Additive Manufacturing in the Development of Scalable Models of Technological Equipment

Ildar Sabanaev^{1,*} and Alexey Dinmuhametov¹

¹Nizhnekamsk Chemical Technology Institute, 47 Stroiteley str., Nizhnekamsk, Russian Federation

Abstract. The article presents the results of a study of effective methods for the development of full-scale models of technological equipment for chemical and petrochemical industries based on the use of additive manufacturing. It is shown that 3D printing can be used to prepare and test various elements of heat and mass transfer devices with great accuracy and in the shortest possible time. It is concluded that the use of additive manufacturing allows for significant efficiency of research work in the field of industrial chemistry and petrochemistry.

1 Introduction

Despite its relative novelty, additive manufacturing is widely used in various fields of science, technology, and even in everyday life. When a limited manufacturing of products is required, the use of such tool is not only justified, but also proves to be the most effective in comparison with others. It is not surprising that additive manufacturing is rapidly developing, improving and covering all new spheres of human activity [1], [2]. Its use is justified both for the manufacture of small parts and for large-scale production. For example, article [3] discusses technologies of large-scale additive manufacturing, which are used in construction and architecture, and, in particular, technologies for printing concrete using an automated process based on the extrusion method.

They give a great positive effect in science, including in the field of research of technological processes, equipment and improvement of hardware design in chemical and petrochemical machine and apparatus construction [4]. In this area, the most promising directions can be considered the development of heat and mass transfer equipment, which has the best performance in heat and mass transfer. The use of additive manufacturing makes it possible to speed up the process of development and approbation of technological equipment elements of different purpose and complex geometry and, which is essential, to increase the accuracy of their manufacture in terms of compliance with dimensions and design features [5].

A natural experiment using large-scale models of technological machines and devices makes it possible not only to verify the results of mathematical and computer modeling, but also to significantly supplement them, to bring them as close as possible to the values that arise in real production conditions. The experimental technique using 3D printing and computational modeling as digital tools for the best design and manufacture of chemical

* Corresponding author: sabanaevia@nchti.ru

reactors and the design of catalysts was applied by the authors of [6]. Their research aimed to ensure the interaction of the latest technologies at the intersection of chemistry and materials science, on the one hand, and digital manufacturing and computational modeling, on the other.

Scale models developed using 3D printing tools are fully functional analogs of the device, observing the geometric similarity of the shape and its internal elements. The elements of equipment built with the help of additive manufacturing, as noted by many researchers, have a high accuracy of shape [7] and, at the same time, are highly technological to manufacture. This allows in a short time to make various modifications of the investigated devices and conduct an experiment to find the best geometric shape [8]. Similar results were obtained in [9]. The authors note that 3D-printed rectangular cross-section catalytic mixers coated with a $\text{Pd}/\text{Al}_2\text{O}_3$ metal oxide catalyst have shown excellent catalytic performance for the continuous hydrogenation of nitroaromatics.

2 Experimental part

This article presents the results of studying ways to improve the efficiency of a technological unit for separating hydrocarbons. The main element of the plant in a production environment is a distillation column with a height of 7600 mm, a diameter of 800 mm, with sixteen trays carrying cap-type contact devices. For the manufacture of a real apparatus, low-carbon deoxidized steel is used. This material is characterized by good strength and toughness in the temperature range from 40 ° C to + 200 ° C. It is used for welded chemical equipment that is not in contact with aggressive media. The steel is well deformed and cut. Sheets made of this steel are well stamped and easily welded by all types of electric welding.

In laboratory conditions, a scale model for studying the studied process can be made of ABS plastic on a reduced scale by printing on a 3D printer. According to the accepted terminology [10], 3D printing from polymer materials belongs to a group of methods based on material extrusion, where the material is fed through a nozzle or a jet. When forming a solid model of the apparatus from plastic, it was decided to fully observe the geometric similarity to the original. The only exception was the thickness of the column, which had to be slightly increased in order to ensure sufficient strength and rigidity. The choice of ABS plastic as a material is explained by its inertness with respect to the components of the liquid mixture to be separated, as well as by its low price and availability, which is important given the need for its significant consumption.

During the study, three-dimensional computer models of parts were developed using a CAD system, converted to STL format. Then the model was vectorized and loaded into a 3D printer. The 3D printer used in the work, like any other, has restrictions on the dimensions of the parts being created. In our case, the critical dimension is the height of the apparatus. The solution to the problem is to split the distillation column into separate sections - rings. After casting, all the rings are joined along the flanges and connected by small-sized bolted joints, as well as sealed with rubber gaskets. After assembly, the column apparatus is connected to the rest of the elements of the technological unit model (Fig. 1).

Fig. 1. Physical model of the experimental setup with a printed 3D model at a scale of 1:10

All fittings: for feed supply, distillate extraction, reflux supply, vat extraction, are equipped with special adapters for mating with threaded elements and subsequent connection with pipeline fittings. Column support is standard cylindrical. The welded method of joining the column with the support, used in the standard apparatus, has been replaced with an adhesive joint.

The three-dimensional models of plates with contact devices (Fig. 2) are printed as a single non-separable element with a simple fastening device inside the ring (Fig. 3), which makes them easy to replace. For research, several types of original contact devices were manufactured. Previously, the shape and design features of the proposed plates were tested using computer modeling and unsuccessful options were rejected. The experiment was carried out in order to select the most effective device by comparing them with each other and with the standard type of contact devices based on the results of the experiments.

Fig. 2. 3D printed model of a plate with contact devices

The technology of three-dimensional printing of plastic equipment elements makes it possible, among other things, to solve the problem of optimizing the heat exchangers involved in the technological unit by intensifying the heat exchange process based on the

use of special design techniques, such as, for example, the use of pipes with artificial discrete roughness. Such effect such as cross knurling with any given profile can be easily modeled when printed on a 3D printer. As a rule, when solving such problems, several characteristic profiles are of greatest interest - wing, rectangular, trapezoidal, round, parabolic with different step and height of the protrusion into the inner space of the pipe. Due to the known limitations on the longitudinal dimension during printing, the pipe is formed from several segments, which are then connected to a single element. To give a smooth surface, each segment is treated in a solvent before joining. The elements of chemical equipment developed in this way are not disposable, but allow several - according to [11] from 5 to 10 test cycles.

Fig. 3. Elements of the column apparatus printed on a 3D printer

To assess the intensity of heat transfer during the experiment, the heat transfer coefficient is calculated based on the measurement of the heat transfer coefficients on the pipe surfaces similarly to the method described in [12]. A diagram of the device for conducting an experiment with a pipe made with periodic artificial roughness in the form of a wing profile is shown in Figure 4. Thermocouples intended for temperature measurement are pre-welded from thin copper and constantan wires and placed into the pipe wall during the 3D printing process on required depth (Fig. 4). The thermocouple wires have good thermal insulation throughout. The outer diameter of the discrete roughness pipe is 20 mm. The pipe thickness, excluding the height of the projections, is 3.4 mm. The height of the protrusion of the elements of artificial roughness h and the pitch of the protrusions S (period) vary in different experiments. The outer pipe has a diameter of 50 mm. Hot air is injected into the annular space as a heat carrier.

To determine the value of the heat transfer coefficient on the pipe surfaces α_1 and α_2 , the inverse problem of heat transfer is solved, whose solution essence is to restore the calculated temperature profile from the dynamics of the temperature change curve $T_1(\tau)$ and $T_2(\tau)$ measured using thermocouples at the given points $r = R_1, r = R_2$.

Fig. 4. Diagram of installing thermocouples in the printed segment

The mathematical model of the problem in the form of a differential equation in a cylindrical coordinate system, as well as boundary and initial conditions, in dimensional form is represented by formulas (1) - (4):

$$\rho c \frac{\partial T}{\partial \tau} = \lambda \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) \quad (1)$$

$$\lambda \frac{\partial T}{\partial r} \Big|_{r=R_2} = -\alpha_2 [T_{C2} - T_2] \quad (2)$$

$$\lambda \frac{\partial T}{\partial r} \Big|_{r=R_1} = \alpha_1 [T_{C1} - T_1] \quad (3)$$

$$T \Big|_{\tau=0} = T_0 = T_{C1} \quad (4)$$

where c , ρ , λ are thermophysical characteristics of the pipe wall material;

T_{c1} , T_{c2} are temperatures of hot and cold environments

R_1 , R_2 are outer and inner radii of the inner pipe;

ρ is polar coordinate.

When solving the problem, boundary conditions (2) and (3) of mathematical model (1) are well interpolated on basis of experimental data $T_1(\tau)$ and $T_2(\tau)$ by polynomials of the sixth degree. The main equation is solved by the finite-difference approximation method. To solve the problem, a computer program has been developed that simulates each test in the experiment. Computer simulation of the process aims to find the best approximation to the measured values. The sign of the end of iterations is the minimum value of the F-criterion, calculated from the variance of the previously constructed regression model and experimental data, and the variance calculated from the results of solving the problem by the numerical method. The simulated values of the heat transfer coefficients, which give the best approximation to the experimental data, are taken as a result of solving the problem.

3 Conclusions

The study made it possible to solve the entire set of the tasks.

First, with the help of additive manufacturing, a scale model of the column apparatus has been built and its performance has been shown.

Secondly, a number of experiments was carried out to develop contact devices of different geometry in order to determine the most effective of them in terms of intensity of mass transfer. It was shown that, thanks to the use of additive manufacturing, it became possible to significantly reduce the time for constructing physical models of devices in chemical and petrochemical technology, to expand the options for new types of devices proposed for research, to increase the accuracy of the dimensions and shape of structural parts of technological equipment.

In addition, using 3D printing technology, different variants of the inner pipe of the heat exchanger used in the model of the technological unit were built. The variants were considered where profiles with an increased value of the heat transfer coefficient due to the use of artificial discrete roughness on the inner surface were used. It was shown that, despite the low thermal conductivity of polymeric materials, for research purposes, the use of plastic pipes in a heat exchanger can be justified due to simplicity of manufacturing heat transfer intensifiers of any geometric profile, ease of introducing thermocouples into any point of the pipe wall.

And in conclusion, it can be noted that the authors of the work have developed a computer model that uses the experiment results to calculate heat transfer coefficients, which makes it possible to compare various options for the design of pipes with artificial surface roughness.

References

1. Y.W. Tay, B. Panda, S.C. Paul¹, M.J. Tan¹, S. Qian, K.F. Leong 2016 Materials Science Forum. **861**, pp. 177-181.
2. C. Chua, K. Leong 2014 Fourth Edition of Rapid Prototyping. <https://doi.org/10.1142/9008>, Pages: 548.
3. S. Lim, R.A. Buswell, T.T. Le, S.A. Austin, A.G.F. Gibb, T. Thorpe 2012 Autom. Constr. **21**, pp. 262–268.
4. N.O. Sadik, S.M. Mus, O.M. Musa 2018 Invention Journal of Research Technology in Engineering & Management (IJRTEM). **2(2)**, pp. 24-26.
5. A.V. Dmitriev, I.A. Sabanaev, O.S. Dmitrieva 2017 Journal of Engineering Physics and Thermophysics. **90(3)**, pp. 715-720.
6. C. Parra-Cabrera, C. Achille, S. Kuhn, R. Ameloot 2017 Chemical Society Reviews. **47(1)** DOI:10.1039/C7CS00631D.
7. S. Ford 2014 Journal of International Commerce and Economics. Published electronically, <http://www.usitc.gov/journals>.
8. N. Efimenko, I. Sabanaev, I. Madyshev 2019 MATEC Web of Conferences. **298** <https://doi.org/10.1051/matecconf/201929800026>.
9. R. Lebl, Y. Zhu, D. Ng 2020 Catalysis Today. DOI:10.1016/j.cattod.2020.07.046
10. ISO/ASTM 52900-15, Standard Terminology for Additive Manufacturing-General Principles Terminology, (2015).
11. M.R. Penny, S.T. Hilton 2020 Reaction Chemistry & Engineering. **5(5)**, DOI:10.1039/C9RE00492K.
12. I. Faizrahmanov, I. Sabanaev 2020 IOP Conf. Ser.: Mater. Sci. Eng. 709 033050 <https://doi.org/10.1088/1757-899X/709/3/033050>