in areas close to the channel entrance. The maximum temperature is observed in the same areas as in the flat channel, and near the protrusions as well. The average temperature at the outlet from the channel is 70.5 °C (figure 4, b). The gas flow velocity pattern is similar to that of a flat channel, but there are increased velocities on the ridges and stagnant zones with low velocities in the areas between the ridges (figure 4, e), which is expected when a laminar flow moves in channels of a similar shape. The pressure drop across this lug passage is approximately 3.0 Pa.

Along the spiral channel: significant heating of the gas is observed after passing the middle of the calculated region of motion. At the same time, in the near-wall regions along the inertia of the gas movement, the temperature is significantly higher than in other zones. Abundant mixing together with flow heating occurs after passing through the middle of the calculated region of motion. Average temperature at the outlet from the channel is 72.4 °C (figure 4, c). The picture of the current velocity is very different from the two previously considered channels. In a spiral canal, the speed is fairly uniform and is approximately equal to the speed at the entrance to the canal (1 m/s) (figure 4, f). This can be
explained by the constant mixing of the flow while moving in a spiral. The pressure drop across the spiral duct is approximately 3.6 Pa.

Even with a small scale of the computational domain (height, width and length of the channel 5x20x120 mm) and an air velocity of 1 m / s, we observe a significant improvement in thermohydraulic characteristics when using a channel with protrusions (figure 3, 4, b, e), as well as a spiral channel (figure 3, 4, c, f). The use of these channels shows an increase in the average outlet temperature by 1.5 °C in the channel with protrusions and by 3.5 °C in the spiral channel compared to the flat channel. In this case, an increase in the pressure drop by 0.9 Pa is observed in the channel with protrusions and by 1.5 Pa in the spiral channel as compared to the flat channel. Also in the spiral channel, a significantly homogeneous distribution of velocities is observed throughout the entire channel.

4. Conclusions

Under the conditions of our problem, we observed a significant improvement in thermohydraulic performance when using a channel with protrusions (figure 4, 4, b, e), as well as a spiral channel (figure 3, 4, c, f) compared to a flat channel (figure 3, 4, a, d). The use of these channels showed an increase in the average outlet temperature by 1.5 °C in the channel with protrusions and by 3.5 °C in the spiral channel compared to the flat channel. In this case, an increase in the pressure drop by 0.9 Pa was observed in the channel with protrusions and by 1.5 Pa in the spiral channel as compared to the flat channel. Also, in the spiral channel, a significantly homogeneous distribution of velocities was observed throughout the channel.

The use of developed surfaces in the purification of gas streams is a promising direction in the development of industry.

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