Issues of development of research equipment elements by FDM printing

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Abstract. The article presents the results of the analysis on the issue of using additive technologies in the field of chemistry and petrochemistry. Possible areas of application are identified and a range of tasks in the practice of scientific experiment in the study of chemical and petrochemical processes that can be effectively solved with the help of such tools are outlined. It is shown that low-cost methods for developing models of technological equipment elements based on FDM printing can be quite effectively applied in practice. The conclusion is made on the basis of a study of the strength, resistance to strong solvents and tightness of the created structures.

1 Introduction

The article deals with the application of additive technologies in the study of technological processes of chemical and petrochemical industries in the course of work on the topic of a master's thesis. The topic of the thesis involves research in the development of elements of scientific and laboratory equipment for chemical and petrochemical processes using FDM printing technology. FDM printing is one of the most accessible tools in the rich palette of additive technologies. It is characterized by low cost of consumables and ease of maintenance. This enables it to be used in educational institutions for educational and research purposes.

The solution to the research problem will allow the development of tools for scientific equipment prototyping and modeling of technological processes of chemical and petrochemical technology, which will make it possible to provide technical support in conducting scientific research in order to develop new technologies in the chemical and petrochemical industry, as well as the tasks of optimizing the design of machines and apparatuses of chemical processes.

Some of the most interesting applications of additive technologies in chemical engineering and apparatus building include:

- development of effective designs of contact devices in apparatuses for mass transfer processes;
- intensification of heat exchange processes in apparatuses due to new design solutions;
- development of new schemes for the implementation of technological processes based on the results of scientific research;

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- design of automated complexes for the implementation of technological processes using programmable controllers;
- design of training complexes and digital twins for operators and machinists using elements of physical modeling of equipment.

The accumulated world experience in the use of additive technologies shows that modeling and prototyping of processes and apparatuses in chemical technology is a very effective way of laboratory research. Analysis of scientific publications suggests that such studies are carried out in various directions.

In research tasks, the possibility of visual observation of the process is of great interest. When metals and their alloys are used as structural materials for the manufacture of the equipment case, as is customary in chemical technology, it is not possible to directly see and record videos. In laboratory conditions, equipment items that require transparency are made of glass. Modern additive technologies make it possible to create complex-shaped parts of apparatuses from transparent materials, even more complex than what traditional glass blowing technologies can provide. The article [1] presents the results of a study of the possibility of using the stereolithographic method of printing from silicate glass. To do this, the authors of the work stirred fine particles of silicon dioxide and nanocomposite (amorphous silicon nanoparticles) in a photopolymer resin. This composition was used for 3D printing. After the polymer hardened, the models were subjected to high-temperature sintering. The finished products turned out to be quite transparent and retained the required shape.

The issues of obtaining silicon-carbon ceramics with a given porosity using one of the varieties of stereolithography technology are considered in [2].

An interesting approach to the formation of case parts of chemical equipment was proposed in [3]. As a material, the authors propose to use ceramic compositions, which sinter very quickly at high temperatures. Additive technologies are involved here at the first stage of the process in the formation of geometry, when using SLA 3D printing, a base is created on which ceramic materials are applied. In this case, the apparatus body is much stronger and more airtight than the plastic case formed by 3D printing and more corrosion resistant than the carbon steel case.

The technologies proposed in [1] and [3] are, in a certain sense, specific and more laborious and, most likely, fully justify themselves under certain conditions of the technological process. In contrast to them, the article [4] proposes to use a simpler and more technological method for the manufacture of housings and other elements of chemical equipment – the method of layer-by-layer deposition, and use cheap polypropylene as a material. This enables to create pilot plants for the semi-industrial production of dosage formulations. The equipment built in this way was tested under various operating modes and showed high efficiency. It is noted that the use of this technology is limited by the working pressure of the process, its temperature and loaded chemical reagents. In addition, the time resource of the developed equipment is completely unknown. In those cases when the listed parameters are within acceptable limits, the method proposed in [4] seems to be the most optimal.

Another area of application of additive technologies in research and development of technological processes in chemistry and petrochemistry is creation of catalytic complexes for laboratory reactor equipment [5]. As the authors of the work showed, the problem of efficient catalyst preparation, at least for laboratory equipment or pilot plants, can be solved.

A review of the technologies most widely used in the development of research equipment for studying chemical processes: SLA – stereolithography, MJM – multi jet modeling, SLM – selective laser melting, LS – laser sintering, FDM – fused deposition method, is given in [6]. At the same time, the authors note that there is a problem of increasing the thermal and chemical compatibility of various materials used in printing. Its solution would significantly expand the possibilities of additive technologies in the development of research equipment for chemical laboratories.

Prospects for the development of engineering and technology as applied to additive manufacturing are discussed in articles [7] and [8]. In [9], it is noted that the use of 3D printing in relation to chemical processes opens up a new research space at the nexus of chemistry and technology.

2 Experiment

Common and inexpensive materials were used in the work: ABS plastic, PLA, and polypropylene. The issues of constructing complex geometric shapes of parts used in research equipment in the study of chemical and petrochemical processes; strength of their structures; tightness; solvent resistance and manufacturability were considered. The target processes for the study were hydrodynamic, heat and mass transfer processes occurring in typical apparatuses for chemical and petrochemical industries.

The hydrodynamics of flows, as is known, plays a decisive role in heat and mass transfer processes. This, to the full extent, is also true for apparatuses with a packing layer made of discrete material. The equipment that provides technological process in the packing layer is widely used in chemical and petrochemical industries. Such apparatuses include absorption and adsorption columns, distillation columns, and reactors. The question of effective development of research models for studying the processes in packing layers using additive technologies is of interest.

As a model, the process of air filtration through a layer of random packing made of ABS plastic elements was considered. The observed profile of air flow velocities in the layer of bulk material was of interest. Since the measurement of velocities in a dispersed layer is a difficult task, it was decided to determine them indirectly, using the known relationships between them and the intensity of heat transfer. It was decided to determine the heat transfer coefficient by the method proposed in [11].

To determine the distribution of the flow velocity over the packing cross section, a special container for the packing with a diameter of 50 mm was designed and molded by FDM printing. Its 3D model is shown in Figure 1.

Thermocouples pre-welded from wires with a diameter of 0.2–0.3 mm were used as temperature sensors. Thanks to the frameless design of the 3D printer, using a frame structure, it is possible to fuse sensors into the body of the rod at the casting stage.

The container is lowered into the body of the apparatus, covered with cuttings of an ABS plastic bar used for printing, with a diameter of 2.75 and a length of 4–5 mm. Next, the container is covered with a lid and latched with special locks (Fig. 1).

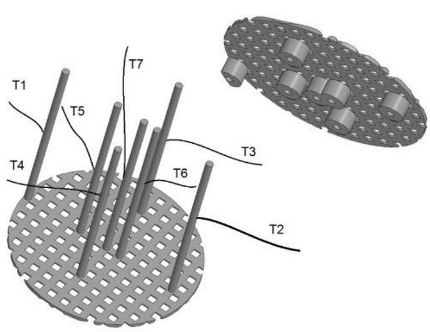

Fig. 1. 3D model of a container for a packing with rods with temperature sensors

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The usage of long rods makes it possible to simulate heat transfer according to the ‘air – infinite cylinder’ scheme. The mathematical model is a heat transfer equation in a cylindrical coordinate system, the initial and boundary conditions are:

$$\begin{cases} \rho c \dfrac{\partial T}{\partial \tau} = \lambda \left(\dfrac{\partial^2 T}{\partial r^2} + \dfrac{1}{r} \dfrac{\partial T}{\partial r} \right) \\ \lambda \dfrac{\partial T}{\partial r} \Big|_{r=R} = -\alpha \left[T_C(\tau) - T_P(\tau) \right] \\ \dfrac{\partial T}{\partial r} \Big|_{r=0} = 0 \\ T \big|_{\tau=0} = T_0 \end{cases}, \qquad (1)$$

where c, ρ, λ are thermophysical characteristics (heat capacity, density, thermal conductivity) of the cylindrical element material constituting the dispersed layer;

α is heat transfer coefficient on the surface of the rod;

r is a cylindrical coordinate, T is temperature, τ is time, Tc(τ) is temperature of the medium (hot air in the heat exchange zone at the current time), Tp(τ) is temperature at the center of the element at the current time.

Tc(τ) and Tp(τ) functions are determined on the basis of experimental data and subsequent approximation by polynomials (Fig. 2). The measurement is carried out at seven points, remote at different distances from the axis of the cylinder, using sensors fused into the corresponding rods (Fig. 1).

The solution to the mathematical model (1) is carried out numerically using a specially developed program. The desired value is the calculated value of the heat transfer coefficient α, which is obtained as a result of solving the inverse problem of thermal conductivity by fitting the simulated temperature change graph to the graph of measured values approximated by a polynomial. Based on these results, the air flow velocity around the cylindrical rods is calculated according to the formula 3.8 [10, p.83]. The resulting velocity distribution over the pipe section is shown in Figure 3. Integrating the velocity profiles shown in Figure 3 gives an air volume flow of 0.645 l/s and an average velocity of 0.33 m/s.

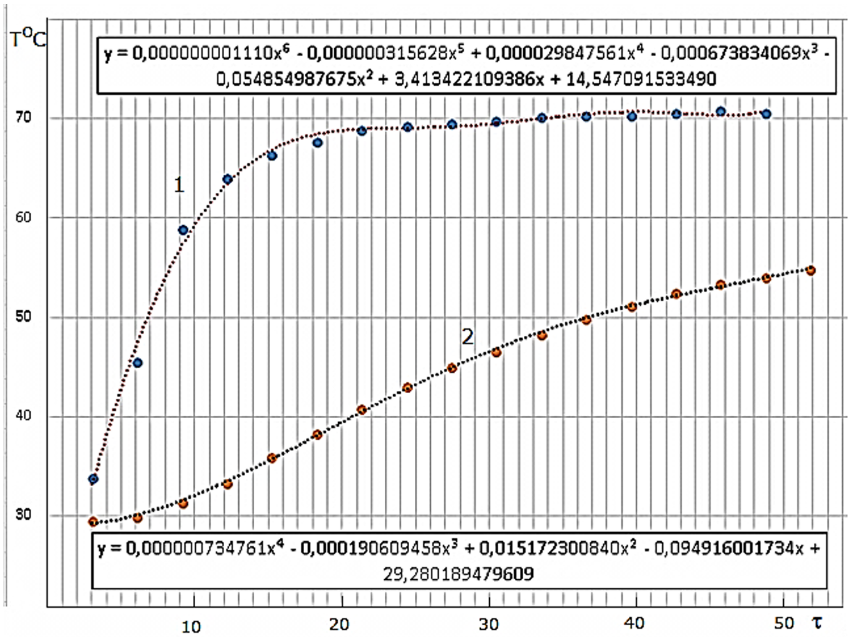

Fig. 2. Approximation of experimental data by polynomials: 1 – temperature of the medium, 2 – temperature inside the ABS plastic rod

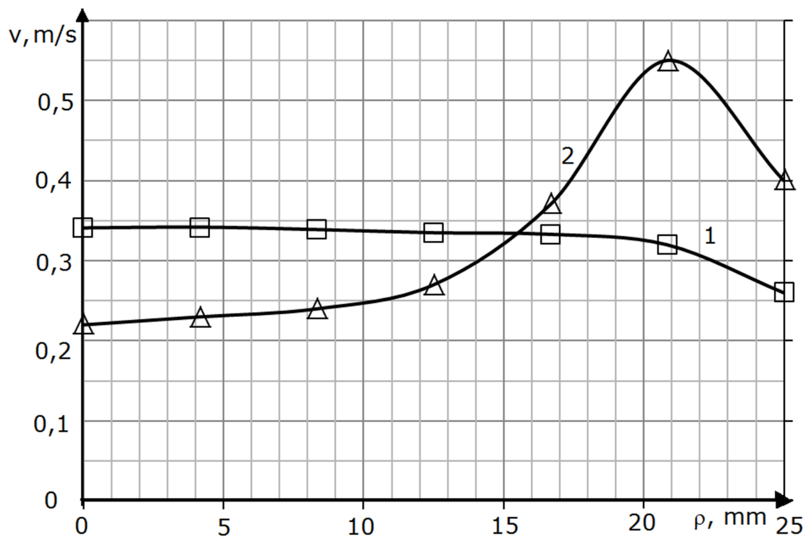

Fig. 3. Flow velocity profile over the pipe section (right segment): 1 – before entering the dispersed layer, 2 – in the layer at the height of temperature sensors installation

The results of measurements and calculations show that the initially almost uniform velocity profile inside the layer is distorted, growing from the center to the periphery. Presumably, such unevenness is generated by the dispersed layer itself, which obviously leads to a decrease in the intensity of heat and mass transfer processes inside the packing.

With the help of additive technologies, it is possible to exert a targeted influence on the velocity profile of the gas phase inside the mass transfer apparatus by forming special geometry of the packing model. For example, Figure 4 shows one variant of such a device

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that redirects part of the flow from the center of the cylinder to the periphery. At the same time, the design feature of the model is such that it makes it easy to remove the so-called support for overhanging elements after printing. In Figure 4, this is not so clearly visible, but the transverse gratings are printed in such a way that each grating located above is displaced along both horizontal axes by the value of the diameter of the rod. As a result, the section normal to the direction of flow is completely blocked, but in the lateral direction there are gaps equal to the diameter of the rod. The air flow contacts with the liquid film on the bottom and side surfaces of the rod, goes around it and moves into the free volume of the cell. A small part of the flow, having encountered some resistance in the forward direction, rushes along the guide to the center of the packing, along the way contacting with the liquid that breaks off from the contact device rods located above.

Comparison of the main characteristics of the obtained packing with corresponding characteristics of the most common packings, for example, Pahl rings, shows good results. With approximately the same, for example, in comparison with Pahl rings, free volume – 90% and packing density – 96 kg/m^3, the specific surface is almost one and a half times higher – 400 m^2/m^3.

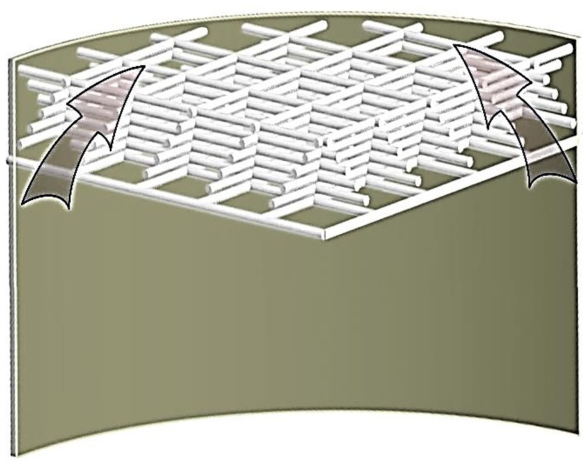

Fig. 4. 3D model of the contact device element in section (segment of 90 degrees) acting on the profile of the gas phase flow velocities

Using this technique, it is easy to create packings that affect the flow structure by moving it in the desired direction, for example, by twisting it in a spiral. To do this, pre-printed standard modules with the same locks as in a children's construction sets, which are assembled both in-plane and in elevation.

Comparison of the efficiency of packing-type contact devices printed on a 3D printer was carried out in the constructed model of a laboratory mass transfer apparatus, in which water was supplied from above through a sprinkler as a liquid phase, and air was supplied from below towards the water flowing through the packings as a gas phase. The efficiency of this or that device was evaluated by the degree of humidification of initially dry air by parallel measurement of its humidity at the inlet and at the outlet of the packing layer.

In addition, the issue of the resistance of the material of printed products to solvents, which is important for chemical equipment, was considered. The tests were carried out according to two methods: three-minute exposure of samples at room temperature in a bath with a solvent, which was acetone; and the same length of exposure in solvent vapor at the temperature of its evaporation. The processed products were tested on a tensile testing machine [12] after 2, 14 and 60 days. ABS plastic showed that its tensile strength after solvent exposure decreased from 38.74 MPa to 26.05 MPa (bath) and 28.75 MPa (steam). Thus, the strength of ABS plastic is reduced by a third. For PLA plastic, the tensile strength of samples decreased even more: for treated with solvent vapors from 53.95 MPa to 13.48 MPa, for exposed in the bath – up to 36.28 MPa. However, what is interesting is that after some time (14 and 60 days), PLA plastic samples regain some of their strength (Fig. 5).

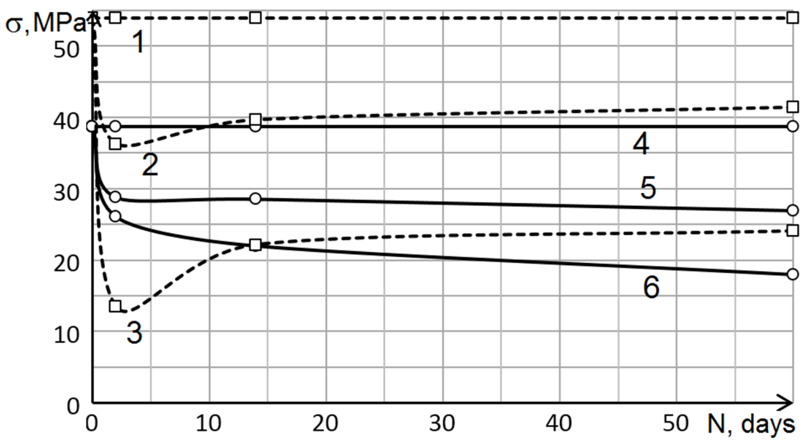

Fig. 5. Dynamics of change in the tensile strength of samples printed on a 3D printer: 1, 4 – from ABS and PLA without processing; 2, 3 – solvent-treated ABS (steam and bath); 5, 6 – solvent-treated PLA (steam and bath)

In any case, a short-term effect of the solvent to the elements of equipment made of plastic by 3D printing does not lead to their destruction without a significant load. For example, at an excess pressure of 1 bar, the normal stresses in the wall of the cylindrical body of the model do not exceed 1.5 MPa, and there is still a fairly large margin of safety.

3 Conclusion

The present studies have shown that the design of scientific research equipment for studying technological processes in petrochemistry can be based on the use of FDM printing tools from inexpensive materials: ABS and PLA plastics. This ensures sufficient strength and tightness. The resistance of materials to strong solvents is not sufficient for studying long-term processes, but short-term exposure is quite acceptable. In addition, the experiment can be carried out using model reagents that do not affect these types of materials. The main advantages of using additive technologies in modeling processes and equipment in chemistry and petrochemistry are low time and financial costs for the design of research equipment. An important circumstance is that the researcher is able to build most of the laboratory equipment on his own without specialized organizations, which gives flexibility to the experiment, allowing changes in the design of equipment elements along the way.

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